Quantum Gravity and Emergent Cosmology: A Group Field Theory Perspective

A collective effort: D. Oriti, E. Wilson-Ewing, A. Jercher, T. Ladstätter, A. Pithis, S. Gielen, V. Husain, H. Mehmood, R. Dekhil, L. Mickel, A. Calcinari, P. Pellecchia, F. Greco. . .

Luca Marchetti

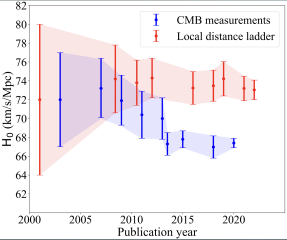
Loops '26

Hangzhou

May 29

OIST
Kavli IPMU

An exciting time for Cosmology



- Hubble tension[1]

[1] Hu, Yang 2302.05709;

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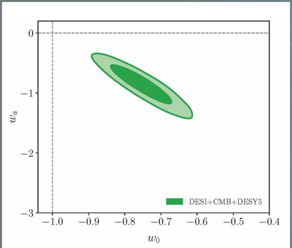

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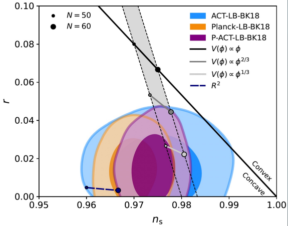

- Hubble tension[1], dynamical dark energy[2], constraints on inflation[3]...

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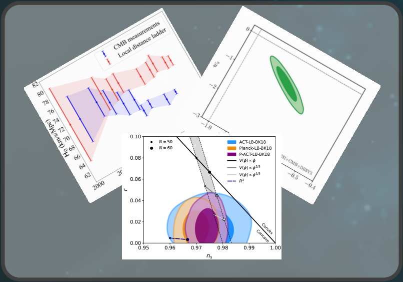

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Theory is lagging behind!

Current approaches largely phenomenological:

- Limited fundamental explanatory power.
- Theoretical tensions.
  (e.g. stable phantom DE very difficult to realize, inflationary UV/Planck sensitivity...)
- Model selection challenges.
  (e.g. excessively large set of parameters, sensitivity to prior-volume effects).

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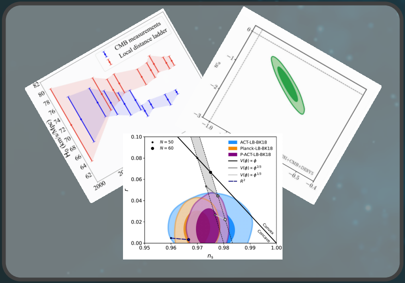

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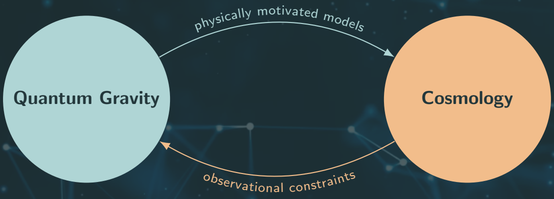

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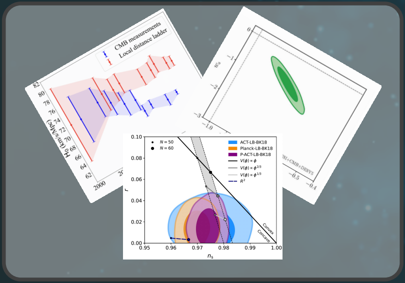

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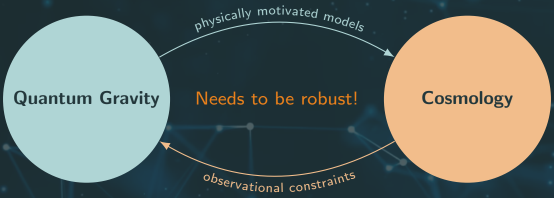

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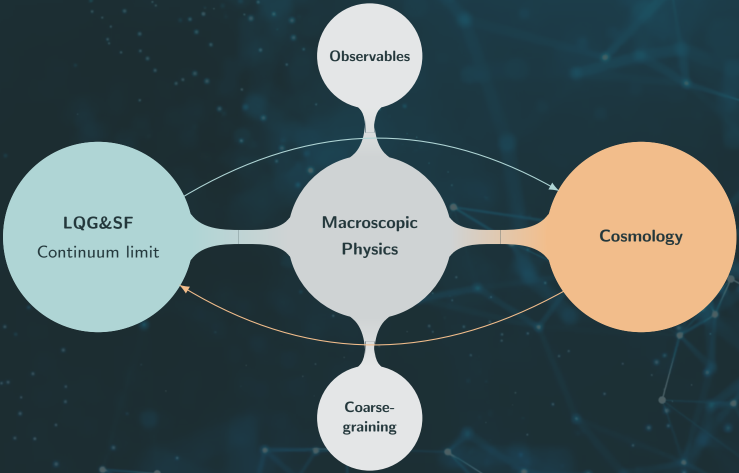
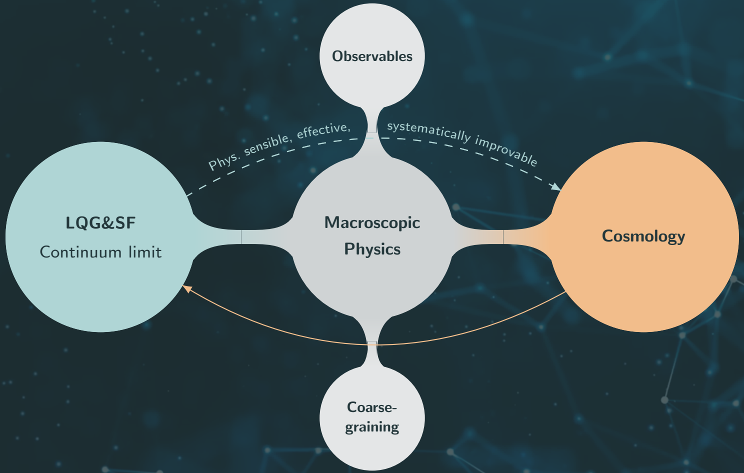

