Standard Model Background *of* the Cosmological Collider

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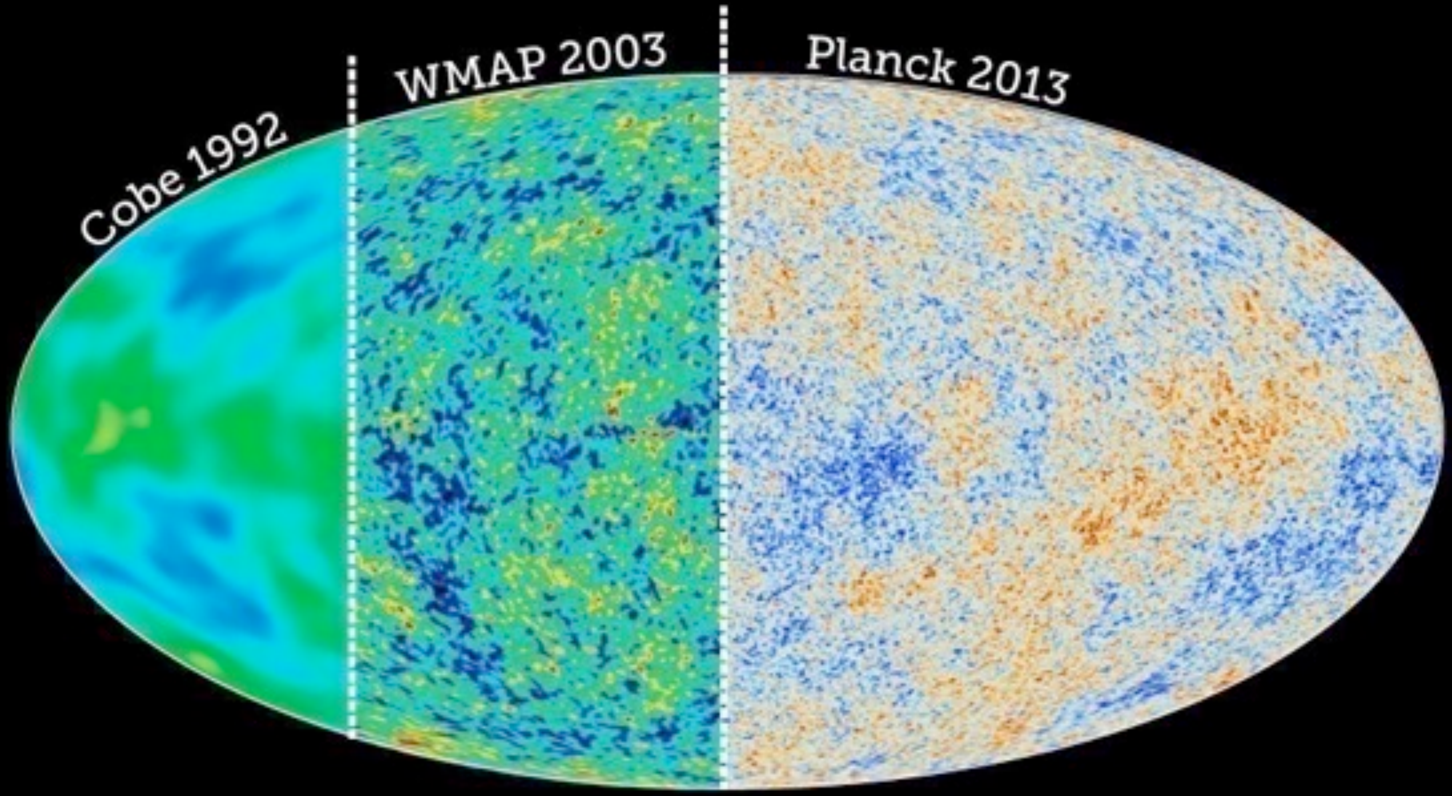
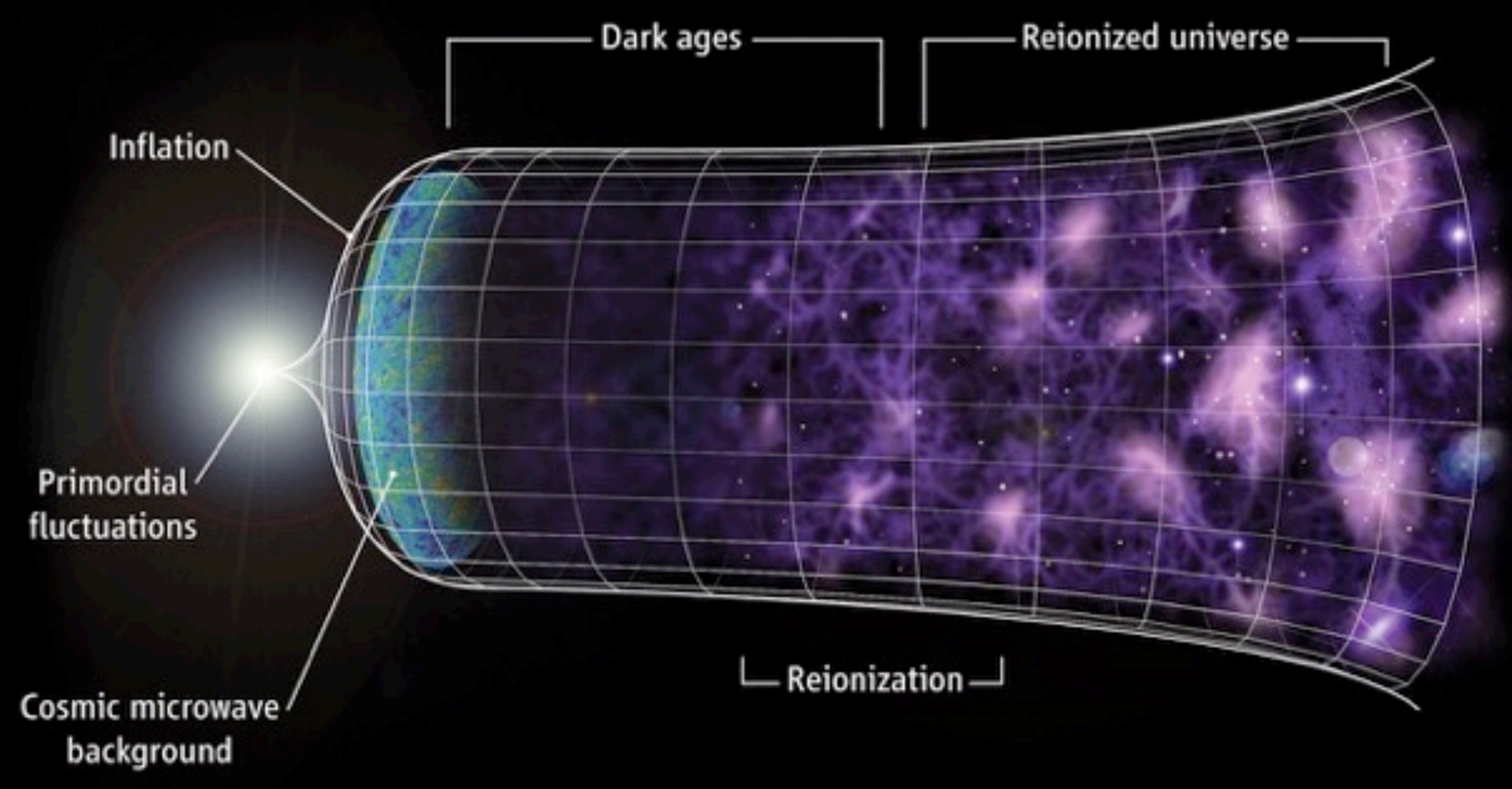
Collaboration with Xingang Chen & Yi Wang
1604.07841 | 1610.06597 | 1612.08122 | 1703.10166

