Covariant EFT of Gravity and Cosmology

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The Quantum and Gravity
II Flag Meeting

Trento
6 June 2016

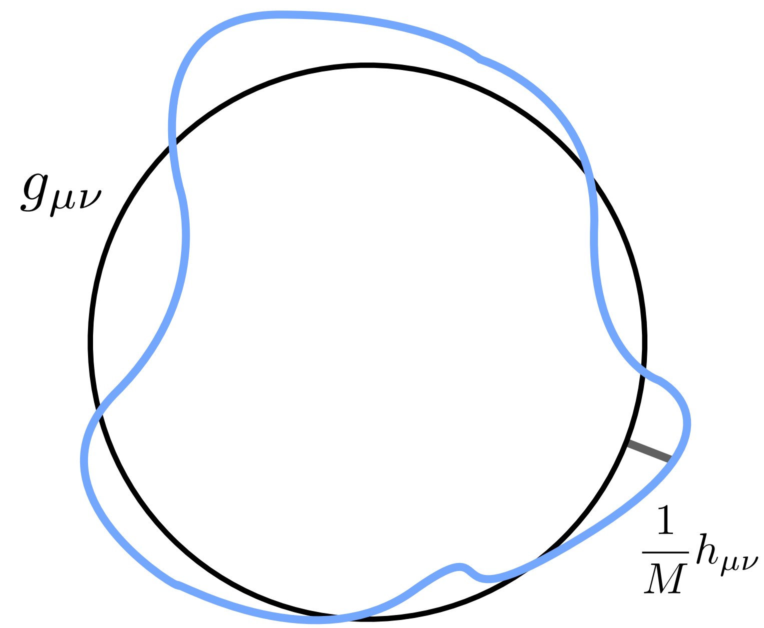
in collaboration with Rajeev K. Jain
arXiv:1507.06308
arXiv:1507.07829
arXiv:1603.00028

CP³ Origins

Outline of the talk

- Covariant EFT of gravity
- Curvature expansion and heat kernel
- Cosmological effective actions
- Effective Friedmann equations
- Unified evolution of the universe
- A cosmological model from first principles

EFT of Gravity



- The theory of small fluctuations of the metric

$$g_{\mu\nu} \to g_{\mu\nu} + \sqrt{16\pi G}h_{\mu\nu} = g_{\mu\nu} + \frac{1}{M}h_{\mu\nu}$$

- Planck's scale is the characteristic scale of gravity

$$M \equiv \frac{1}{\sqrt{16\pi G}} = \frac{M_{Planck}}{\sqrt{16\pi}}$$

$$M_{Planck} = \frac{1}{\sqrt{G}} = 1.2 \times 10^{19}\,\mathrm{GeV}$$

- Classical theory (CT) is successful over many orders of magnitude

EFT of Gravity

$$S_{eff}[g] = M^2 \left[I_1[g] + \frac{1}{M^2} I_2[g] + \frac{1}{M^4} I_3[g] + \ldots \right]$$

UV action contains all couplings expressed in terms of the scale M

$$I_1[g] = \int d^4x \sqrt{g} \left[M^2 c_0 - c_1 R \right]$$

$$I_2[g] = \int d^4x \sqrt{g} \left[c_{2,1} R^2 + c_{2,2} \mathrm{Ric}^2 + c_{2,3} \mathrm{Riem}^2 \right]$$

$$I_3[g] = \int d^4x \sqrt{g} \left[c_{3,1} R \Box R + c_{3,2} R_{\mu\nu} \Box R^{\mu\nu} + c_{3,3} R^3 + \ldots \right]$$

Derivative expansion of the UV action

Covariant EFT of Gravity

$$e^{-\Gamma[g]} = \int_{1PI} \mathcal{D}h_{\mu\nu}\, e^{-S_{eff}[g+\frac{1}{M}h]}$$

$$= \int_{1PI} \mathcal{D}h_{\mu\nu}\, e^{-M^2\left\{I_1[g+\frac{1}{M}h]+\frac{1}{M^2}I_2[g+\frac{1}{M}h]+\dots\right\}}$$

EFT: saddle point expansion in $\frac{1}{M^2}$

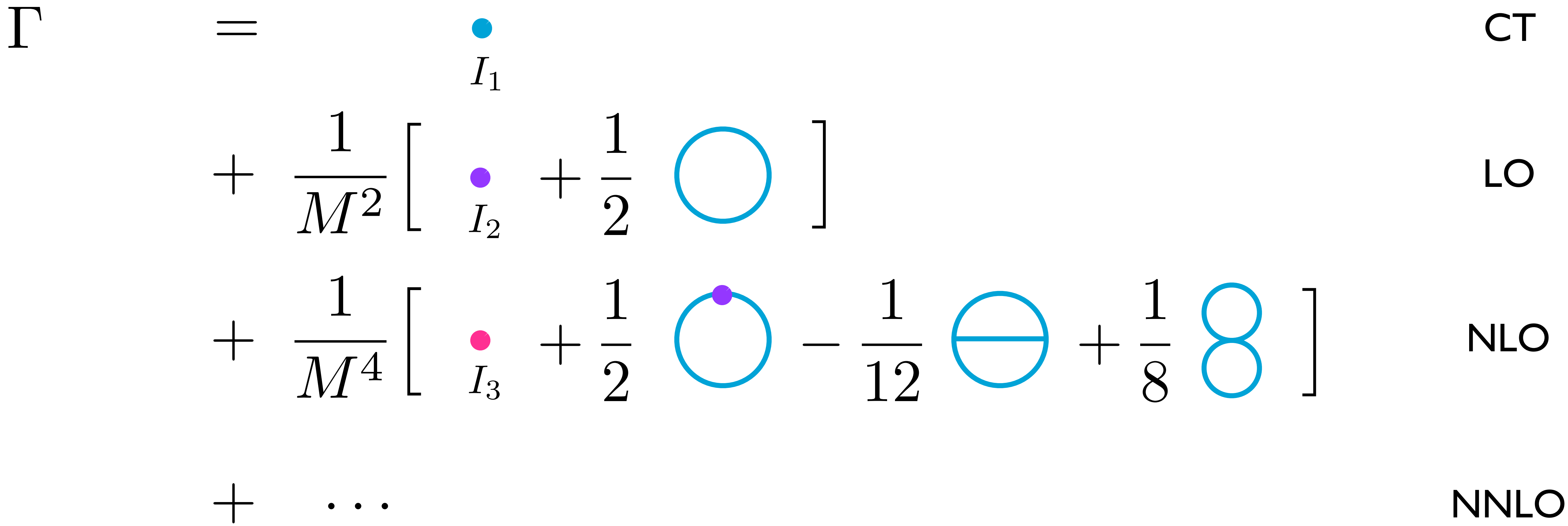
$$\Gamma[g] = I_1[g]$$

$$+ \frac{1}{M^2}\left\{I_2[g] + \frac{1}{2}\mathrm{Tr}\log I_1^{(2)}[g]\right\}$$

$$+ \frac{1}{M^4}\left\{I_3[g] + \frac{1}{2}\mathrm{Tr}\left[\left(I_1^{(2)}[g]\right)^{-1} I_2^{(2)}[g]\right] + \text{2-loops with } I_1[g]\right\}$$