Observables
LQG&SF
Continuum limit
Macroscopic
Physics
Cosmology
Coarse-
graining


Observables
Phys. sensible, effective,
systematically improvable
LQG&SF
Continuum limit
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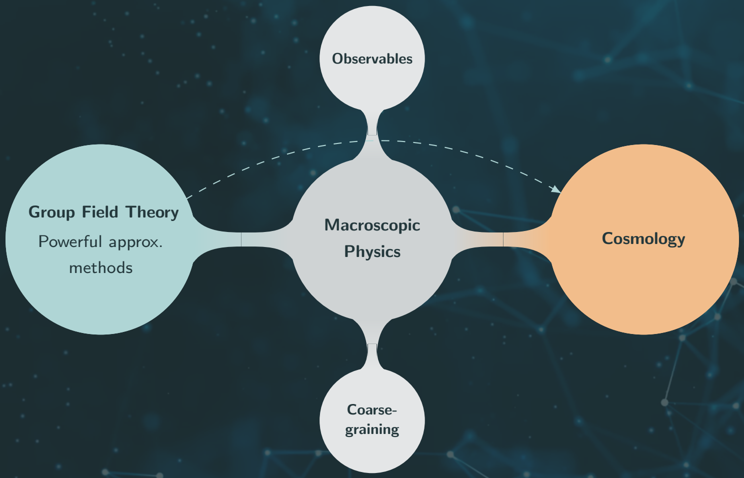
Observables
Group Field Theory
Powerful approx. methods
Macroscopic Physics
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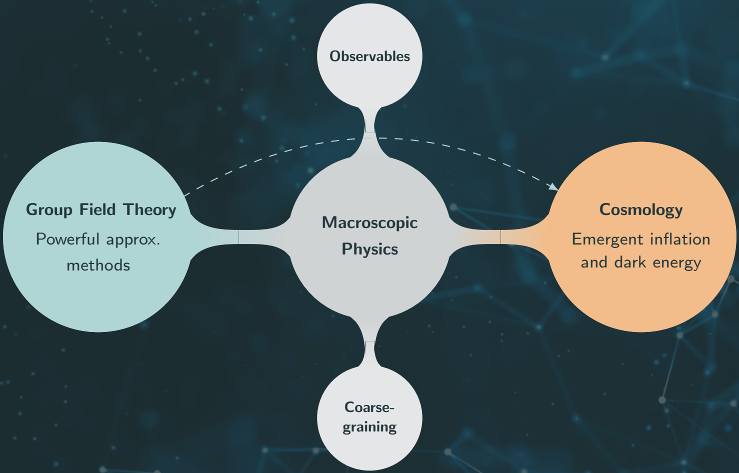
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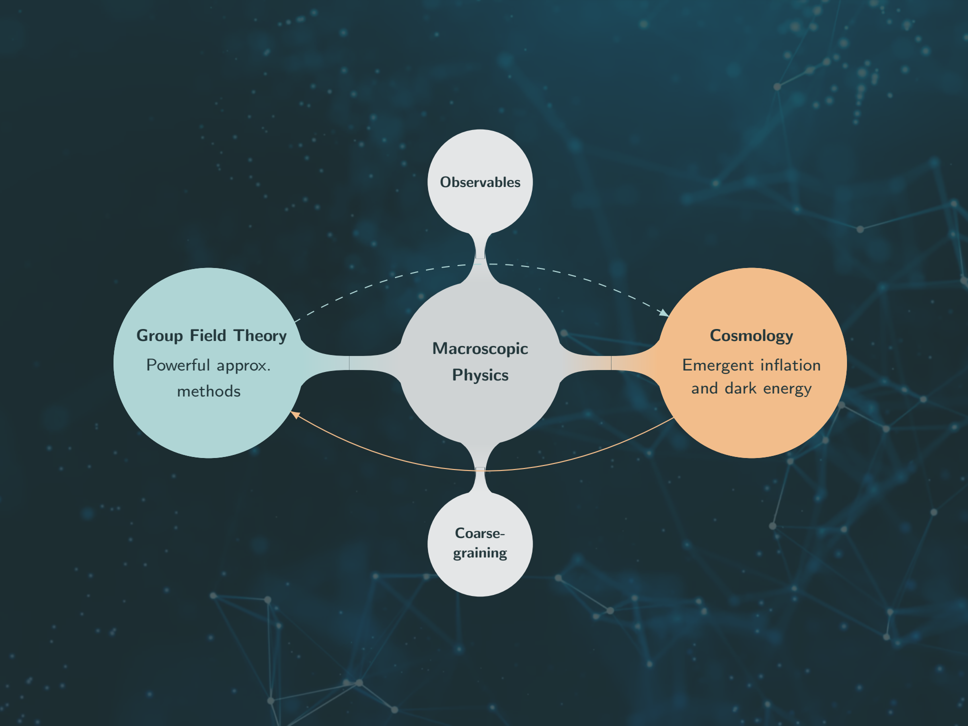