Primordial perturbations



- Precious information from very early universe
- Nearly scale invariant scalar power spectrum
- Non-Gaussianities

Primordial perturbations: Inflation paradigm



- Exponentially fast expansion ~ Poincaré patch of dS
- Energy scale up to $H \sim 10^{14}\mathrm{GeV}$
- Predictability

Primordial perturbations: Inflation paradigm

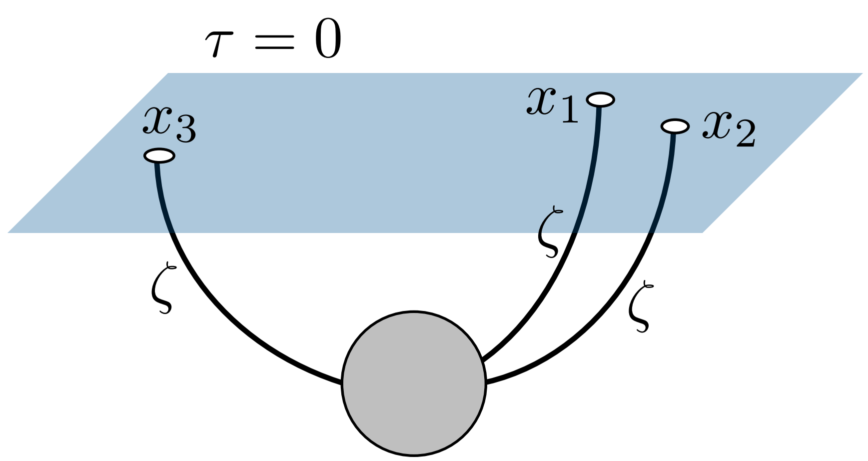
- Model-building approach:
  Single-field / multi-field / quasi-single-field…
  particle / string connections…

- Need information of new physics at extremely high energy

- Hope: identify / constrain models via precise measurement of primordial fluctuations

- Reality: very nontrivial constraints, yet still too large degeneracy, at least at linear level