$$+ \dots$$

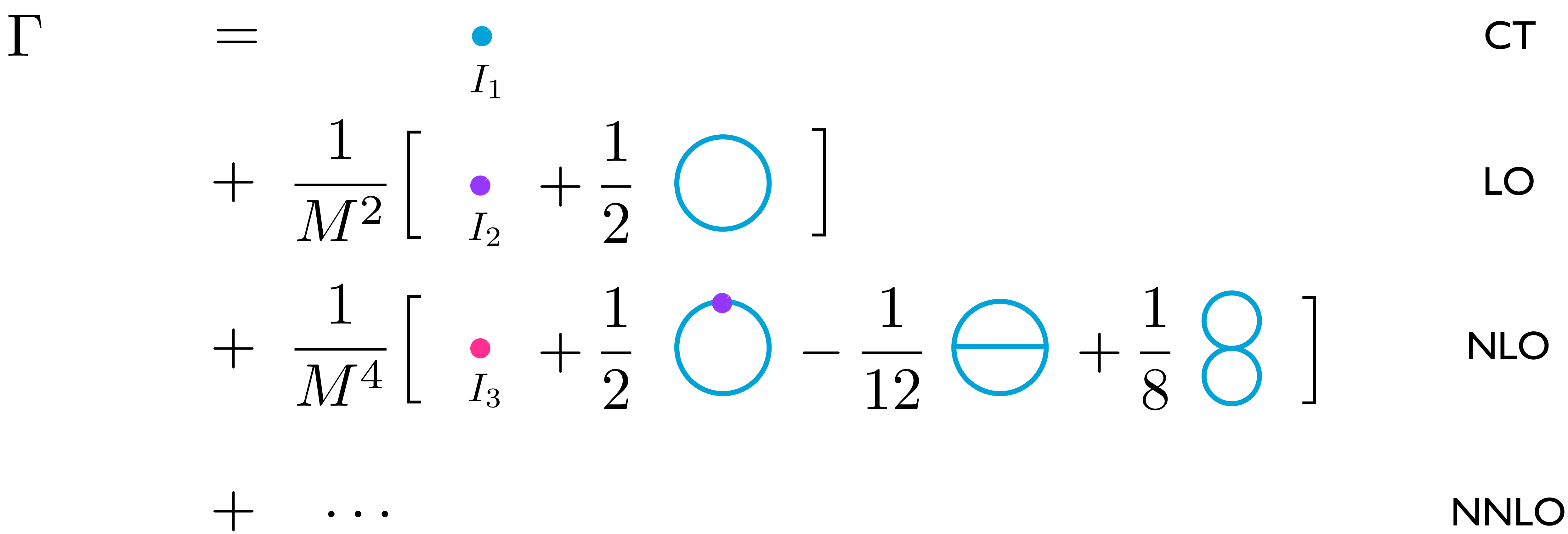
Covariant EFT of Gravity



CEFT of Gravity I
A. C. and K. J. Jain
arXiv:1507.06308

Covariant EFT of Gravity

The EFT recipe in three lines

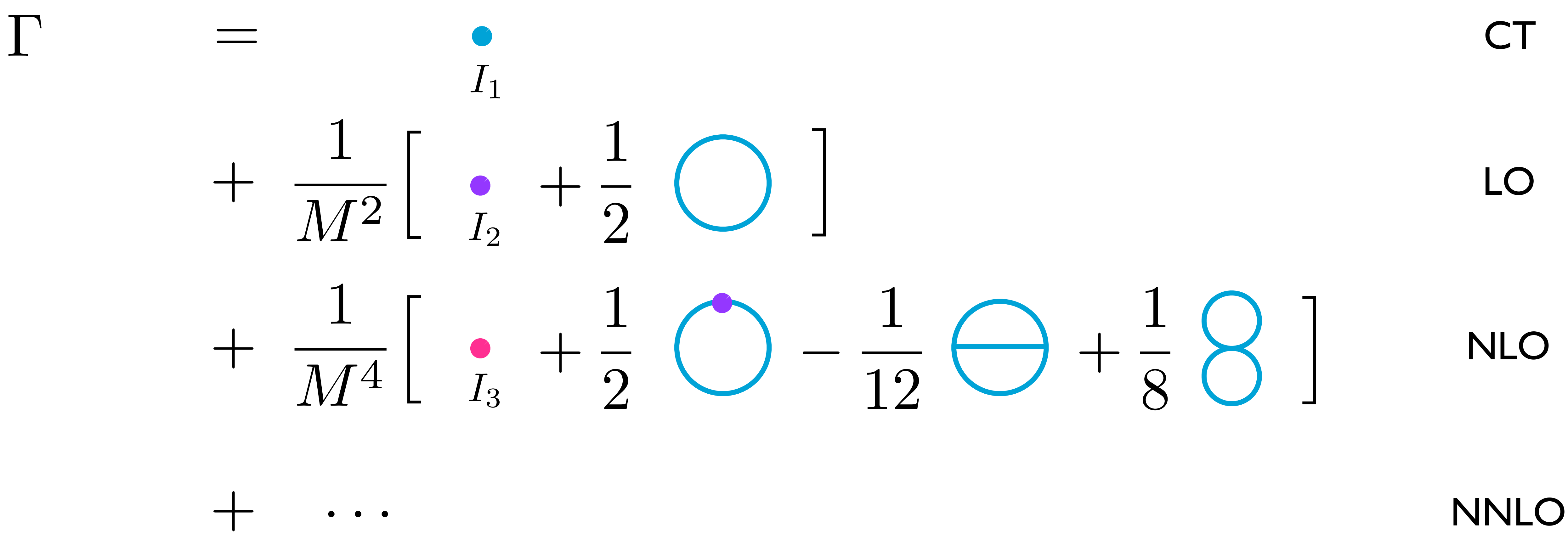


1) the general lagrangian of order E^2 is to be used both at tree level and in loop diagrams

2) the general lagrangian of order $E^{n\geq 4}$ is to be used at tree level and as an insertion in loop diagrams

3) the renormalization program is carried out order by order

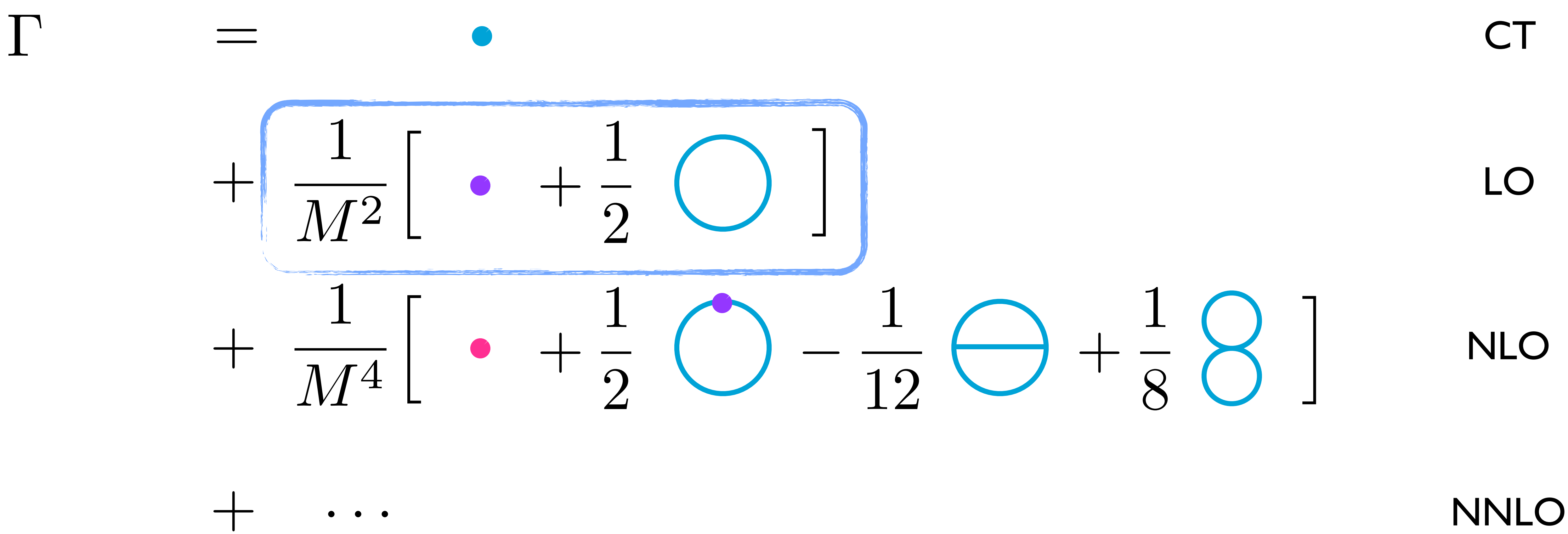
Covariant EFT of Gravity



Many QFT computations are contained
in this expression:
CEFT is a powerful organizing principle

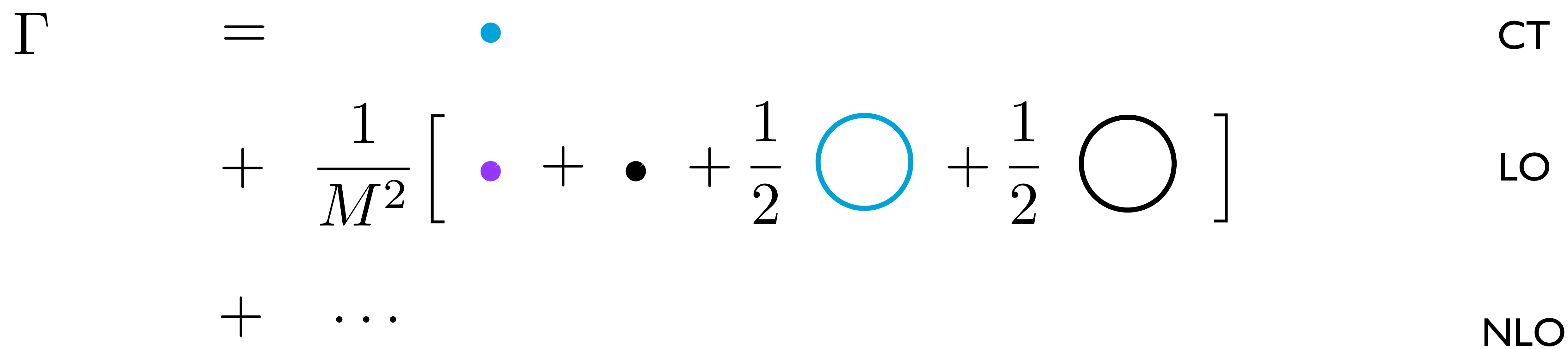
Covariant EFT of Gravity

LOQG: the only QG we will ever observe?