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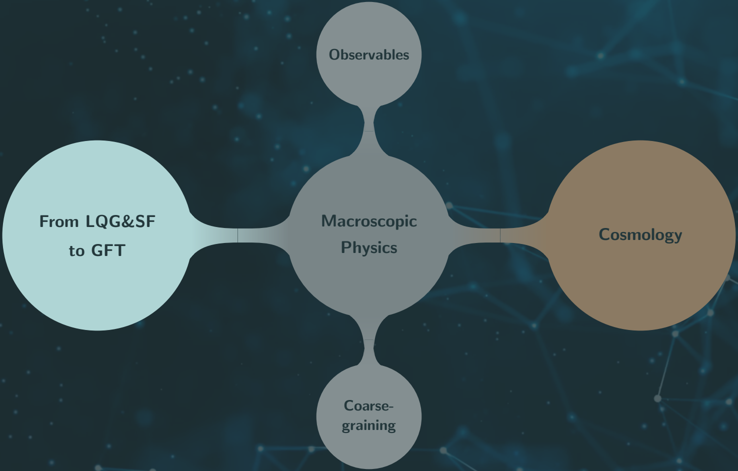
Observables
From LQG&SF to GFT
Macroscopic Physics
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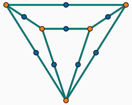
Coarse-graining

From LQG&SF to Group Field Theories (I)

Spinfoams Combinatorics

Boundary graphs[1]

- Bisected boundary graphs: in one-to-one correspondence with boundary graphs.



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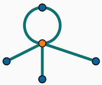

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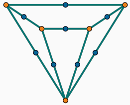

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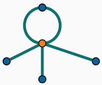

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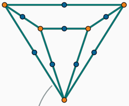
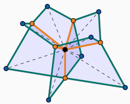


Atoms and molecules[1]

- Spinfoam atom: Constructed from boundary graph via a one-to-one bulk map.



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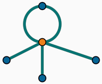

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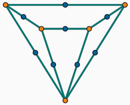

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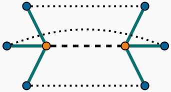

- Spinfoam atom: Constructed from boundary graph via a one-to-one bulk map.
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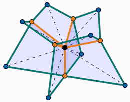

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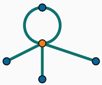

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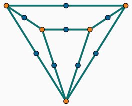

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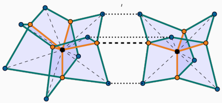

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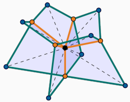

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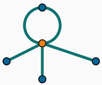

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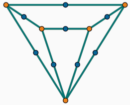

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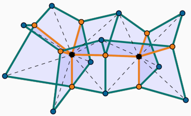

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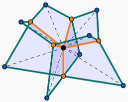

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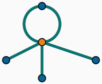

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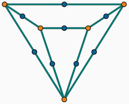

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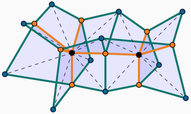

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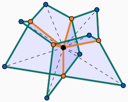

Models

Quantum Gravity dynamics[2]

$$Z_{\mathrm{sf}} = \underbrace{\sum_{\mathfrak{m}\in\mathfrak{M}}}_{\text{Sum over molecules}} \underbrace{w(\mathfrak{m})}_{\text{Measure factor}} \overbrace{A(\mathfrak{m})}^{\text{Spinfoam amplitude}}$$

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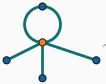
From LQG&SF to Group Field Theories (II)

General Structure

Fields and Observables[1]



Group field Group manifold

$\phi(\mathbf{g}) : \mathcal{G} \to \mathbb{C}$ (Generates associated Fock space of boundary patches, related to $\mathcal{H}_{\text{diff}}$)

QG Models

Quantum Gravity dynamics[1,2]

- $\mathcal{G}$: Encodes spinfoam (geometry and matter) data. Regular simplicial models $\mathcal{G} = G^4 \times M$, with $G = \mathrm{SU}(2)$ or $\mathrm{SL}(2, \mathbb{C})$.

  M matter manifold: for n real scalars, $M = \mathbb{R}^n$

[1] Oriti, Ryan, Thürigen 1409.3150; Freidel 0505016; [2] Reisenberger, Rovelli 0002083; Oriti 1110.5606; Krajewski 1110.5606...

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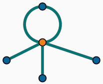
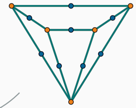


$$\phi(\mathbf{g}) : \mathcal{G} \to \mathbb{C}\,,$$

Patches generating $\mathfrak{b}$

$$B_{\mathfrak{b}}[\phi] = \int [\mathrm{d}\mathbf{g}]\, \mathcal{B}_{\mathfrak{b}}(\{\mathbf{g}\}_{\{\mathfrak{p}\}\in\mathfrak{b}}) \prod_{\{\mathfrak{p}\}\in\mathfrak{b}} \phi_{\mathfrak{p}}(\mathbf{g}_{\mathfrak{p}}) + \text{c.c}\,.$$

Trace "observables" Boundary graph



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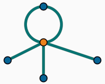

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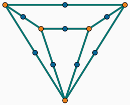

Action[1]

$$S[\phi] = \overbrace{K[\phi]}^{\text{Kinetic}} + \sum_{\mathfrak{b}} \overbrace{V_{\mathfrak{b}}[\phi]}^{\text{Interactions}}$$

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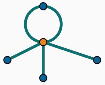

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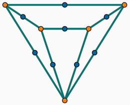
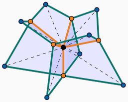


Action[1]

$$S[\phi] = K[\phi] + \sum_{\mathfrak{b}} V_{\mathfrak{b}}[\phi]$$

$$V_{\mathfrak{b}}[\phi] = \int [\mathrm{d}\mathbf{g}]\, \mathcal{V}_{\mathfrak{b}}(\{\mathbf{g}\}_{\{\mathfrak{p}\}\in\mathfrak{b}}) \prod_{\{\mathfrak{p}\}\in\mathfrak{b}} \phi_{\mathfrak{p}}(\mathbf{g}_{\mathfrak{p}}) + \text{c.c.}\,,$$



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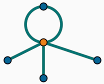

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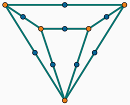

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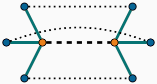

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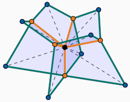


QG Models

Quantum Gravity dynamics[1,2]

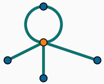
- $\mathcal{G}$: Encodes spinfoam (geometry and matter) data. Regular simplicial models $\mathcal{G} = G^4 \times M$, with $G = \mathrm{SU}(2)$ or $\mathrm{SL}(2, \mathbb{C})$.

