Exploring Particle Physics and Quantum Gravity via Primordial Inflation

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FZU, 16.01.2025.

FZU Institute of Physics of the Czech Academy of Sciences

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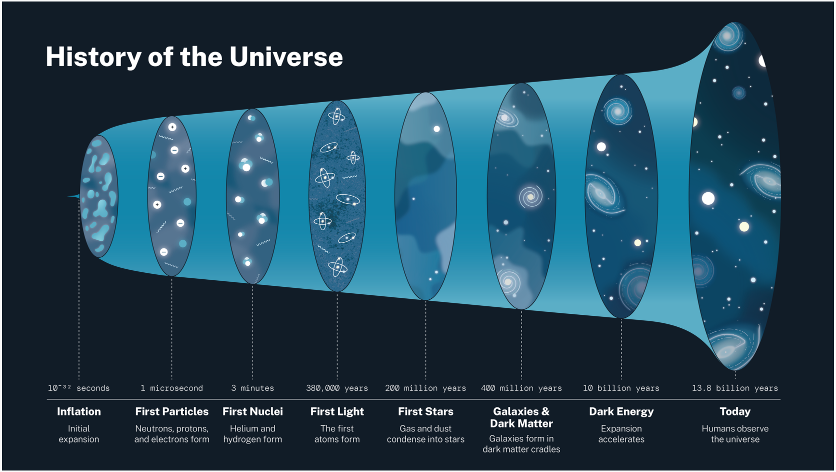
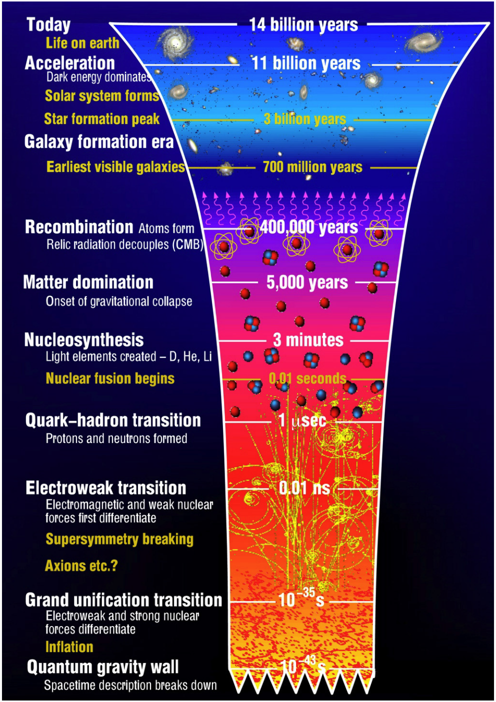
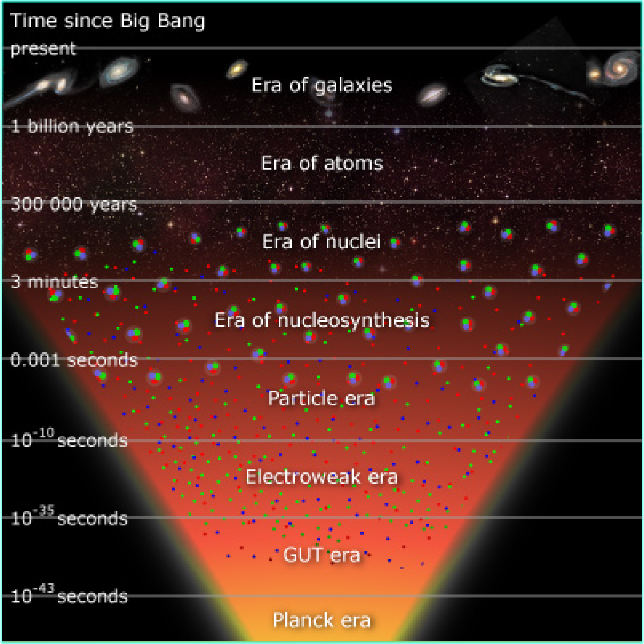