Primordial perturbations: Non-Gaussianity

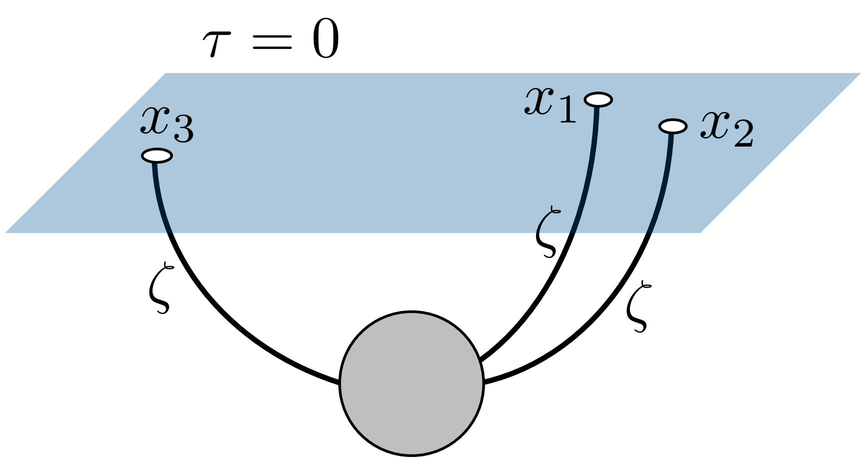


- Non-Gaussianities: information about interactions

- Small for single field slow-roll, $f_{NL} \ll 1$
  — Very weak self-interaction, dominated by gravity

- More exotic models predict large $f_{NL} \sim 1$ or even $\gg 1$
  — more strongly interacting

Primordial perturbations: Non-Gaussianity



- Non-Gaussianities: information about interactions

- Observationally: (Planck 2015, 68% CL)

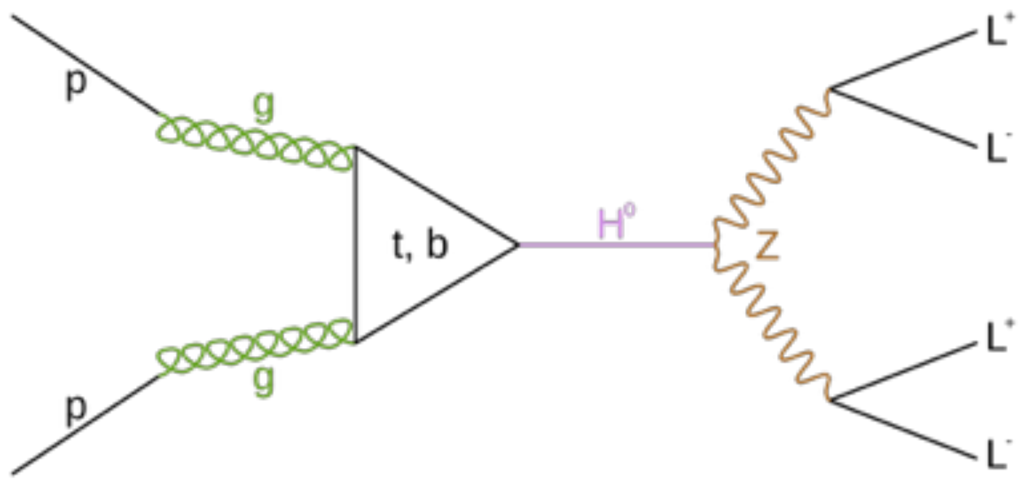
$$f_{NL}^{\rm local} = 2.5 \pm 5.7 \qquad f_{NL}^{\rm equil} = -16 \pm 70 \qquad f_{NL}^{\rm ortho} = -34 \pm 33$$

- Future probe:
  LSS $f_{NL} \sim \mathcal{O}(0.1)$ 21cm tomography $f_{NL} \sim \mathcal{O}(0.01)$
  Muñoz et al., 1506.04152; Meerburg et al., 1610.06559

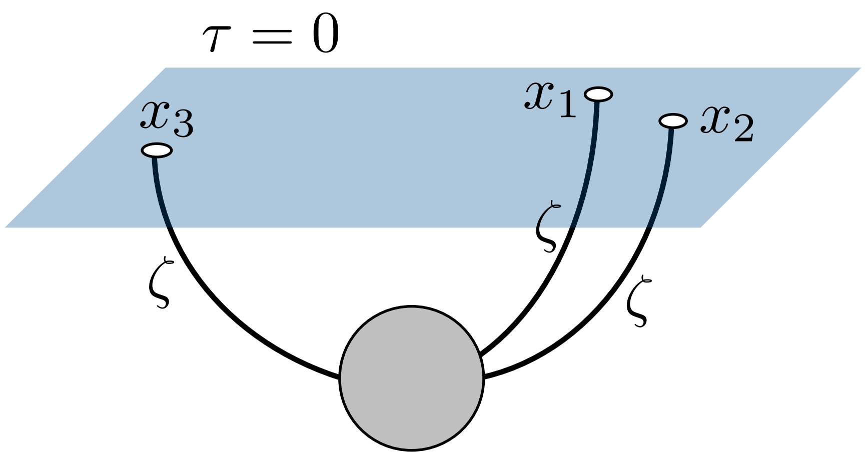
- Motivations for going beyond $f_{NL} \sim 1$?