[1] Oriti, Ryan, Thürigen 1409.3150; Freidel 0505016; [2] Reisenberger, Rovelli 0002083; Oriti 1110.5606; Krajewski 1110.5606...

From LQG&SF to Group Field Theories (II)

General Structure

Fields and Observables[1]



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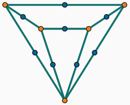

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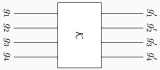

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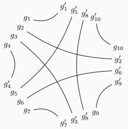

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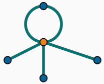

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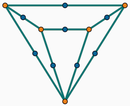

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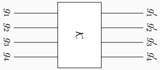

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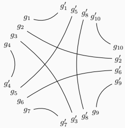

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Combinatorial weights

Feynman amplitudes

$$Z_{\text{GFT}} = \sum_{\Gamma} w(\Gamma) A(\Gamma)$$

Sum over Feynman diagrams

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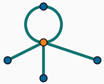

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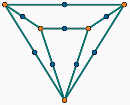

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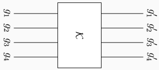

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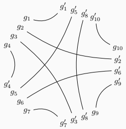

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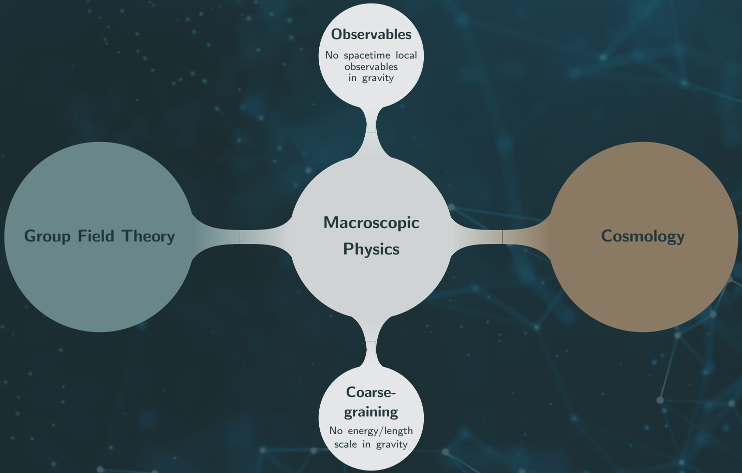
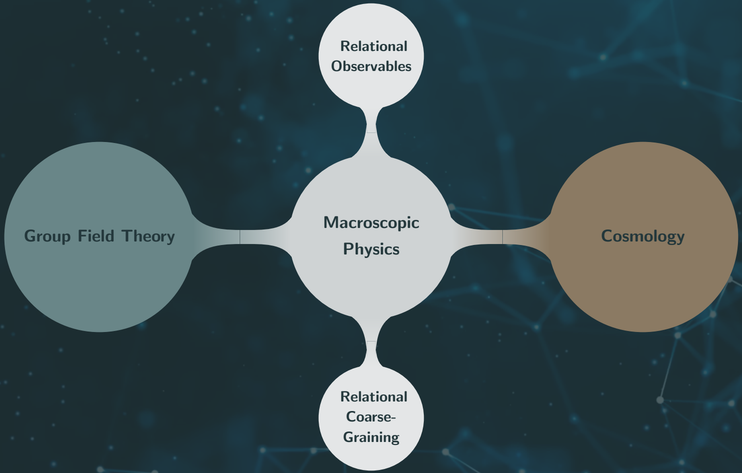

Observables
No spacetime local observables in gravity
Group Field Theory
Macroscopic Physics
Cosmology
Coarse-graining
No energy/length scale in gravity


Relational Observables
Group Field Theory
Macroscopic Physics
Cosmology
Relational Coarse-Graining

Relational Gravity Field Space

Observables for Gravity

- **Dynamical Frames**[1]: $R[\varphi] : \mathcal{N} \to \mathcal{O}_R$ such that $R[f_\star \varphi] = R \circ f^{-1}$.

  Spacetime region $\uparrow$ $\uparrow$ Orientation space region

[1] Goeller et al. 2206.01193... [2] Rovelli 1991; Dittrich 0507106... [3] Aguilar, Ferrero, Höhn, LM (next week); [4] Aguilar, Ferrero, Höhn, LM (to appear);

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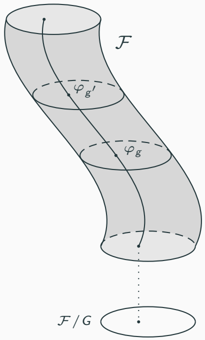

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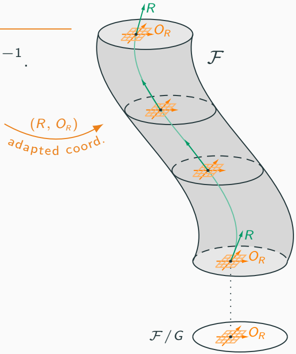

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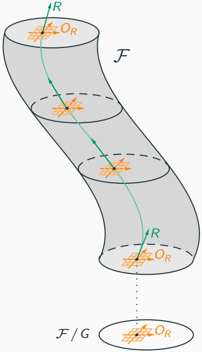
Invariant Relational Path-Integral[3]

Global frame

$$Z = \int \mathcal{D}\hat{O}_R[\det \bar{\mathfrak{G}}_R \det \gamma]^{1/2}[\hat{O}_R]e^{iS_R[\hat{O}_R]}$$

Induced horizontal metric

Gauge orbit metric/QRF contribution



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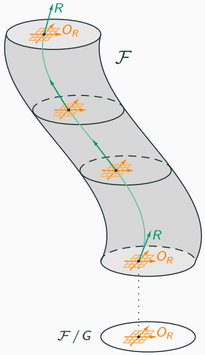

QRFs for Gravity and Relational RG

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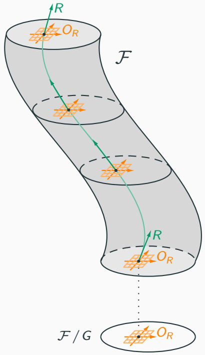

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Effective actions

Effective Actions and Relational RG

- Relational effective action[3]: coupling $\underbrace{J_R}_{\text{Relational sources}} \cdot \hat{O}_R$ leads to $\underbrace{\Gamma_R[O_R]}_{\text{Gauge-invariant effective action}}$ and frame-covariant quantum shell.