History of the Universe
10⁻³² seconds
1 microsecond
3 minutes
380,000 years
200 million years
400 million years
10 billion years
13.8 billion years
Inflation
Initial expansion
First Particles
Neutrons, protons, and electrons form
First Nuclei
Helium and hydrogen form
First Light
The first atoms form
First Stars
Gas and dust condense into stars
Galaxies & Dark Matter
Galaxies form in dark matter cradles
Dark Energy
Expansion accelerates
Today
Humans observe the universe

credit: NASA



credit: CTC Cambridge


Time since Big Bang
present
Era of galaxies
1 billion years
Era of atoms
300 000 years
Era of nuclei
3 minutes
Era of nucleosynthesis
0.001 seconds
Particle era
10^{-10} seconds
Electroweak era
10^{-35} seconds
GUT era
10^{-43} seconds
Planck era

credit: ESA

- Can we utilize primordial inflation to probe beyond standard model physics? (e.g. cosmological collider program)

Arkani-Hamed, Maldacena, *Cosmological Collider Physics,* [arXiv:1503.08043 [hep-th]].

- Incredible energy scale of expansion,

$$E_{\rm inf}/E_{\rm LHC} \sim 10^{12}$$

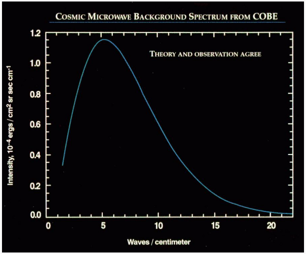
- Does this energy scale excite only very heavy physics?

- Where do we get signals from?

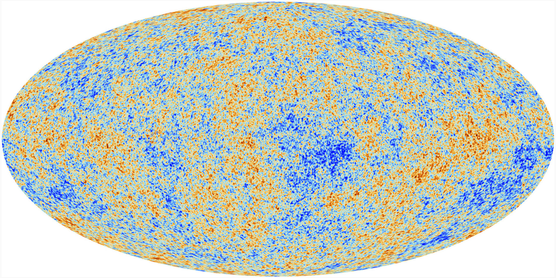
- for several decades: Cosmic Microwave Background (CMB)
- quite recent: Gravitational Wave Background (GWB)

Cosmic Microwave background (CMB) 1

Universe permeated by the most perfect black body radiation at $T = 2.7\mathrm{K}$
(COBE satellite launched 1989)



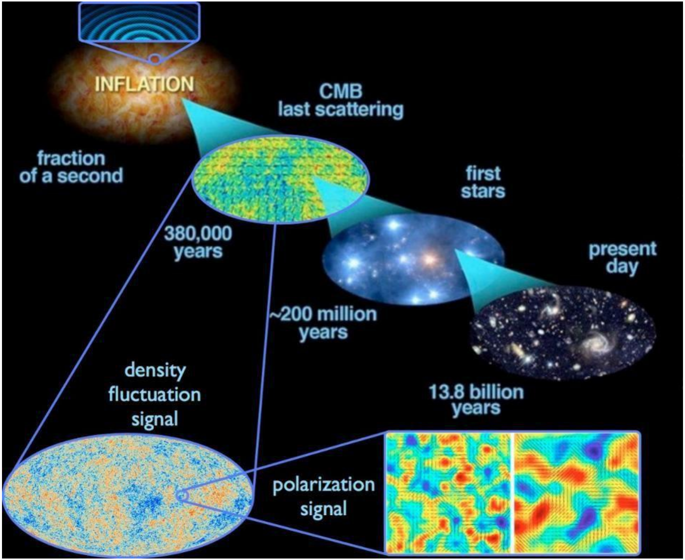
credit: NASA/COBE Science Team



credit: Planck

Temperature fluctuation $\sim 10^{-5}$
(Planck satellite launched 2009)