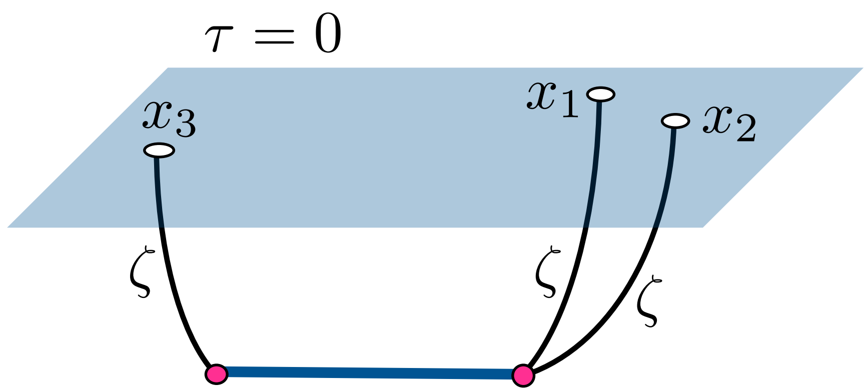
Primordial perturbations: Non-Gaussianity

- Analogy from particle physics:
  past: $e,\ \mu,\ p,\ \pi,\ldots$ nowadays: Higgs, heavy quarks, BSM



- Lessons: making use of well-studied "external" particles to probe unknown "internal" particles and their physics





Cosmological collider

- Using primordial perturbations as a probe of very high energy collisions during inflation

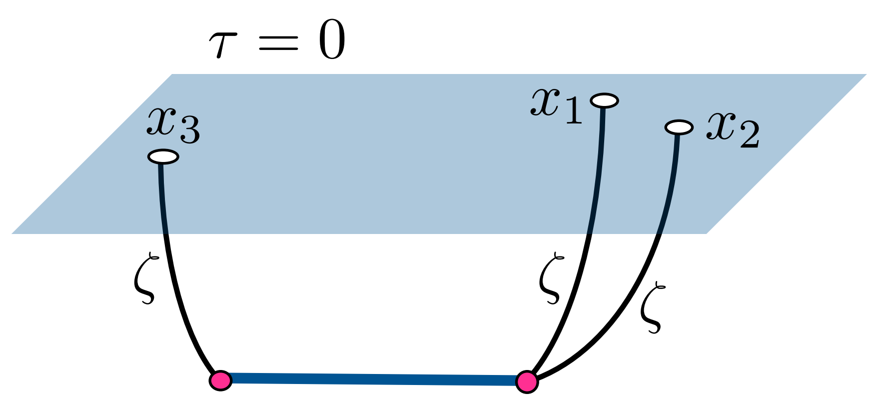
- Much higher energy than any ground based collider we can ever dream of (up to 10^{14} GeV)

- Not-too-large non-G from inflaton
  — "external particles" are not strongly interacting
  — More like electrons or photons than protons or jets

- New particles interacting with inflaton (scalar perturbation) could leave signals in inflaton correlators

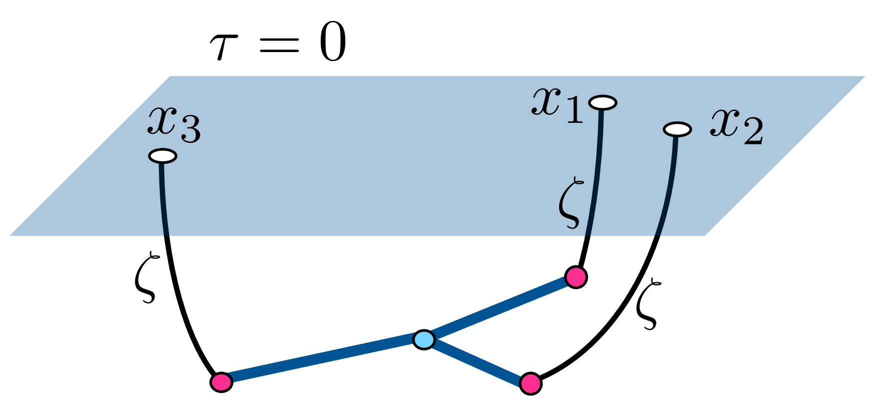
Cosmological collider

- Primordial perturbations (non-G) as a probe of new physics



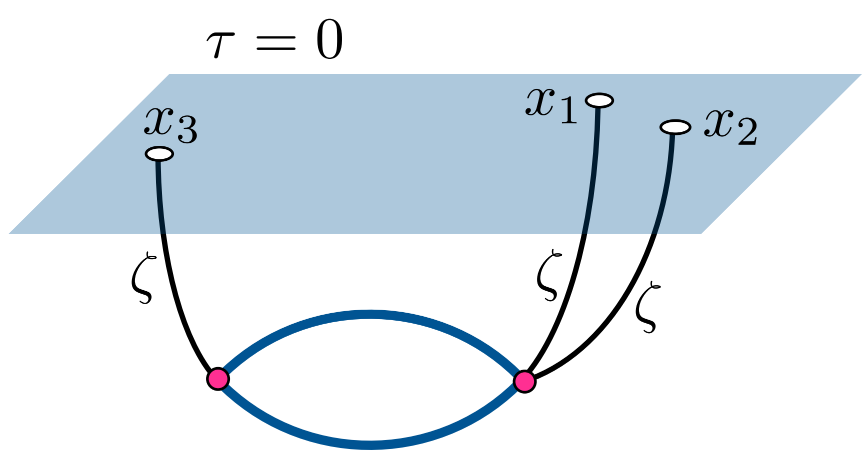
heavy (new) particles

Chen, Wang, 0911.3380;1205.0160
Pi, Sasaki, 1205.0161
Arkani-Hamed, Maldacena, 1503.08043
Chen, Namjoo, Wang, 1509.03930