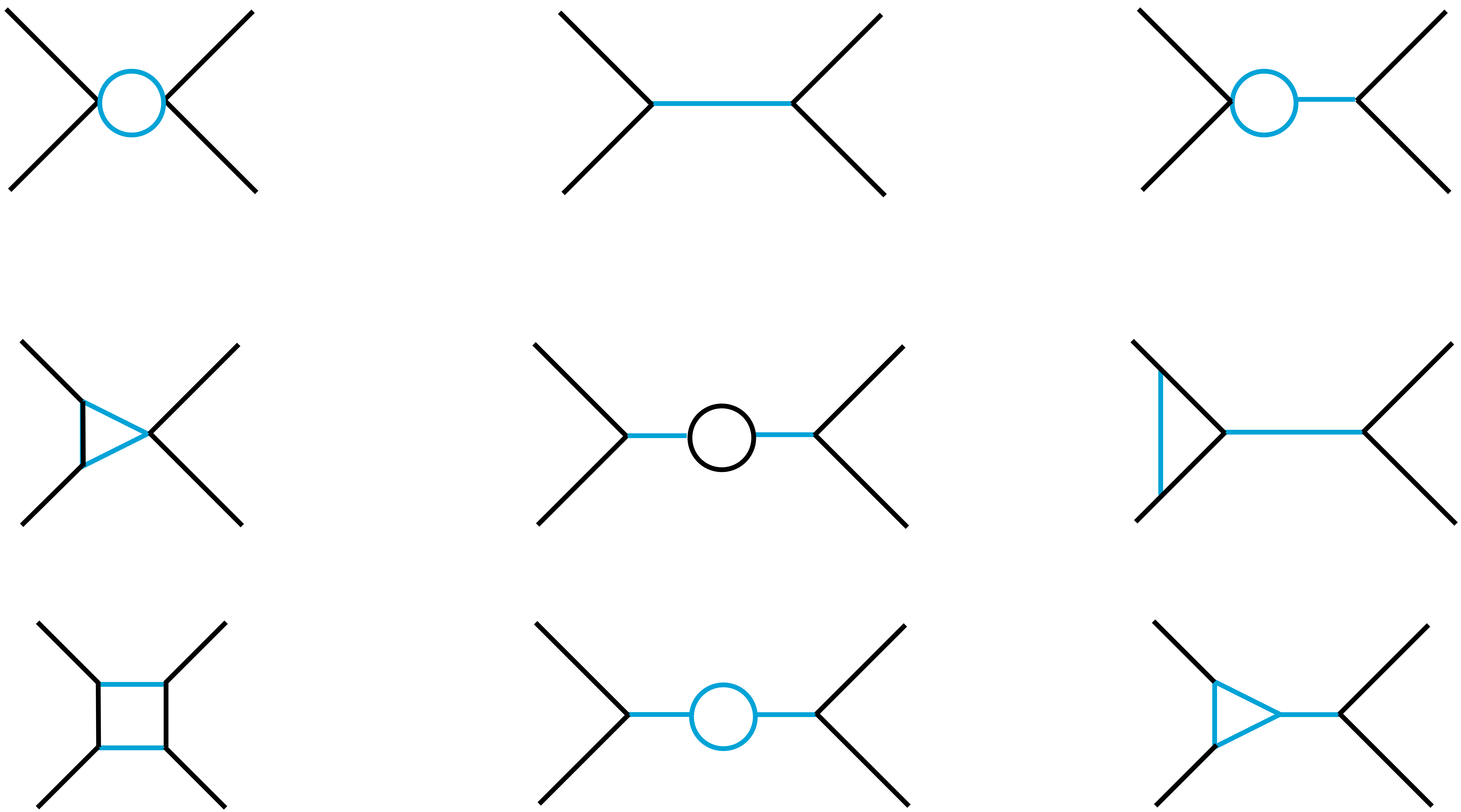
Even if one has a fundamental theory it is generally difficult to compute phenomenological parameters directly...

Including matter

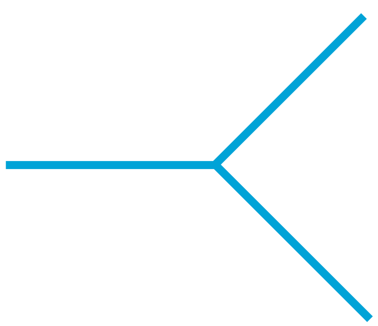


Computations to date are only in flat space via Feynman diagrams

Corrections to Newton's potential



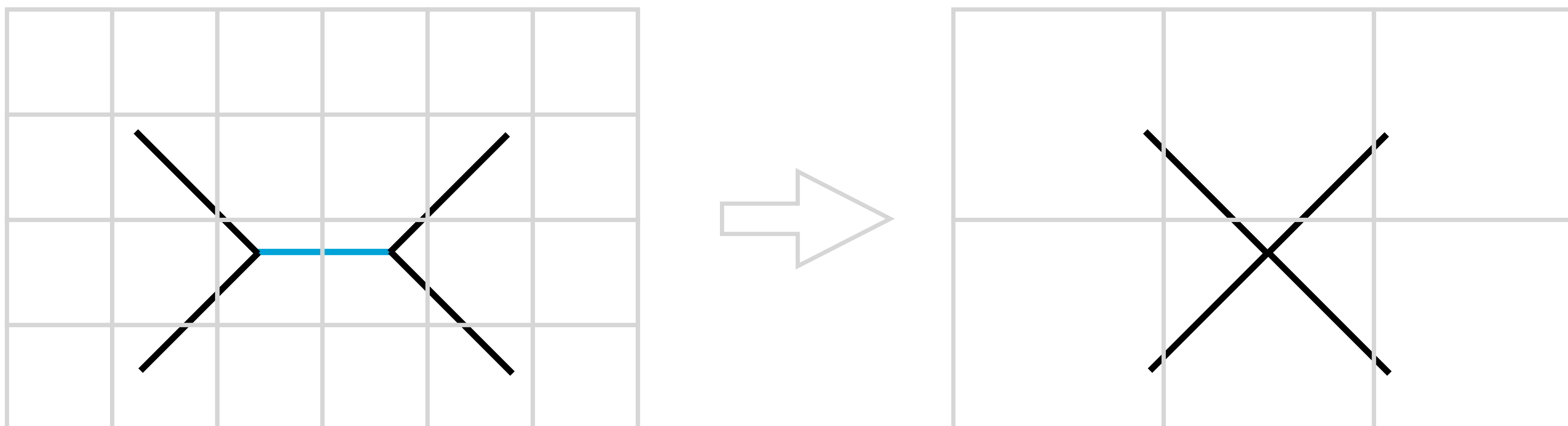
Corrections to Newton’s interaction



$$
\begin{aligned}
= \; & \frac{i\kappa}{2}\Bigg(P_{\alpha\beta,\gamma\delta}\left[k^\mu k^\nu + (k-q)^\mu (k-q)^\nu + q^\mu q^\nu - \frac{3}{2}\eta^{\mu\nu}q^2\right] \\
& +2q_\lambda q_\sigma\left[I^{\lambda\sigma,}{}_{\alpha\beta}I^{\mu\nu,}{}_{\gamma\delta} + I^{\lambda\sigma,}{}_{\gamma\delta}I^{\mu\nu,}{}_{\alpha\beta} - I^{\lambda\mu,}{}_{\alpha\beta}I^{\sigma\nu,}{}_{\gamma\delta} - I^{\sigma\nu,}{}_{\alpha\beta}I^{\lambda\mu,}{}_{\gamma\delta}\right] \\
& +\Big[q_\lambda q^\mu\left(\eta_{\alpha\beta}I^{\lambda\nu,}{}_{\gamma\delta}+\eta_{\gamma\delta}I^{\lambda\nu,}{}_{\alpha\beta}\right) + q_\lambda q^\nu\left(\eta_{\alpha\beta}I^{\lambda\mu,}{}_{\gamma\delta}+\eta_{\gamma\delta}I^{\lambda\mu,}{}_{\alpha\beta}\right) \\
& -q^2\left(\eta_{\alpha\beta}I^{\mu\nu,}{}_{\gamma\delta}+\eta_{\gamma\delta}I^{\mu\nu,}{}_{\alpha\beta}\right) - \eta^{\mu\nu}q^\lambda q^\sigma\left(\eta_{\alpha\beta}I_{\gamma\delta,\lambda\sigma}+\eta_{\gamma\delta}I_{\alpha\beta,\lambda\sigma}\right)\Big] \\
& +\Big[2q^\lambda\Big(I^{\sigma\nu,}{}_{\alpha\beta}I_{\gamma\delta,\lambda\sigma}(k-q)^\mu + I^{\sigma\mu,}{}_{\alpha\beta}I_{\gamma\delta,\lambda\sigma}(k-q)^\nu \\
& -I^{\sigma\nu,}{}_{\gamma\delta}I_{\alpha\beta,\lambda\sigma}k^\mu - I^{\sigma\mu,}{}_{\gamma\delta}I_{\alpha\beta,\lambda\sigma}k^\nu\Big) \\
& +q^2\left(I^{\sigma\mu,}{}_{\alpha\beta}I_{\gamma\delta,\sigma}{}^{\nu} + I_{\alpha\beta,\sigma}{}^{\nu}I^{\sigma\mu,}{}_{\alpha\delta}\right) + \eta^{\mu\nu}q^\lambda q_\sigma\left(I_{\alpha\beta,\lambda\rho}I^{\rho\sigma,}{}_{\gamma\delta}+I_{\gamma\delta,\lambda\rho}I^{\rho\sigma,}{}_{\alpha\beta}\right)\Big] \\
& +\Big\{\left(k^2+(k-q)^2\right)\left(I^{\sigma\mu,}{}_{\alpha\beta}I_{\gamma\delta,\sigma}{}^{\nu}+I^{\sigma\nu,}{}_{\alpha\beta}I_{\gamma\delta,\sigma}{}^{\mu} - \frac{1}{2}\eta^{\mu\nu}P_{\alpha\beta,\gamma\delta}\right) \\
& -\left(k^2\eta_{\gamma\delta}I^{\mu\nu,}{}_{\alpha\beta}+(k-q)^2\eta_{\alpha\beta}I^{\mu\nu,}{}_{\gamma\delta}\right)\Big\}\Bigg)
\end{aligned}
$$