Cosmic Microwave background (CMB) 2



credit: ESA/Planck

Gravitational Wave Background (GWB) 1

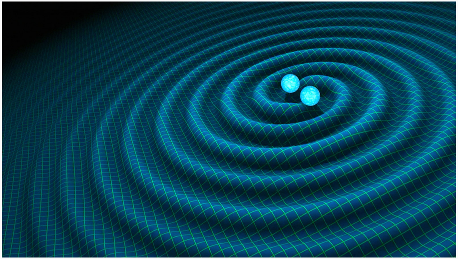
Very clean signal because of weak interactions ✓

Very difficult to detect because of weak interactions ✗

⟶ still in early stages of development

Gravitational waves first detected less than a decade ago (localized source: from black hole mergers)

LIGO Scientific and Virgo Collaborations, *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys.Rev.Lett. 116 (2016) 6, 061102, [1602.03837]



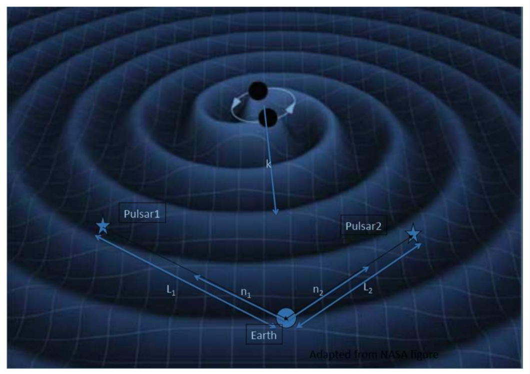
credit: R. Hurt/Caltech-JPL

Gravitational Wave Background (GWB) 2

Cosmological stochastic background?

Pulsar timing arrays — measure correlations between pairs of pulsars

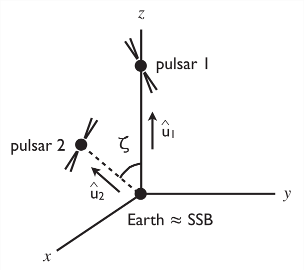
NANOGrav Collaboration, *The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background*, Astrophys.J.Lett. 951 (2023) 1, L8, [2306.16213]



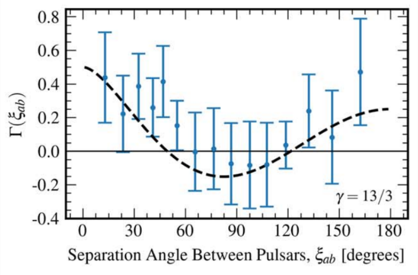
credit: NASA

Gravitational Wave Background (GWB) 2

Hellings–Downs curve: characteristic shape of pulsar timing delay correlations for GW



Am. J. Phys. 83, 635–645 (2015)



Astrophys.J.Lett. 951 (2023) 1, L8

Fundamental physics from early Universe cosmology?

Very difficult... but energy scales are fantastic!

$$E_{\text{inf}}/E_{\text{LHC}} \sim 10^{12}$$

Inflation is the most promising period

- BSM physics?

<u>*Let us also understand very well the signals of known physics originating from extreme conditions of primordial Universe.*</u>

- Quantum gravity?

<u>Very small, but not hopelessly small?</u>

Primordial inflation

Expanding cosmological space (FLRW line element)

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

Rate of expansion captured by the Hubble rate

$$H = \frac{\dot{a}}{a}$$

Acceleration/deceleration captured by the slow-roll parameter

$$\epsilon = -\frac{\dot{H}}{H^2}\,, \qquad (\text{acceleration}: \epsilon < 1,\ \text{deceleration}: \epsilon > 1)$$