new strong interactions
via enhanced non-G

Chen, Wang, 0911.3380
Chen, Wang, ZZX, 1703.10166



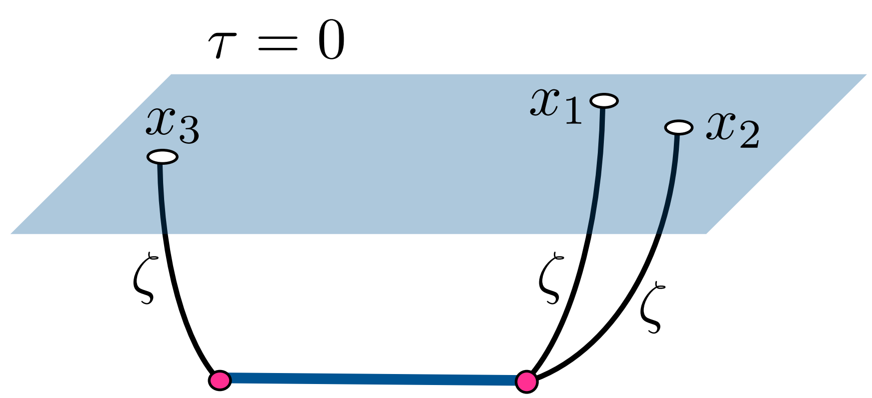
loop effects

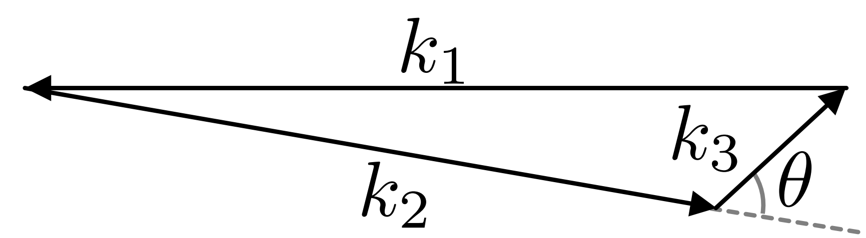
Arkani-Hamed, Maldacena, 1503.08043
Chen, Wang, ZZX, 1612.08122

Cosmological collider: Discovery channels

- Most significant channels may not be most sensitive channels [diphoton channel in Higgs discovery]