The truth behind Feynman diagrams...

Corrections to Newton's interaction

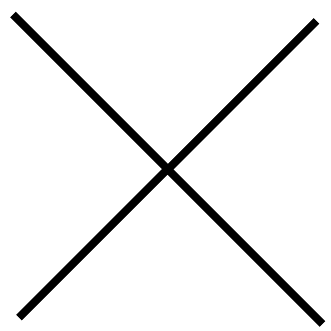


$$V = -\frac{GMm}{r}\left[1 + 3\frac{G(M+m)}{c^2 r} + \frac{41}{10\pi}\frac{G\hbar}{c^3 r^2} + \cdots\right]$$

Leading quantum corrections to Newton's potential

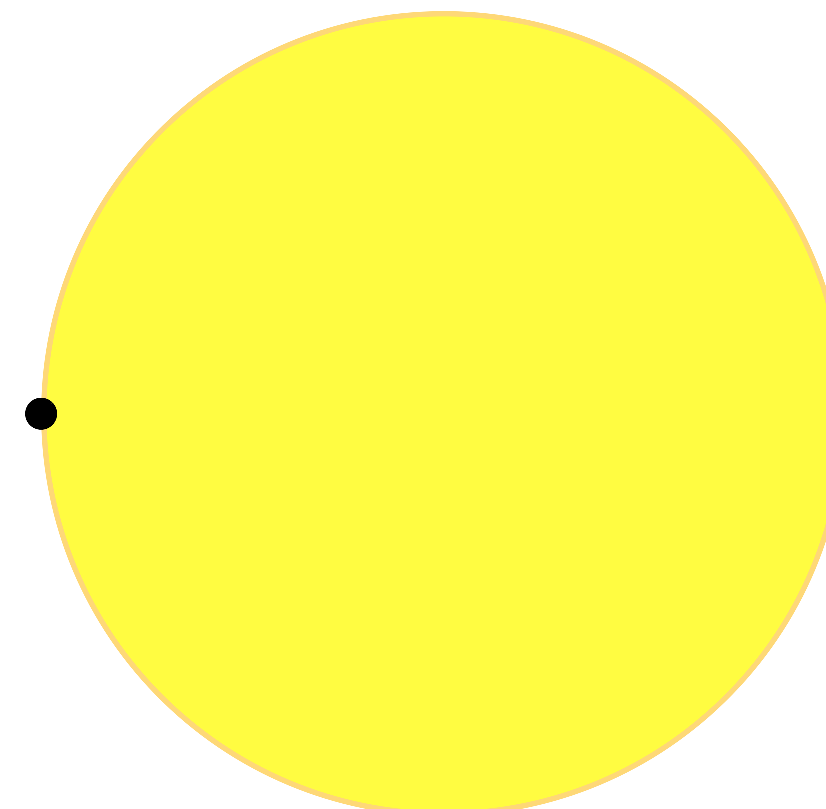
J.F. Donoghue, Phys. Rev. Lett. 72, 2996 (1994)

Corrections to Newton's interaction



$$\frac{GM_\odot}{c^2 r_\odot} \sim 10^{-6}$$

$$\frac{G\hbar}{c^3 r_\odot^2} \sim 10^{-88}$$



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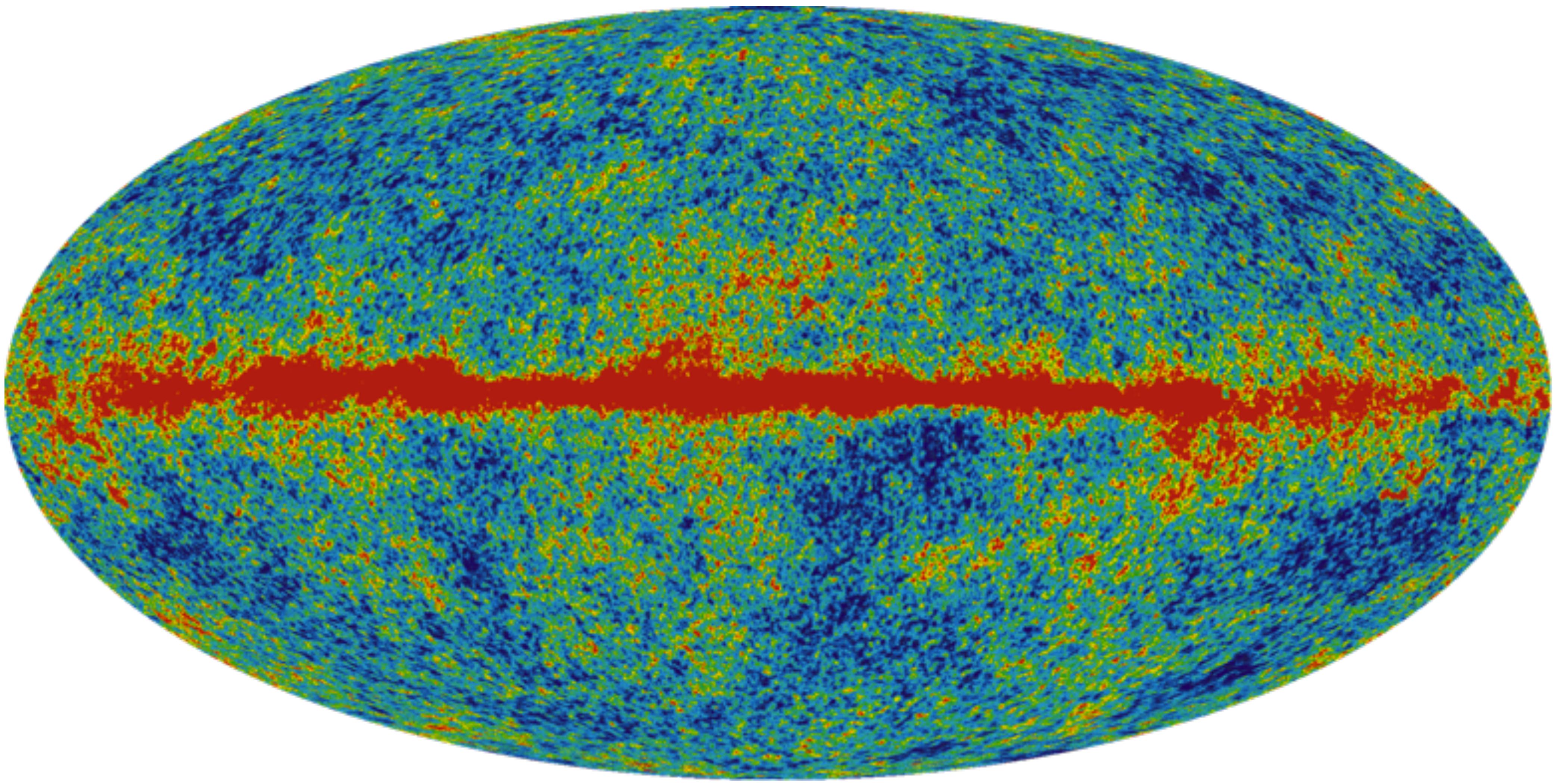
Leading quantum corrections to Newton's law are incredibly small!

Can we ever observe quantum gravity effects?



Look for physical situations where
LO corrections are enhanced

Covariant EFT of Gravity

$$\Gamma = \underset{I_1}{\bullet} \qquad \text{CT}$$

$$+ \frac{1}{M^2}\left[\underset{I_2}{\bullet} + \frac{1}{2} \bigcirc \right] \qquad \text{LO}$$

$$+ \cdots \qquad \text{NLO}$$

How can we compute the effective action on an arbitrary background?