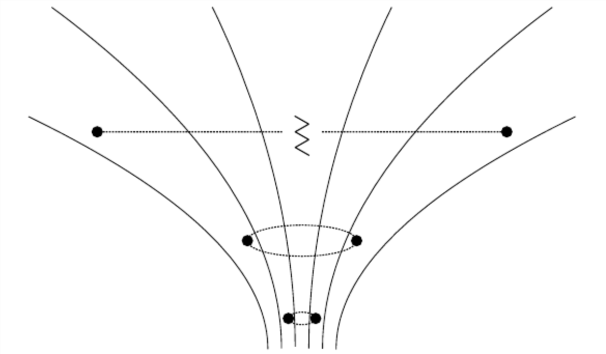
Primordial inflation:

$$0 < \epsilon \ll 1 \qquad \Longrightarrow \qquad H \approx \text{const.} \qquad \Longrightarrow \qquad a(t) \sim e^{Ht}$$

Gravitational particle production 1

Accelerated expansion of space creates long wavelength quanta

Parker, *Particle creation in expanding universes*, Phys.Rev.Lett. 21 (1968) 562-564



from Glavan, Rigopoulos, JCAP 02 (2021) 021, arXiv:1909.11741 [gr-qc]

Gravitational particle production 2

Only for non-conformally coupled fields

Example: electromagnetism does not see expanding universe

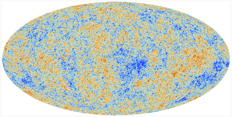
$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{4} g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma} \right] = \int d^4x \left[-\frac{1}{4} \eta^{\mu\rho} \eta^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma} \right]$$

Scalars and **gravitons** are not conformally coupled

$\longrightarrow$ primordial power spectra of scalar and tensor cosmological perturbations

Starobinsky, *Spectrum of relict gravitational radiation and the early state of the universe* JETP Lett. 30 (1979) 682-685, Pisma Zh.Eksp.Teor.Fiz. 30 (1979) 719-723

Mukhanov, Chibisov, *Quantum Fluctuations and a Nonsingular Universe* JETP Lett. 33 (1981) 532-535, Pisma Zh.Eksp.Teor.Fiz. 33 (1981) 549-553

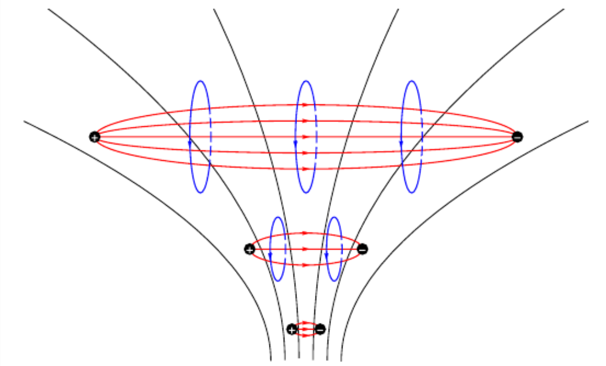


credit: Planck

Gravitational particle production 3

Conformal fields couple to scalars and gravitons

— effects of rapid expansion communicated via interactions



from Glavan, Rigopoulos, JCAP 02 (2021) 021, arXiv:1909.11741 [gr-qc]

Scalar electrodynamics (SQED) in inflation 1

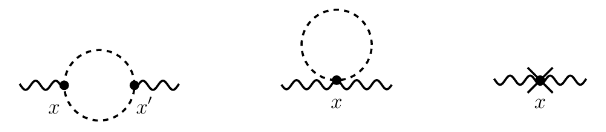
Massless complex scalar interacting with a photon in inflation

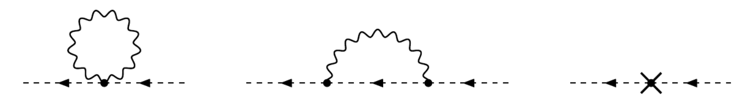
$$S\big[\Phi,\Phi^*,A_\mu\big] = \int d^Dx\,\sqrt{-g}\left[-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - (D_\mu\Phi)^*(D_\nu\Phi)\right]$$

Φ	:	`complex scalar`
A_μ	:	`vector potential`
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$	:	`vector field strength`
$D_\mu = \partial_\mu + i\boldsymbol{q}A_\mu$	:	$U(1)$ `covariant derivative`
$\boldsymbol{q}$	:	$U(1)$ `charge`

Scalar electrodynamics (SQED) in inflation 2

Scalar electrodynamics





Prokopec, Tornkvist, Woodard, *One loop vacuum polarization in a locally de Sitter background*, Annals Phys. 303 (2003) 251-274 [arXiv:gr-qc/0205130 [gr-qc]]

Kahya, Woodard, *Charged scalar self-mass during inflation*, Phys. Rev. D **72** (2005), 104001 [arXiv:gr-qc/0508015].