- In cosmological collider: squeezed limit of bispectrum



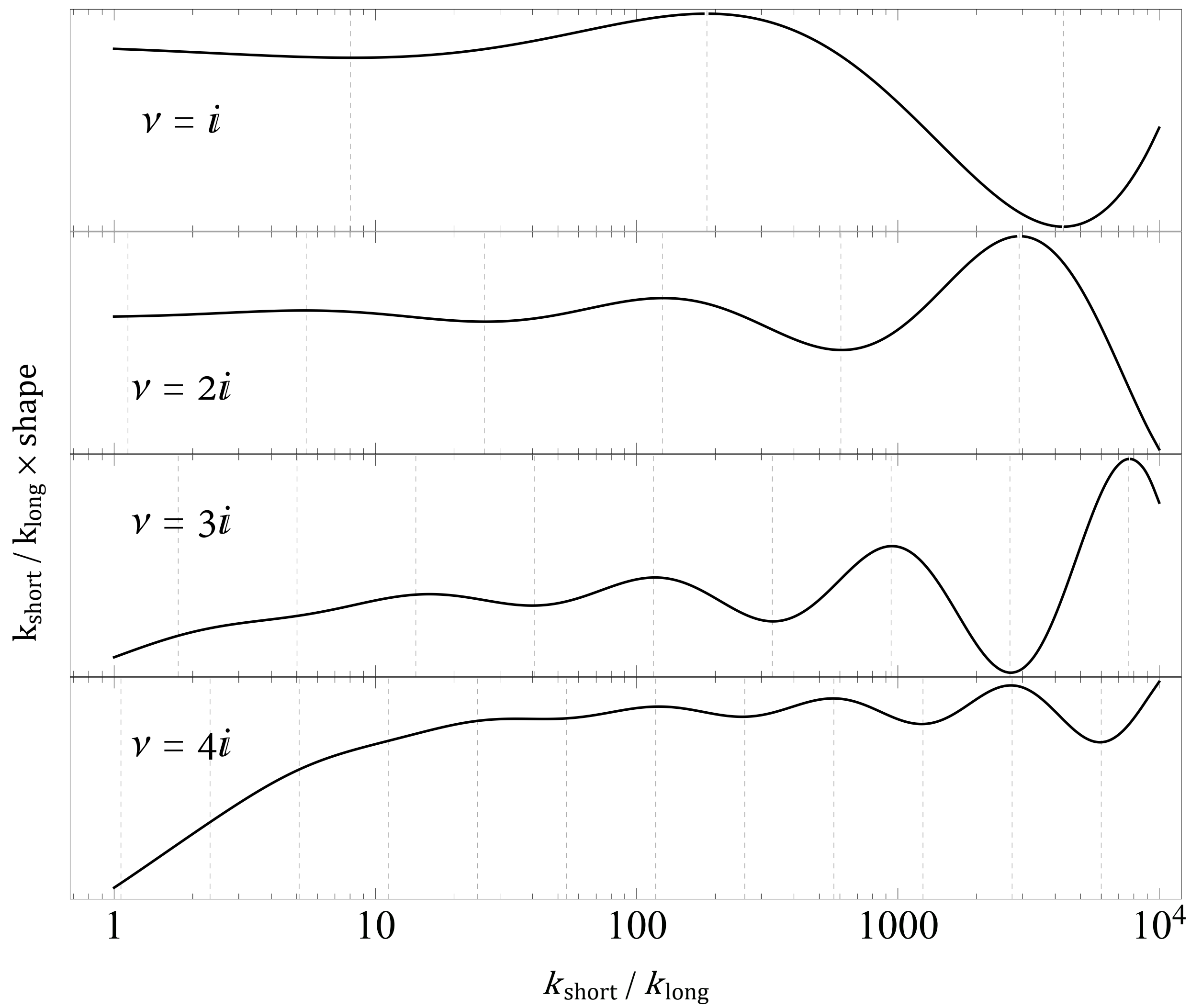


Arkani-Hamed, Maldacena, 1503.08043

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle' \propto \epsilon e^{-\pi \,\mathrm{Im}\nu} \left[C(\nu) \left(\frac{k_3}{k_1} \right)^{3/2-\nu} + \mathrm{c.c.} \right] P_s(\cos\theta)$$

$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}, \quad (s = 0); \qquad \nu = \sqrt{(s - \frac{1}{2})^2 - \frac{m^2}{H^2}}, \quad (s \geq \frac{1}{2})$$

Cosmological collider: Discovery channels



Chen, Namjoo, Wang, 1509.03930
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$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle' \propto \epsilon e^{-\pi\,\mathrm{Im}\nu}\left[C(\nu)\left(\frac{k_3}{k_1}\right)^{3/2-\nu} + \mathrm{c.c.}\right]P_s(\cos\theta)$$

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Cosmological collider

- Before exploring new physics, can we recover known physics?
- Known physics: SM
- The Hubble scale during inflation >> electroweak scale
- Why SM relevant?

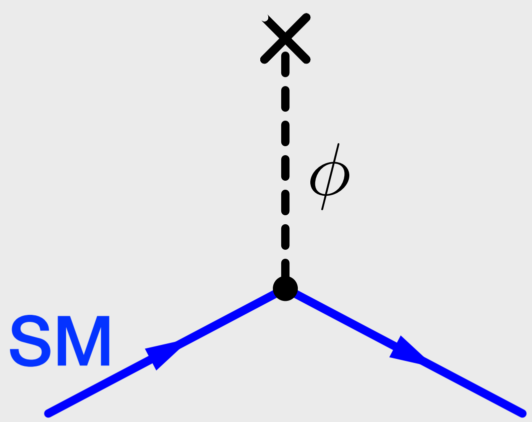
"Aren't they massless?!"

— A Surprising No.

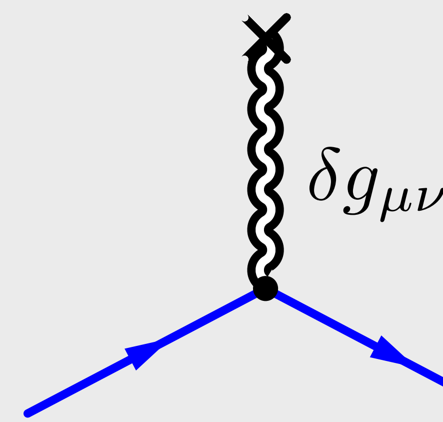
(or not surprising?)

Standard Model mass spectrum

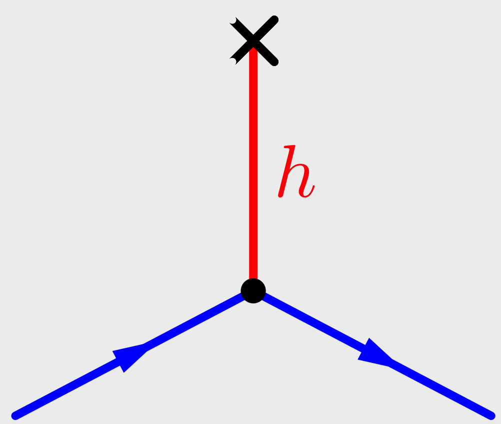
Four ways to go massive:



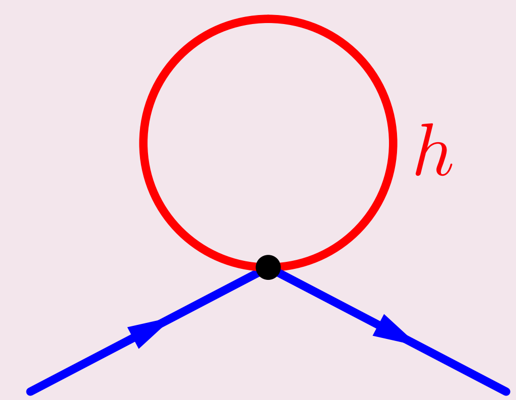
Inflaton background
via SM-inflaton couplings



dS background via
Gravitational coupling



Higgs background



Loop corrections
(thermal background?)