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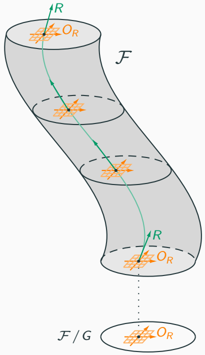

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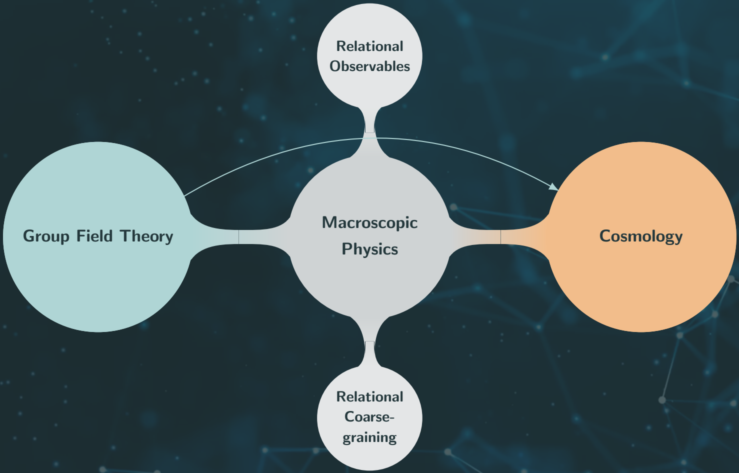
- Relational RG[4]: Introduce a regulator $\mathcal{R}[\bar{\Box}_R / k^2]$ on frame space to define relational (F)RG flow.

Physical coarse-graining = Relational RG

[1] Goeller et al. 2206.01193... [2] Rovelli 1991; Dittrich 0507106... [3] Aguilar, Ferrero, Höhn, LM (next week); [4] Aguilar, Ferrero, Höhn, LM (to appear);



Relational Observables
Group Field Theory
Macroscopic Physics
Cosmology
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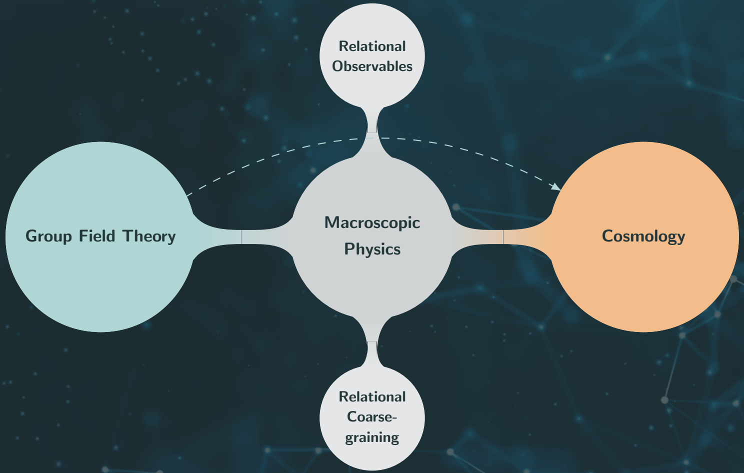
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GFT mean-field theory

Effective

LQG and macro physics [1]

"Perspective neutral" GFT action

Peaking function (frame reduction)

$$\Gamma_{\mathrm{GFT};R}[\sigma_R] \simeq S_{\mathrm{GFT};R}[\sigma_R] \equiv S_{\mathrm{GFT}}[\eta_R \sigma_R]$$

Relational GFT EA

Relational classical GFT action

[1] LM, Oriti 2008.02774-2112.12677; LM et al. 2110.15336-2209.04297-2211.12768 [2] Oriti, Sindoni, Wilson-Ewing 1602.05881; [3] LM, Wilson-Ewing

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$$\Gamma_{\mathrm{GFT};R}[\sigma_R] \simeq S_{\mathrm{GFT};R}[\sigma_R] \equiv S_{\mathrm{GFT}}[\eta_R\sigma_R]$$

- Refinement: MFA includes all tree level graphs; equivalently described by coherent state $|\eta_R\sigma_R\rangle$.

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Macroscopic quantities = mean relational observables

- Collective behavior is captured by one-body observables $O[\sigma]$, quadratic in the mean-field σ.[2]
- Their relationally local representation[1,3] is $O_R[\sigma_R](x) \equiv O[\eta_R \sigma_R](x)$, η_R peaked on $R = x$.

Full construction beyond MFT available using QRF techniques[3]

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Coarse-graining

Macroscopic dynamics = relational GPE[1,2]

$$\boxed{\mathcal{K}_R[\sigma_R] + \mathcal{V}_R[\sigma_R] = 0\,.}$$

- Usually $\mathcal{K}_R$ is a 2nd order frame-differential operator. $\mathcal{V}_R$ generally non-local and non-linear.
- Cosmology: Non-linear and non-local extension of quantum cosmology (QG relational GPE).