Covariant EFT of Gravity

$$\Gamma = \underset{I_1}{\bullet} \qquad \text{CT}$$

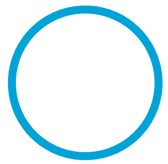
$$+ \frac{1}{M^2}\left[\underset{I_2}{\bullet} + \frac{1}{2} \bigcirc \right] \qquad \text{LO}$$

$$+ \quad \cdots \qquad \text{NLO}$$

How can we compute the effective
action on an arbitrary background?

Heat kernel methods!

Curvature expansion

• $+\frac{1}{2}$  $= -\frac{1}{2(4\pi)^{d/2}} \int d^dx \sqrt{g}\, \mathrm{tr}\, \mathcal{R}\, \gamma_i \left(\frac{-\Box}{m^2} \right) \mathcal{R} + \ldots$

The finite physical part of the effective action is covariantly encoded in the structure functions which can be computed using the non-local heat kernel expansion

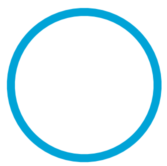
$$\gamma_i\left(\frac{X}{m^2}\right) \equiv \lim_{\Lambda_{UV}\to\infty} \int_{1/\Lambda_{UV}^2}^{\infty} \frac{ds}{s} s^{-d/2+2} \left[f_i(sX) - f_i(0)\right] e^{-sm^2}$$

Non-local heat kernel structure functions

Non-local heat kernel

A. O. Barvinsky and G. A. Vilkovisky, Nucl. Phys. B 282 (1987) 163
I. G. Avramidi, Lect. Notes Phys. M 64 (2000) 1
A. Codello and O. Zanusso, J. Math. Phys. 54 (2013) 013513

Curvature expansion

- $+\frac{1}{2}$  $= -\frac{1}{2(4\pi)^2}\int d^4x\sqrt{g}\,\mathrm{tr}\Big[\mathbf{1}R_{\mu\nu}\gamma_{Ric}\Big(\frac{-\Box}{m^2}\Big)R^{\mu\nu} + \frac{\mathbf{1}}{120}R\gamma_R\Big(\frac{-\Box}{m^2}\Big)R$

$$-\frac{1}{6}R\gamma_{RU}\Big(\frac{-\Box}{m^2}\Big)\mathbf{U} + \frac{1}{2}\mathbf{U}\gamma_U\Big(\frac{-\Box}{m^2}\Big)\mathbf{U} + \frac{1}{12}\mathbf{\Omega}_{\mu\nu}\gamma_\Omega\Big(\frac{-\Box}{m^2}\Big)\mathbf{\Omega}^{\mu\nu}\Big]$$

Explicit form for the structure functions

$$\gamma_{Ric}(u) = \frac{1}{40} + \frac{1}{12u} - \frac{1}{2}\int_0^1 d\xi\,\left[\frac{1}{u} + \xi(1-\xi)\right]^2 \log\left[1 + u\,\xi(1-\xi)\right]$$

$$\gamma_R(u) = -\frac{23}{960} - \frac{1}{96u} + \frac{1}{32}\int_0^1 d\xi\,\Big\{\frac{2}{u^2} + \frac{4}{u}\left[1+\xi(1-\xi)\right] - 1 + 2\xi(2-\xi)(1-\xi^2)\Big\}\log\left[1 + u\,\xi(1-\xi)\right]$$

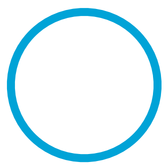
$$\gamma_{RU}(u) = \frac{1}{12} - \frac{1}{2}\int_0^1 d\xi\,\left[\frac{1}{u} - \frac{1}{2} + \xi(1-\xi)\right]\log\left[1 + u\,\xi(1-\xi)\right]$$

$$\gamma_U(u) = -\frac{1}{2}\int_0^1 d\xi\,\log\left[1 + u\,\xi(1-\xi)\right]$$

$$\gamma_\Omega(u) = \frac{1}{12} - \frac{1}{2}\int_0^1 d\xi\,\left[\frac{1}{u} + \xi(1-\xi)\right]\log\left[1 + u\,\xi(1-\xi)\right]$$

$$u \equiv \frac{-\Box}{m^2}$$

Curvature expansion

- $+\frac{1}{2}$  $= -\frac{1}{2(4\pi)^2}\int d^4x\sqrt{g}\,\mathrm{tr}\Big[\mathbf{1}R_{\mu\nu}\gamma_{Ric}\Big(\frac{-\Box}{m^2}\Big)R^{\mu\nu} + \frac{\mathbf{1}}{120}R\gamma_R\Big(\frac{-\Box}{m^2}\Big)R$
$-\frac{1}{6}R\gamma_{RU}\Big(\frac{-\Box}{m^2}\Big)\mathbf{U} + \frac{1}{2}\mathbf{U}\gamma_U\Big(\frac{-\Box}{m^2}\Big)\mathbf{U} + \frac{1}{12}\mathbf{\Omega}_{\mu\nu}\gamma_\Omega\Big(\frac{-\Box}{m^2}\Big)\mathbf{\Omega}^{\mu\nu}\Big]$

$$u \ll 1$$

$$\gamma_{Ric}(u) = -\frac{u}{840} + \frac{u^2}{15120} - \frac{u^3}{166320} + O(u^4)$$

$$\gamma_R(u) = -\frac{u}{336} + \frac{11u^2}{30240} - \frac{19u^3}{332640} + O(u^4)$$

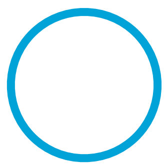
$$\gamma_{RU}(u) = \frac{u}{30} - \frac{u^2}{280} + \frac{u^3}{1890} + O(u^4)$$

$$\gamma_U(u) = -\frac{u}{12} + \frac{u^2}{120} - \frac{u^3}{840} + O(u^4)$$

$$\gamma_\Omega(u) = -\frac{u}{120} + \frac{u^2}{1680} - \frac{u^3}{15120} + O(u^4)$$

$$u \equiv \frac{-\Box}{m^2}$$

Curvature expansion

- $+\frac{1}{2}$  $= -\frac{1}{2(4\pi)^2}\int d^4x\sqrt{g}\,\mathrm{tr}\Big[\mathbf{1}R_{\mu\nu}\gamma_{Ric}\Big(\frac{-\Box}{m^2}\Big)R^{\mu\nu} + \frac{\mathbf{1}}{120}R\gamma_R\Big(\frac{-\Box}{m^2}\Big)R$
$-\frac{1}{6}R\gamma_{RU}\Big(\frac{-\Box}{m^2}\Big)\mathbf{U} + \frac{1}{2}\mathbf{U}\gamma_U\Big(\frac{-\Box}{m^2}\Big)\mathbf{U} + \frac{1}{12}\mathbf{\Omega}_{\mu\nu}\gamma_\Omega\Big(\frac{-\Box}{m^2}\Big)\mathbf{\Omega}^{\mu\nu}\Big]$

$$u \gg 1$$

$$\gamma_{Ric}(u) = \frac{23}{450} - \frac{1}{60}\log u + \frac{5}{18u} - \frac{\log u}{6u} + \frac{1}{4u^2} - \frac{\log u}{2u^2} + O\Big(\frac{1}{u^3}\Big)$$

$$\gamma_R(u) = \frac{1}{1800} - \frac{1}{120}\log u - \frac{2}{9u} + \frac{\log u}{12u} + \frac{1}{8u^2} + \frac{\log u}{4u^2} + O\Big(\frac{1}{u^3}\Big)$$

$$\gamma_{RU}(u) = -\frac{5}{18} + \frac{1}{6}\log u + \frac{1}{u} - \frac{1}{2u^2} - \frac{\log u}{u^2} + O\Big(\frac{1}{u^3}\Big)$$

$$\gamma_U(u) = 1 - \frac{1}{2}\log u - \frac{1}{u} - \frac{\log u}{u} - \frac{1}{2u^2} + \frac{\log u}{u^2} + O\Big(\frac{1}{u^3}\Big)$$

$$\gamma_\Omega(u) = \frac{2}{9} - \frac{1}{12}\log u + \frac{1}{2u} - \frac{\log u}{2u} - \frac{3}{4u^2} - \frac{\log u}{2u^2} + O\Big(\frac{1}{u^3}\Big)$$

$$u \equiv \frac{-\Box}{m^2}$$

LO effective action to $\mathcal{R}^2$

$$\Gamma[g] = \frac{1}{16\pi G}\int d^4x\sqrt{g}\,(2\Lambda - R) + \frac{1}{2\lambda}\int d^4x\sqrt{g}\,C^2 + \frac{1}{\xi}\int d^4x\sqrt{g}\,R^2$$
$$+ \int d^4x\sqrt{g}\,C_{\mu\nu\alpha\beta}\,\mathcal{G}\left(\frac{-\Box}{m^2}\right)C^{\mu\nu\alpha\beta} + \int d^4x\sqrt{g}\,R\,\mathcal{F}\left(\frac{-\Box}{m^2}\right)R + O(\mathcal{R}^3)$$