SM-Inflaton couplings

- They must exist (for successful reheating)
- At least gravitational, but can be much stronger
- Very model dependent
- Assuming shift symmetry, a simple parameterization:

$$\begin{aligned}\mathscr{L} \supset & - f_H(X)\mathbf{H}^\dagger \mathbf{H} - f_{DH}(X)|\mathrm{D}_\mu \mathbf{H}|^2 \\ & - f_{\Psi_i}(X)\overline{\Psi}_i \not{D} \Psi_i - \frac{1}{4} f_{A_a}(X) F_{a\mu\nu} F_a^{\mu\nu},\end{aligned} \qquad X \equiv (\partial_\mu \phi)^2$$

- Generalizations: higher spin coupling / no shift symmetry

SM-Inflaton couplings

$$\begin{aligned}\mathscr{L} \supset & - f_H(X)\mathbf{H}^\dagger\mathbf{H} - f_{DH}(X)|\mathrm{D}_\mu\mathbf{H}|^2 \\ & - f_{\Psi_i}(X)\bar{\Psi}_i \not{D}\Psi_i - \frac{1}{4} f_{A_a}(X) F_{a\mu\nu}F_a^{\mu\nu},\end{aligned} \qquad X \equiv (\partial_\mu\phi)^2$$

- Corrections from SM-inflaton couplings:
- Mass correction: $\Delta M_h^2 = \dfrac{f_H(X_0)}{1 + f_{DH}(X_0)}$ $\qquad X_0 \equiv -\dot{\phi}_0^2$
- Correction to couplings, e.g.,

$$\lambda = \frac{\lambda_{\rm SM}}{[1 + f_{DH}(X_0)]^2} \qquad\qquad g^2 = \frac{g_{\rm SM}^2}{1 + f_W(X_0, \phi_0)}$$

- "Calibration" limit (Part 1): $f_{DH}(X_0),\ f_{\Psi_i}(X_0),\ f_{A_a}(X_0) \ll 1$

Gravitational couplings

- Expected to be highly suppressed in general (by Planck mass)
- The only exception: dimensionless Higgs non-minimal coupling

$$S \supset -\int \mathrm{d}^4x\sqrt{-g}\,\xi R\mathbf{H}^\dagger\mathbf{H}$$

$$\Delta M_h^2 = \frac{12\xi H^2 + f_H(X_0)}{1 + f_{DH}(X_0)}$$

- Higgs mass: free parameter in inflation (even in “calibration” limit)

Higgs background

- Very low scale inflation: $H \ll v = 246\mathrm{GeV}$
  — Uninteresting from perspective of cosmological collider

- Higgs inflation: Higgs boson = inflaton

$$\mathscr{L} = \Big(\frac{1}{2}M^2 + \xi\mathbf{H}^\dagger\mathbf{H}\Big)R - |\mathrm{D}_\mu\mathbf{H}|^2 - \lambda(\mathbf{H}^\dagger\mathbf{H})^2$$

$$g_{\mu\nu} \to \frac{M^2 + 2\xi\mathbf{H}^\dagger\mathbf{H}}{M_\mathrm{P}^2}g_{\mu\nu}, \qquad V(h) = \frac{\lambda h^4}{4(1+\xi h^2/M_\mathrm{P}^2)^2}$$

- Huge and time-dependent VEV: $\langle h\rangle \sim \mathcal{O}(10^{16}\mathrm{GeV})$

Higgs background: Higgs inflation

- SM mass spectrum gets overall uplift

$$v = 246\mathrm{GeV} \quad \longrightarrow \quad \langle h \rangle \sim \mathcal{O}(10^{16}\mathrm{GeV})$$

- Original model in tension with collider data (Higgs instability)

- A class of models

- More general analysis

Loop corrections

- Loop corrections can generate nonzero mass contribution even all fields are massless (or very light) at tree level

- Thermal analogy
  Thermal mass in (flat-space) thermal QFT: $M_{\rm th}^2 \propto \lambda T^2$