Macroscopic quantities = mean relational observables

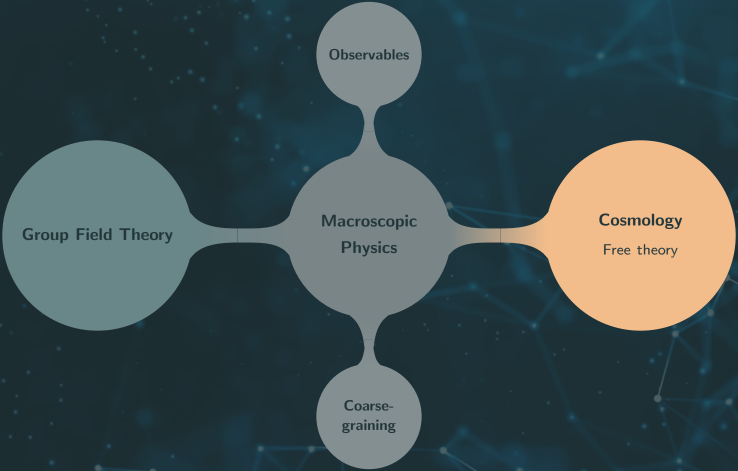
- Collective behavior is captured by one-body observables $O[\sigma]$, quadratic in the mean-field σ.[2]
- Their relationally local representation[1,3] is $O_R[\sigma_R](x) \equiv O[\eta_R\sigma_R](x)$, η_R peaked on $R = x$.

Only geometry+frame matter

Group rep. labels

$$\underbrace{N_R[\sigma_R](x)}_{\text{Number of quanta}} = \sum_{\boldsymbol{\upsilon}} |\sigma_{R;\boldsymbol{\upsilon}}(x)|^2\,, \qquad \underbrace{V_R[\sigma_R](x)}_{\text{Volume operator}} = \sum_{\boldsymbol{\upsilon}} \underbrace{\mathfrak{v}_{\boldsymbol{\upsilon}}}_{\text{Volume eigenvalue}} |\sigma_{R;\boldsymbol{\upsilon}}(x)|^2\,.$$

[1] LM, Oriti 2008.02774-2112.12677; LM et al. 2110.15336-2209.04297-2211.12768 [2] Oriti, Sindoni, Wilson-Ewing 1602.05881; [3] LM, Wilson-Ewing


Observables
Group Field Theory
Macroscopic Physics
Cosmology
Free theory
Coarse-graining

Background[1]

- **Homogeneity**: $\sigma_{R;\boldsymbol{v}}(x) = \sigma_{\chi^0;\boldsymbol{v}}(x^0) \equiv \sigma_{\boldsymbol{v}}(x^0)$.

Minimally coupled,
massless and free scalar

[1] LM, Oriti 2008.02774-2010.09700; Oriti, Sindoni, W.-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091; [2] Jercher, LM, Pithis 2310.17549-2308.13261.

Homogeneous and Isotropic

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$\upsilon_{\text{EPRL}} \in \mathbb{N}/2$, $\upsilon_{\text{BC}} \in \mathbb{R}$

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FLRW Dynamics and Perturbations

Homogeneous and Isotropic

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$$
\begin{aligned}
V_\sigma(x^0) &= \sum\nolimits_{\upsilon} \mathfrak{v}_{\upsilon} |\sigma_{\upsilon}|^2(x^0). \\
&= \bar{V}_0 a^3 \quad \longrightarrow \quad \{\mathcal{H}(V_\sigma), w(V_\sigma)\}\,.
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Same scaling as N_σ

Late times[1]

- Late times (large V_σ) $\to$ large N_σ $\to$ classical.

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$$H^2 \simeq \frac{8\pi G}{3}\rho_{\chi^0}$$

Single mode dominations

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LQC-like bounce

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Cosmic inhomogeneities[2]

- **Frame causal coupling**: (within extended GFT BC)
- **Beyond MFT**: introduce 2-body correlations.

Inhomogeneities from QG correlations

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$$\tilde{\mathcal{R}}''_{\mathrm{GFT}} + k^2 a^4 \tilde{\mathcal{R}}_{\mathrm{GFT}} = \underbrace{j_{\tilde{\mathcal{R}}}(k/M_{\mathrm{pl}})}_{\text{Late-times, mesoscopic, single-mode}}\,,$$

- Corrections are important at trans-Planckian scales.

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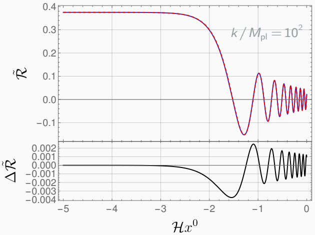

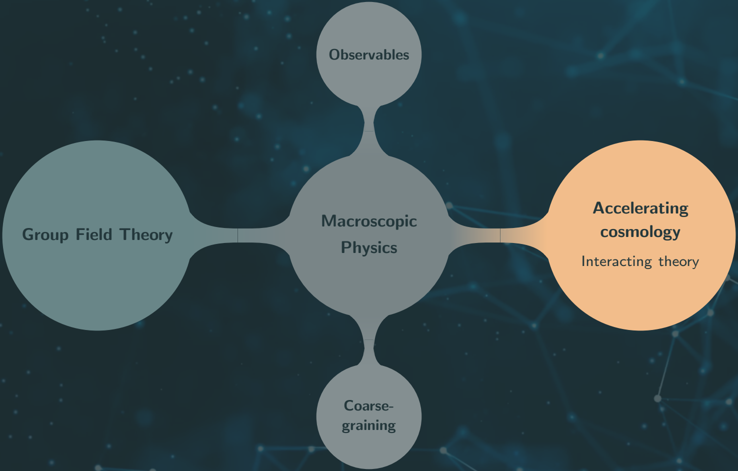
Observables
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Mean-field model

Model and Assumptions[1,2]

kinetic kernel   int. order $\in \mathbb{N}^+$

$$\mathcal{K}_\upsilon[\sigma_\upsilon] + \mathcal{V}_\upsilon[\sigma_\upsilon] = 0\,, \qquad \mathcal{K}_\upsilon = \partial_\chi^2 - E_\chi^2\,, \qquad \mathcal{V}_\upsilon[\sigma_\upsilon] = -\lambda_\upsilon \rho_\upsilon^{l} e^{i((m+1)\theta_\upsilon + \vartheta_\upsilon)}\,,$$

interaction kernel $\in \mathbb{R}$

- Generalized mean-field: Reduces to pseudo-tensorial/spinfoam for $m = 0$ and $m = -(l+1)$, resp.
- Assumptions: Homogeneity, isotropy, single-mode, late times. Interactions are non-perturbative.