Kahya, Woodard, *One Loop Corrected Mode Functions for SQED during Inflation*, Phys. Rev. D **74** (2006), 084012 [arXiv:gr-qc/0608049].

Glavan, Rigopoulos, *"One-loop electromagnetic correlators of SQED in power-law inflation,"* JCAP **02** (2021), 021 [arXiv:1909.11741].

Scalar electrodynamics (SQED) in inflation 3

Use one-loop vacuum polarization to correct the evolution of photons

$$\partial_\nu \left[\sqrt{-g} g^{\mu\rho} g^{\nu\sigma} F_{\rho\sigma}(x)\right] + \int d^4x' \, \boldsymbol{i\left[{}^{\mu}\Pi^{\nu}\right]_{\mathbf{ret}}(x;x')} A_\nu(x') = 0$$

Perturbative result:

Prokopec, Tornkvist, Woodard, *Photon mass from inflation*, Phys.Rev.Lett. 89 (2002) 101301, [arXiv:astro-ph/0205331 [astro-ph]]

$$m_\gamma^2 = \frac{\boldsymbol{q^2 H^2}}{2\pi^2} \times \boldsymbol{\ln(a)}$$

time-dependent photon mass!

$\longrightarrow$ breakdown of perturbation theory!

Scalar electrodynamics (SQED) in inflation 4

Non-perturbative results:

Prokopec, Tsamis, Woodard, *Two Loop Scalar Bilinears for Inflationary SQED,* Class. Quant. Grav. **24** (2007), 201-230 [arXiv:gr-qc/0607094].

Prokopec, Tsamis, Woodard, *Stochastic Inflationary Scalar Electrodynamics,* Annals Phys. **323** (2008), 1324-1360 [arXiv:0707.0847].

Prokopec, Tsamis, Woodard, *Two loop stress-energy tensor for inflationary scalar electrodynamics,* Phys. Rev. D **78** (2008), 043523 [arXiv:0802.3673].

$$m_\gamma^2 = 2\boldsymbol{q^2} \times \langle \Phi^* \Phi \rangle \approx 2\boldsymbol{q^2} \times 1.65 \frac{\boldsymbol{H^2}}{\boldsymbol{q^2}} = 3.3\boldsymbol{H^2}$$

$$m_\phi^2 \approx \frac{\boldsymbol{q^2}\boldsymbol{H^2}}{3\pi^2}$$

no secular growth, but non-perturbatively large photon mass!

Interpret data?

SM photon with dynamically induced mass or heavy BSM vector?

Gravity is weak

Typical energy scale is Planck energy: $E_{\mathrm{P}} = \sqrt{\frac{\hbar c^5}{G}} \sim 1.22 \times 10^{19} \mathrm{GeV}$

Where can we find good candidate systems?

$$\frac{?}{E_{\mathrm{P}}} \sim \frac{?}{10^{19}\mathrm{GeV}} \sim ?$$

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Where can we find good candidate systems?

$$\frac{?}{E_{\mathrm{P}}} \sim \frac{?}{10^{19}\mathrm{GeV}} \sim ?$$

Our best most advanced accelerator:

$$\frac{E_{\mathrm{LHC}}}{E_{\mathrm{P}}} \sim \frac{10^{4}\mathrm{GeV}}{10^{19}\mathrm{GeV}} \sim 10^{-15}$$