Graviton contributions:

$$\mathcal{G}_2(u) = -\frac{1}{2(4\pi)^2}\Big(5\gamma_{Ric}(u) + 3\gamma_U(u) - 12\gamma_\Omega(u) - 4\gamma_{Ric}(u) - \gamma_U(u) + 4\gamma_\Omega(u)\Big)$$

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$$\mathcal{F}_2(u) = -\frac{1}{2(4\pi)^2}\left(\frac{10}{3}\gamma_{Ric}(u) + 10\gamma_R(u) + 6\gamma_{RU}(u) + 4\gamma_U(u) - 2\gamma_\Omega(u) - \frac{8}{3}\gamma_{Ric}(u) - 8\gamma_R(u) + 2\gamma_{RU}(u) - \frac{2}{3}\gamma_U(u) + \frac{2}{3}\gamma_\Omega(u)\right)$$

Matter contributions:

$$\mathcal{G}_0(u), \mathcal{F}_0(u), \mathcal{G}_{1/2}(u), \mathcal{F}_{1/2}(u), \mathcal{G}_1(u), \mathcal{F}_1(u)$$

Cosmological effective action

FRW metric

$$ds^2 = -dt^2 + a^2(t)d\mathbf{x}^2$$

Cosmological effective action

FRW metric

$$ds^2 = -dt^2 + a^2(t)d\mathbf{x}^2$$

Weyl tensor vanishes

$$C_{\alpha\beta\gamma\delta} = 0$$

Cosmological effective action

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Euclidean to Lorentzian

Cosmological effective action

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Euclidean to Lorentzian

A predictive framework for cosmology

$C_{\alpha\beta\gamma\delta} = 0$

Cosmological effective action

$$\Gamma[g] = \frac{\Lambda}{8\pi G}\int d^4x\sqrt{g} - \frac{1}{16\pi G}\int d^4x\sqrt{g}R + \frac{1}{\xi}\int d^4x\sqrt{g}\,R^2 + \int d^4x\sqrt{g}\,R\,\mathcal{F}\left(\frac{-\Box}{m^2}\right)R + O(\mathcal{R}^3)$$

$C_{\alpha\beta\gamma\delta} = 0$

Cosmological effective action

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$$\mathcal{F}\left(\frac{-\Box}{m^2}\right) = \alpha\log\frac{-\Box}{m^2}$$

$$+\,\beta\frac{m^2}{-\Box}$$

$\alpha,\ \beta,\ \gamma,\ \delta$

are calculable constants depending on effective gravitons and matter content

$$+\,\gamma\frac{m^2}{-\Box}\log\frac{-\Box}{m^2}$$

$$+\,\delta\frac{m^4}{(-\Box)^2}$$

$$+\,\ldots$$

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Cosmological effective action

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Leading logs
J. F. Donoghue and B. K. El-Menoufi, Phys. Rev. D 89, 104062 (2014)

$$+\,\beta\frac{m^2}{-\Box}$$

Non-local cosmology
S. Deser and R. P. Woodard, Phys. Rev. Lett. 99, 111301 (2007)

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Non-local gravity and dark energy
M. Maggiore and M. Mancarella, Phys. Rev. D 90, 023005 (2014).

$$+\,\ldots$$

$C_{\alpha\beta\gamma\delta} = 0$

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Cosmological effective action

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$$+\beta\frac{m^2}{-\Box}$$

Non-local cosmology
S. Deser and R. P. Woodard, Phys. Rev. Lett. 99, 111301 (2007)

$\alpha,\ \beta,\ \gamma,\ \delta$

are calculable constants depending on effective gravitons and matter content

$$+\gamma\frac{m^2}{-\Box}\log\frac{-\Box}{m^2}$$

$$+\delta\frac{m^4}{(-\Box)^2}$$

Non-local gravity and dark energy
M. Maggiore and M. Mancarella, Phys. Rev. D 90, 023005 (2014).

$$+\ \ldots$$

$$\Gamma = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2}{2}R - \frac{1}{\xi}R^2 + M^4 R\frac{1}{\Box^2}R\right] + S_{\mathrm{m}}$$

Effective Friedmann equations (local)

Modified Einstein's equations

$$G_{\mu\nu} + \Delta G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Local correction (covariant form)

$$-\frac{\xi}{16\pi G}\Delta G_{\mu\nu}^{R^2} = 2\left(R_{\mu\nu} - \frac{1}{4}g_{\mu\nu}R\right)R - 2\left(\nabla_\mu\nabla_\nu - g_{\mu\nu}\Box\right)R$$

Local correction (FRW form)

$$H^2 + 96\pi\xi G\left[2H\ddot{H} + 6H^2\dot{H} - \dot{H}^2\right] = \frac{8\pi G}{3}\rho$$

CEFT of Gravity II
A. C. and K. J. Jain
arXiv:1507.07829

Effective Friedmann equations (non-local)

$$\frac{1}{16\pi G\delta m^4}\Delta G_{\mu\nu}^{R\frac{1}{\Box^2}R} = -2G_{\mu\nu}S + 2g_{\mu\nu}U + 2\nabla_\mu\nabla_\nu S$$
$$+\ 2\nabla_\mu U\nabla_\nu S - g_{\mu\nu}\nabla^\alpha U\nabla_\alpha S + \frac{1}{2}g_{\mu\nu}U^2$$
$$-\Box U = R$$
$$-\Box S = U$$

$$H^2 - 32\pi G\delta m^4\left(2H^2 S + H\dot{S} + \frac{1}{2}\dot{H}S - \frac{1}{6}\dot{U}\dot{S}\right) = \frac{8\pi G}{3}\rho$$
$$\ddot{U} + 3H\dot{U} = 6\left(2H^2 + \dot{H}\right)$$
$$\ddot{S} + 3H\dot{S} = U$$

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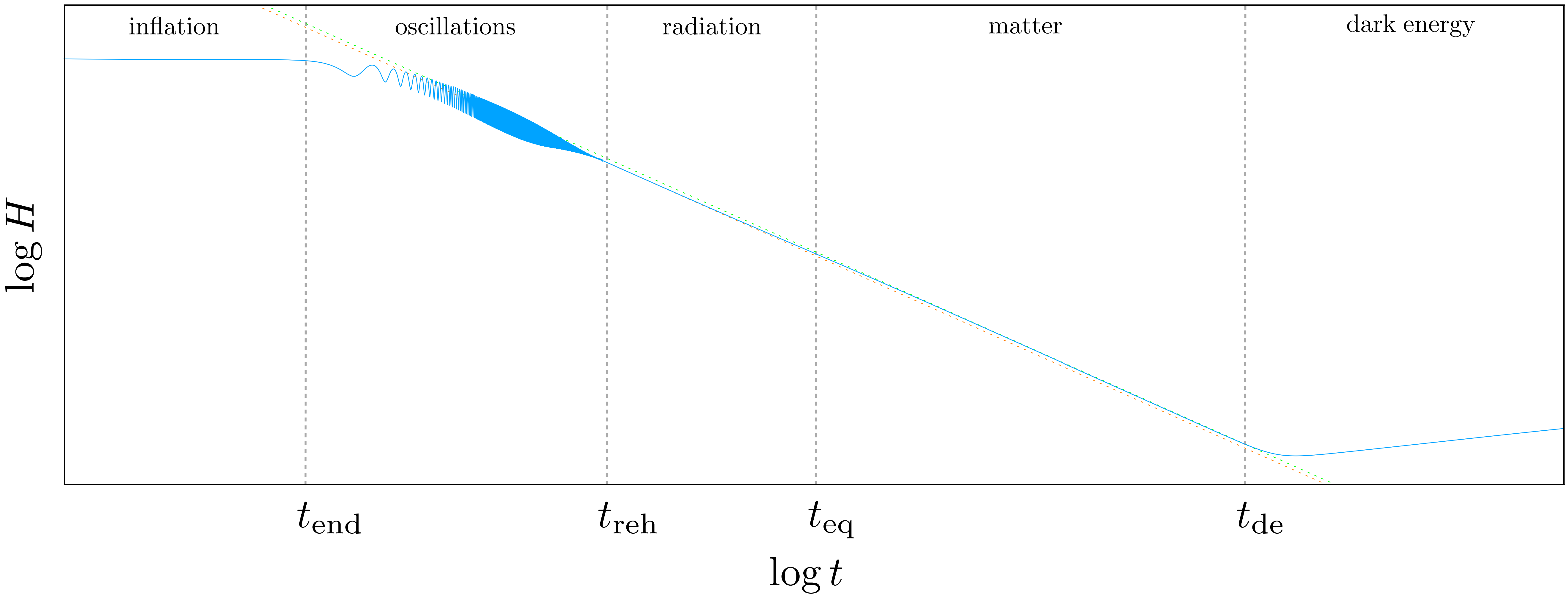
$$\ddot{S} + 3H\dot{S} = U$$