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Emergent acceleration I: Stability

Mean-field model

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Dynamical system

Fixed points[1]

- First order for $x = \theta$, $y = \rho'/\rho^3$, $z = \theta'$.
- FP_∞: $l=5$, $\bar{y}^2 = |\lambda|/3$, $\bar{x} = (n\pi - \vartheta)/m$, $z=0$.

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Cosmological stability

$$H^2 \propto y^2\,, \qquad w = -[(1 + y'/(\rho^2 y^2)]$$

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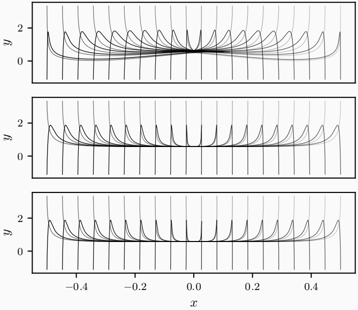
Emergent dS cosmological attractor for $m \leq 0$.



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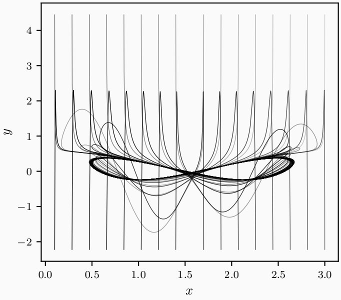
Emergent dS cosmologically unstable for $m > 0$.



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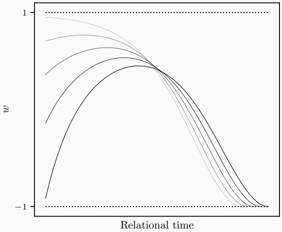
Asymptotics

Asymptotic Λ

- Emergent DE:[1,2,3] For $m \leq 0$ asymptotic dS attractor.

$$\bar{w} = -1, \qquad \bar{\Lambda} = \underbrace{|\lambda|}_{\text{GFT coupling}} \frac{4\pi \overbrace{\chi}^{\text{Clock momentum}}{}^2}{9\underbrace{\mathfrak{v}}_{\text{Volume eigenvalue}}{}^2}$$



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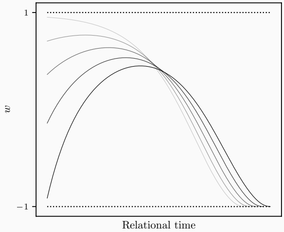

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Emergent acceleration II: Dynamical Dark Energy

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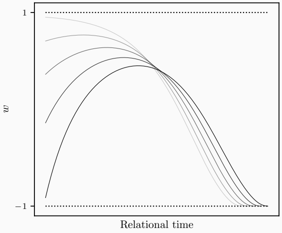


Dynamical behavior

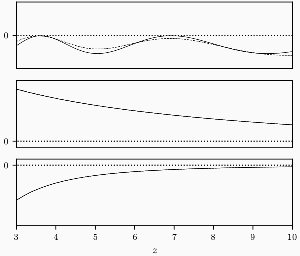
EoS dynamics[1]

$$\delta w(z) = \begin{cases} [\mathcal{T}(z)]^{-6}(\delta w_0 + \delta w_1 \cos 2\Phi(z) + \delta w_2 \sin 2\Phi(z)) \\ \delta w_0 [\mathcal{T}(z)]^{6(\sqrt{1+3m/4}-1)} \\ \delta w_0 [\mathcal{T}(z)]^{-6}\log^2[\mathcal{T}(z)] \end{cases}$$

$\mathcal{T}(z) = (1+z_q)/(1+z)$, $\Phi(z) \propto \log\mathcal{T}(z)$

Different $\mathrm{sgn}(1+3m/4)$

- Quantum features: $z_q \sim \#$ of QG atoms today.



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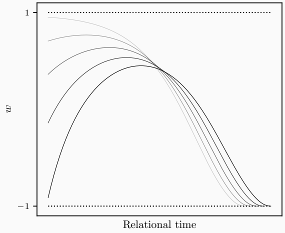
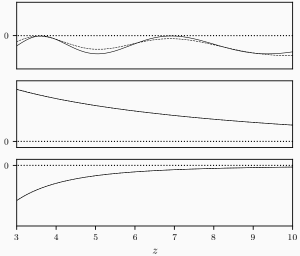


Dynamical behavior

EoS dynamics[1]

$$\delta w(z) = \begin{cases} [\mathcal{T}(z)]^{-6}(\delta w_0 + \delta w_1 \cos 2\Phi(z) + \delta w_2 \sin 2\Phi(z)) \\ \delta w_0 [\mathcal{T}(z)]^{6(\sqrt{1+3m/4}-1)} \\ \delta w_0 [\mathcal{T}(z)]^{-6} \log^2[\mathcal{T}(z)] \end{cases}$$

- Quantum features: $z_q \sim \#$ of QG atoms today.
- Phantom behavior for $m \leq -6$ and $-1.27 \lesssim m \leq 0$



[1] LM, Ladstätter, Oriti 2512.11712; [2] Ladstätter, LM 2508.16194; [3] Oriti, Pang 2105.03751-2502.12419; De Cesare, Pithis, Sakellariadou 1606.00352...