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Our universe expands today

$$\frac{\hbar H_0}{E_{\mathrm{P}}} \sim \frac{10^{-42}\mathrm{GeV}}{10^{19}\mathrm{GeV}} \sim 10^{-61}$$

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Our universe expands today

$$\frac{\hbar H_0}{E_\mathrm{P}} \sim \frac{10^{-42}\mathrm{GeV}}{10^{19}\mathrm{GeV}} \sim 10^{-61}$$

Our Universe expanded much faster in the past

$$\frac{\hbar H_\mathrm{inf}}{E_\mathrm{P}} \sim \frac{10^{14}\mathrm{GeV}}{10^{19}\mathrm{GeV}} \sim 10^{-5}$$

Electromagnetism in de Sitter

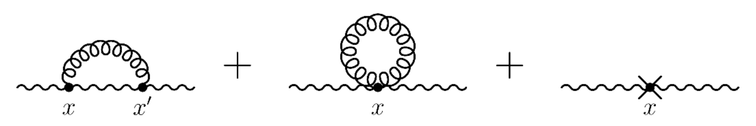
Quantum corrections to electromagnetism in de Sitter

$$\partial_\nu\Big[\sqrt{-g}g^{\mu\rho}g^{\nu\sigma}F_{\rho\sigma}(x)\Big] + \int d^4x'\, \boldsymbol{i\big[{}^\mu\Pi^\nu\big](x;x')}A_\nu(x') = \boldsymbol{J^\mu(x)}$$

$\longrightarrow$ compute retarded vacuum polarization

QFT in curved space & nonequilibrium QFT — Schwinger-Keldysh formalism (in-in, closed-time-path)

Dimensional regularization

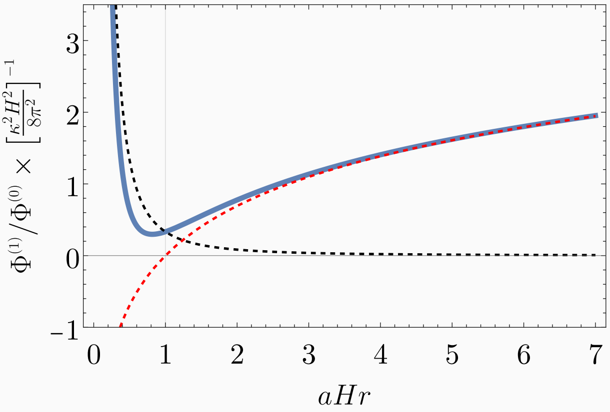


Leonard, Woodard, *Graviton Corrections to Vacuum Polarization during Inflation*, Class.Quant.Grav. 31 (2014) 015010, arXiv:1304.7265 [gr-qc]

Coulomb potential

Glavan, Miao, Prokopec, Woodard, *Electrodynamic Effects of Inflationary Gravitons*, Class.Quant.Grav. 31 (2014) 175002, arXiv: 1308.3453 [gr-qc]

$$\Phi(x) = \Phi^{(0)}(x)\left\{1 + \frac{\kappa^2 H^2}{8\pi^2} \times \left[\frac{1}{3(aHr)^2} + \ln(aHr)\right]\right\}$$



Dynamical photon

Wang, Woodard, *Excitation of Photons by Inflationary Gravitons*,
Phys.Rev.D 91 (2015) 12, 124054, arXiv:1408.1448 [gr-qc]

$$F_{0i} = F_{0i}^{(0)} \left[1 + \frac{\boldsymbol{\kappa^2 H^2}}{\boldsymbol{8\pi^2}} \times \mathbf{ln}(\boldsymbol{a}) \right]$$

Secular enhancement of electric field strength
of a propagating photon.

Are these results physical? Are these results gauge-independent?