$$H^2 = \frac{8\pi G}{3}(\rho + \rho_{DE})$$

CEFT of Gravity II
A. C. and K. J. Jain
arXiv:1507.07829

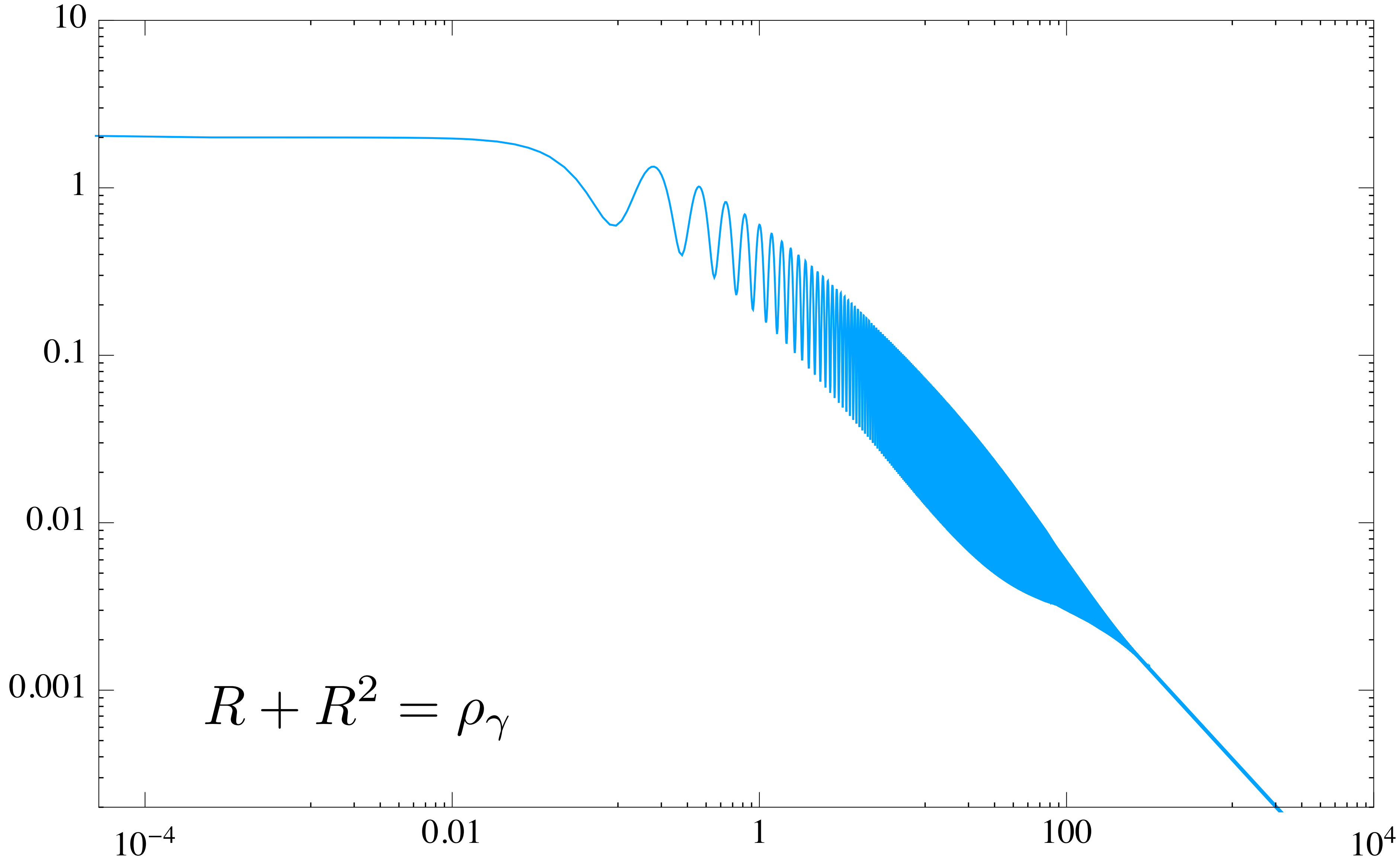
Unified evolution of the universe



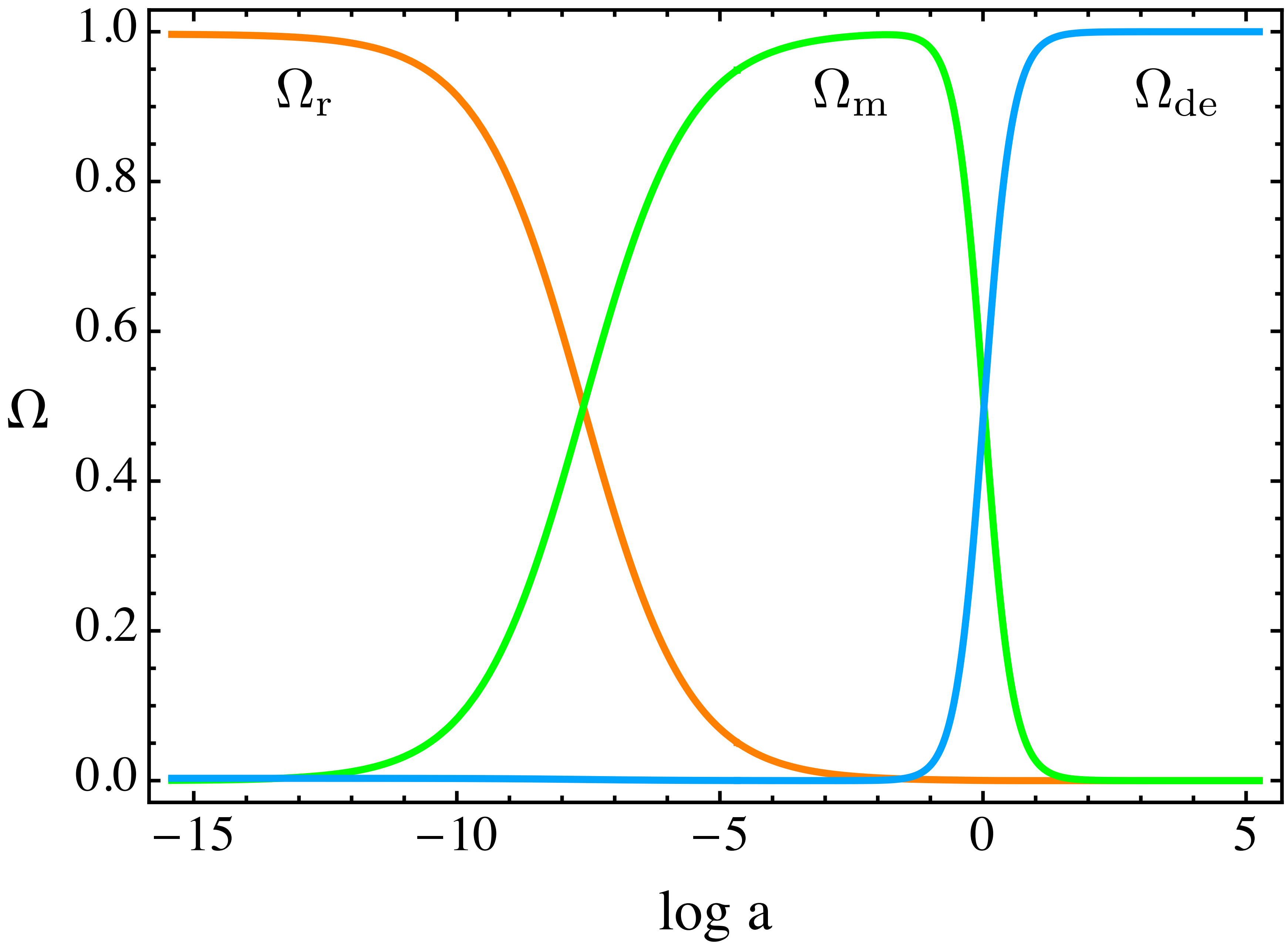
$$\Gamma = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{M_{\rm Pl}^2}{2} R - \frac{1}{\xi} R^2 + M^4 R \frac{1}{\Box^2} R \right] + S_{\rm m}$$