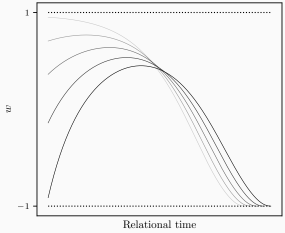
Asymptotics

Asymptotic Λ

- Emergent DE:[1,2,3] For $m \leq 0$ asymptotic dS attractor.

$$\bar{w} = -1, \qquad \bar{\Lambda} = |\lambda| \frac{4\pi_\chi^2}{9\mathfrak{v}^2}$$

- At late times $w(z) = -1 + \delta w(z)$.



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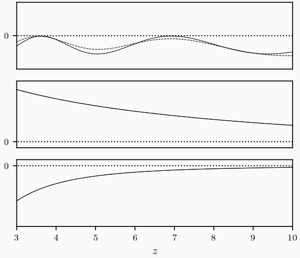
Emergent dynamical (typically phantom) dark energy!



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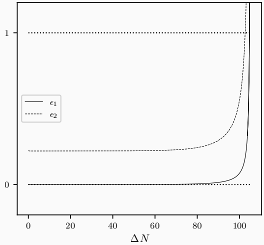
Quasi dS phase

Slow-Roll Inflation[1]

- Quasi dS: For $m > 0$ FP_∞ repulsive; acceleration ends.

$$\epsilon_1(N) = \exp[-\epsilon_2(N_{\text{end}} - N)]$$

$$\epsilon_2(N) = 6(\underbrace{\mu}_{(1+3m/4)^{1/2}} - 1)$$



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Emergent acceleration III: Emergent Inflation

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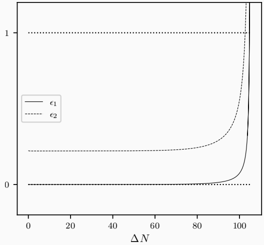
- Graceful exit: Inflation ends after $N_{\text{end}} \gg 1$.



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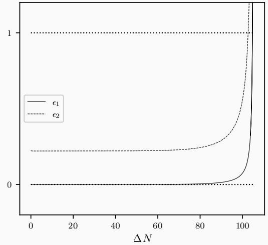


Single-field description

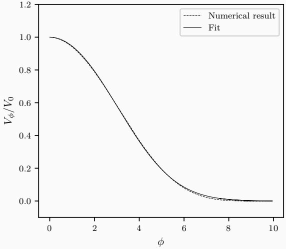
Emergent Inflaton[1]

- SFI: GFT inflation can be described by emergent ϕ:

$$\underbrace{\delta\theta(\phi)}_{\text{GFT phase}} \propto \phi - \phi_0$$

$$V(\phi) = V_0 \left(1 - \frac{(\phi - \phi_0)^2}{3}\right) e^{-2(\phi-\phi_0)^2/\epsilon_2}\,,$$

$\in [\phi_0, \phi_0 + 1]$



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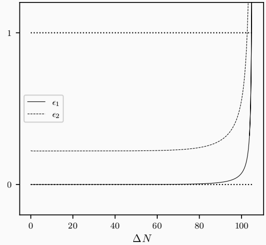

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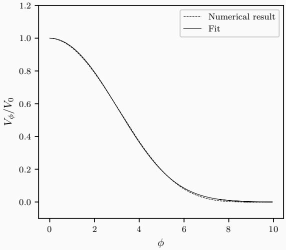
Emergent slow-roll single-field inflation!



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Emergence

Observables and Coarse-Graining

- Which observables in QG? How to coarse-grain (renormalize) without energy/length scales?
- Relational strategy: observables and coarse-graining with respect to quantum reference frames.

Approximate methods

- GFT (relational) mean-field theory (robust; simplest coarse-graining).

Cosmology

QG Effects in Cosmology

- Free theory, FLRW sector: singularity res. and GR matching at late times.
- Free theory, perturbations [Also Greco's talk]: associated with correlations, QG Planck-scale corrections.

QG interactions can produce cosmic acceleration

- Emergent dynamical dark energy [also Pellecchia's talk] (typically phantom) for $m \leq 0$ models.
- Emergent slow-roll inflation (no inflaton) from $m > 0$ models. Equivalent SFI description.

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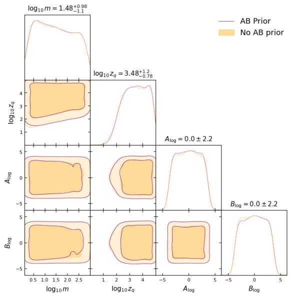
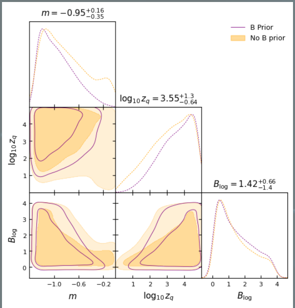
Outlook

Ongoing Works/Future Directions

- From relational path-integrals to relational spinfoams/GFTs.
- Relational coarse-graining in spinfoams/GFTs.
- Coupling with more interesting matter? (e.g. dust[1], interacting scalars[2], radiation...)
- How to obtain primordial power spectra [Also Calcinari's talk]?[4] Inflationary constraints on QG?[5]
- Can a similar mechanism also produce a dark matter component?[6]
- How do predictions on $w(z)$ compare with data?[3]

[1] Fazzini, Giesel, LM (WIP); [2] Ladstätter, LM 2508.16194; [3] da Silva Pereira, LM, Ferreira (WIP): [4] LM, Wilson-Ewing (WIP); [5] LM, Ferreira (WIP); [6] Bose, LM, Tsedrik, Ferreira (WIP);





Probing (L)QG with LSS

Bose, LM, Tsedrik, Ferreira (WIP).