Conjecture: leading secular effects are gauge independent

Miao, Woodard, *Issues Concerning Loop Corrections to the Primordial Power Spectra*,
JCAP 07 (2012) 008, arXiv:1204.1784 [astro-ph.CO]

Dynamical photon

First compute the vacuum polarization in a different gauge

Glavan, Miao, Prokopec, Woodard, *Graviton Loop Corrections to Vacuum Polarization in de Sitter in a General Covariant Gauge*, Class.Quant.Grav. 32 (2015) 19, 195014, arXiv: 1504.00894 [gr-qc]

Solve again the effective field equation for the dynamical photon

Glavan, Miao, Prokopec, Woodard, *One loop graviton corrections to dynamical photons in de Sitter*, Class.Quant.Grav. 34 (2017) 8, 085002, arXiv:1609.00386 [gr-qc]

$$F_{0i} = F_{0i}^{(0)} \left[1 + \frac{\kappa^2 H^2}{8\pi^2} \times \ln(a) \times \frac{1}{6} \left(45 - \frac{2ik}{H} + 5 e^{2ik/H} \right) \right]$$

The coefficient does not agree!

$\longrightarrow$ construct one-loop quantum gravitational observables

Work in progress on observables

Leading quantum gravitational corrections to long range forces derive from nonanalytic corrections to loop amplitudes

Donoghue, *Leading quantum correction to the Newtonian potential*, Phys.Rev.Lett. 72 (1994) 2996-2999, arXiv:gr-qc/9310024 [gr-qc]

Donoghue, *General relativity as an effective field theory: The leading quantum corrections*, Phys.Rev.D 50 (1994) 3874-3888, arXiv:gr-qc/9405057 [gr-qc]

Donoghue, Torma, *On the power counting of loop diagrams in general relativity*, Phys.Rev.D 54 (1996) 4963-4972, arXiv:hep-th/9602121 [hep-th]

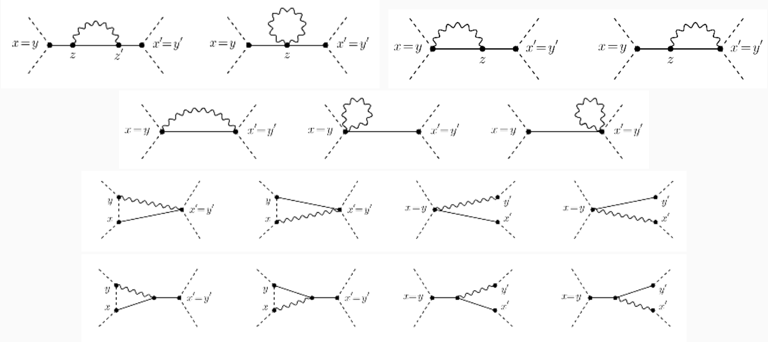
Bjerrum-Bohr, *Leading quantum gravitational corrections to scalar QED* Phys.Rev.D 66 (2002) 084023, arXiv: hep-th/0206236 [hep-th]

Gauge dependence drops out before forming the S-matrix

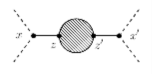
Miao, Prokopec, Woodard, *Deducing Cosmological Observables from the S-matrix*, Phys.Rev.D 96 (2017) 10, 104029, arXiv:1708.06239 [gr-qc]

$\longrightarrow$ form effective self-mass/vacuum polarization and use it to quantum-correct field equations

Work in progress on observables



$\longrightarrow$



Extend this approach to de Sitter

Glavan, Miao, Prokopec, Woodard, *Gauge independent logarithms from inflationary gravitons*, JHEP 03 (2024) 129, arXiv:2402.05452 [hep-th]

Conclusions

Let us work out the SM physics and perturbative quantum gravity in inflation

- One-loop observables? [Fröb, Hack, Khavkine 1801.02632 [gr-qc] ; Fröb, Lima 2303.16218 [gr-qc], . . .]
- Nonperturbative effects?
- Resummation methods?
- Nonequilibrium RG methods?
- Starobinsky's stochastic formalism?

What about corrections from subsequent periods?
Ota, Sasaki, Wang, *One-loop thermal radiation exchange in gravitational wave power spectrum*, arXiv:2310.19071 [astro-ph.CO]