A unified evolution of the universe
A. C. and K. J. Jain, arXiv:1603.00028

Early times: Inflation and reheating



Late times: Dark energy



Deriving the model

$$\mathcal{F}\left(\frac{-\Box}{m^2}\right) = \alpha \log \frac{-\Box}{m^2} + \beta \frac{m^2}{-\Box} + \gamma \frac{m^2}{-\Box} \log \frac{-\Box}{m^2} + \delta \left(\frac{m^2}{-\Box}\right)^2 + \ldots$$

$$m^2 \ll -\Box$$

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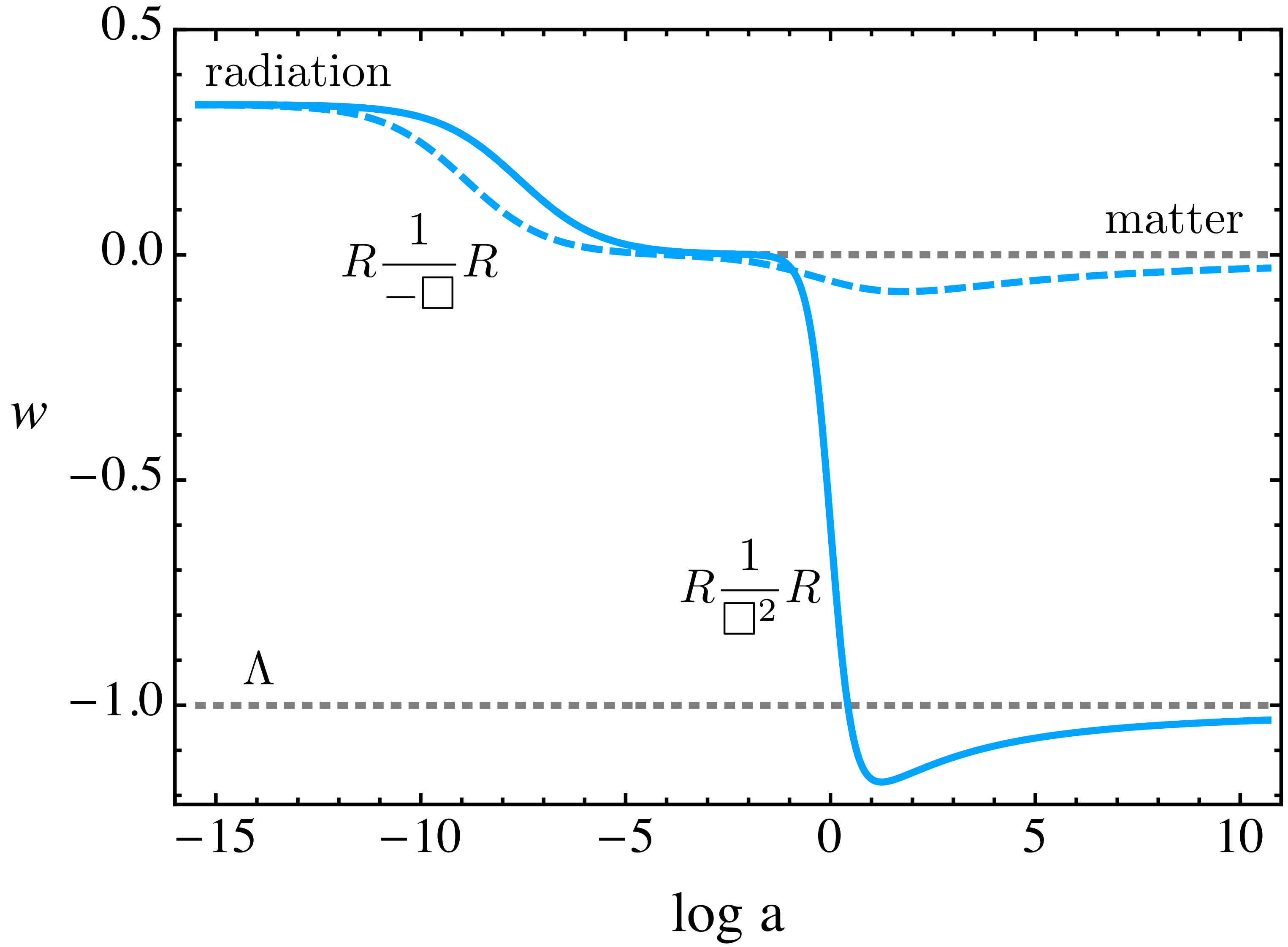

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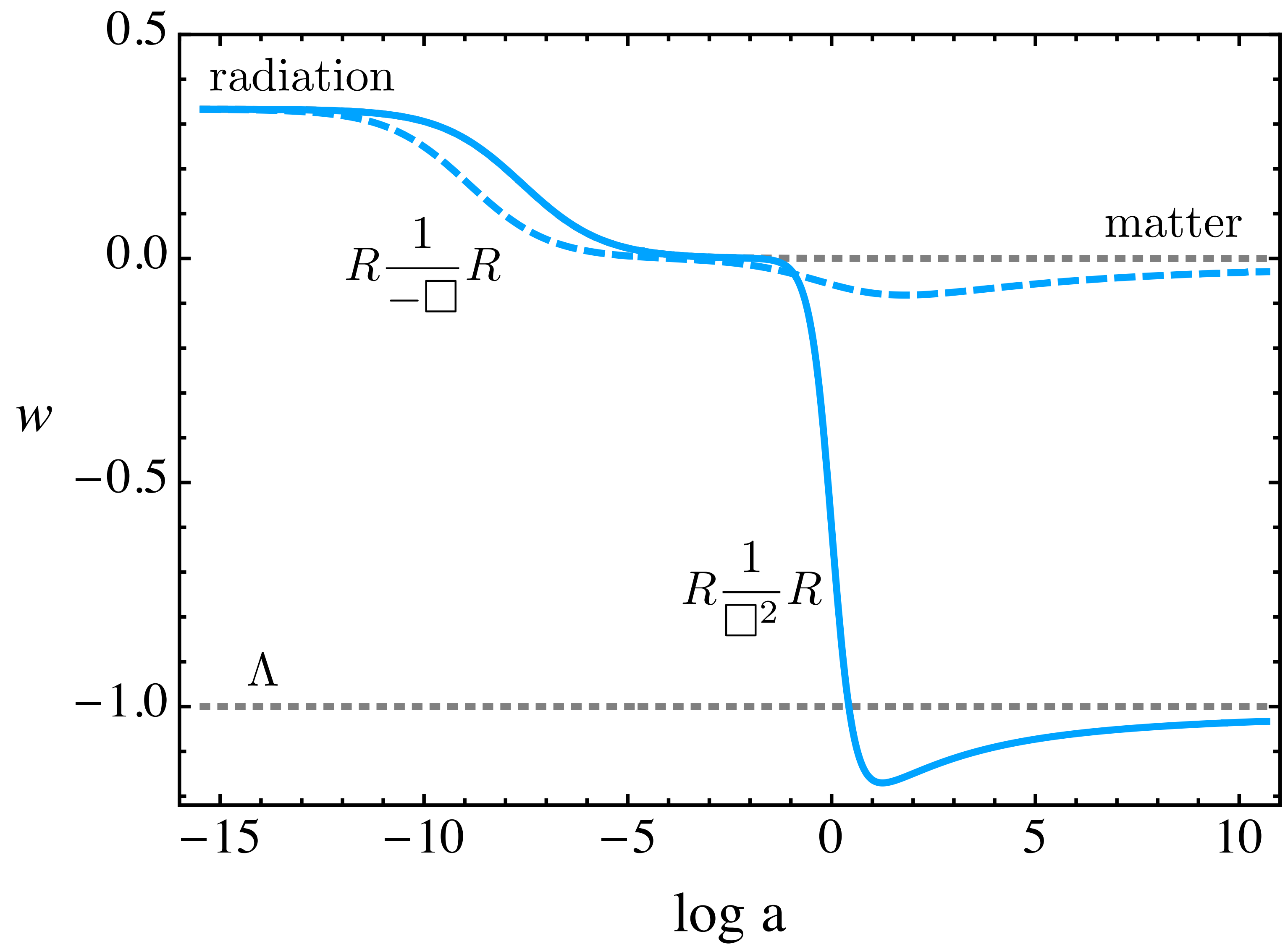

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$M = \delta^{\frac{1}{4}} m$ $\qquad$ $\delta \sim N$ $\qquad$ $\delta \sim \chi^2$

Deriving the model

$$\mathcal{F}\left(\frac{-\Box}{m^2}\right) = \alpha \log \frac{-\Box}{m^2} + \beta \frac{m^2}{-\Box} + \gamma \frac{m^2}{-\Box} \log \frac{-\Box}{m^2} + \delta \left(\frac{m^2}{-\Box}\right)^2 + \ldots$$

$$m^2 \ll -\Box$$

$$\Downarrow$$

$$\Gamma = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{M_{\mathrm{Pl}}^2}{2} R - \frac{1}{\xi} R^2 + M^4 R \frac{1}{\Box^2} R \right] + S_{\mathrm{m}}$$

$$M = \delta^{\frac{1}{4}} m \qquad \delta \sim N \qquad \delta \sim \chi^2$$

A cosmological model from first principles

Conclusions and Outlook

- Next steps in cosmology
- Apply to stars/black holes
- Compute all LO terms
- The role of the conformal anomaly
- Add matter consistently
- Connection with UV quantum gravity
- Falsify

Thank you