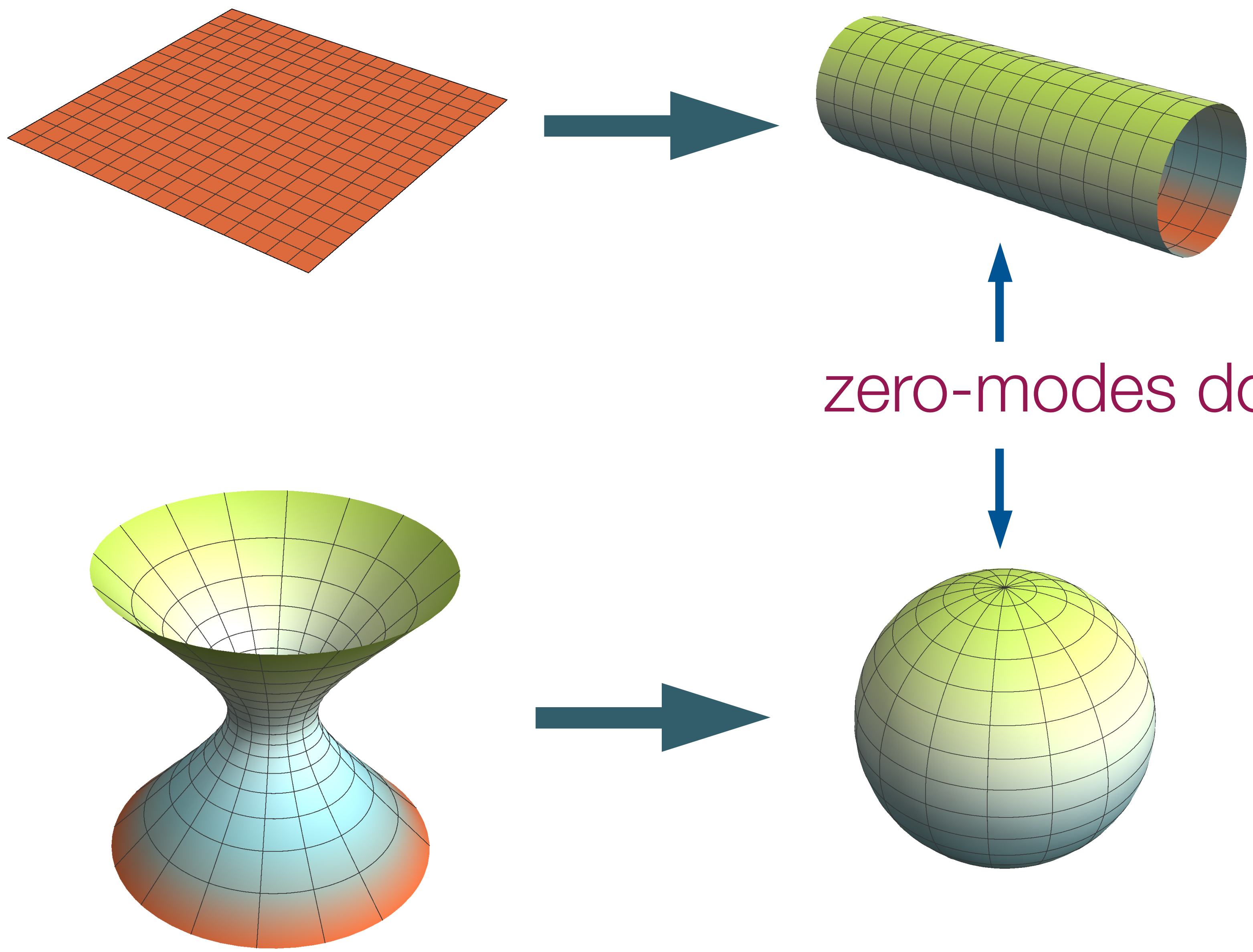
- In dS: $T = H/2\pi$. Qualitatively $\Delta M^2 \sim H^2$

- Analogy only: flat-space thermal QFT inapplicable

  1. Background curvature ~ temperature, non-negligible
  2. BD vacuum preserves dS isometries. (no Doppler shift)

Loop corrections

- Thermal analogy: Euclidean picture

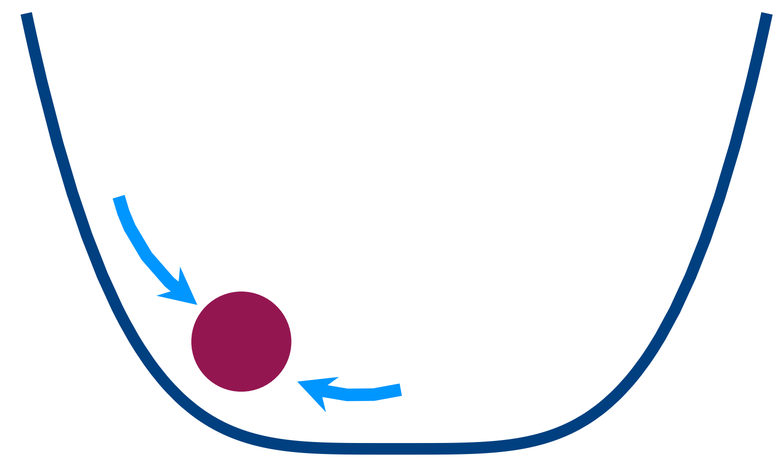


$$\langle \phi_0^2 \rangle \sim T^2$$

$$\langle \phi_0^2 \rangle \sim H^2/\sqrt{\lambda}$$

Loop corrections

- Thermal analogy: real-time picture
- Massless $\lambda\phi^4$ in dS
- Classical rolling-down: $\phi^2 \sim H/(\lambda t)$
- Quantum fluctuation: $\langle\phi^2\rangle \sim H^3 t$



IR growth / late-time divergence

- Equilibrium reached at $t \sim (\sqrt{\lambda}H)^{-1}$ $\longrightarrow$ $\langle\phi^2\rangle \sim H^2/\sqrt{\lambda}$

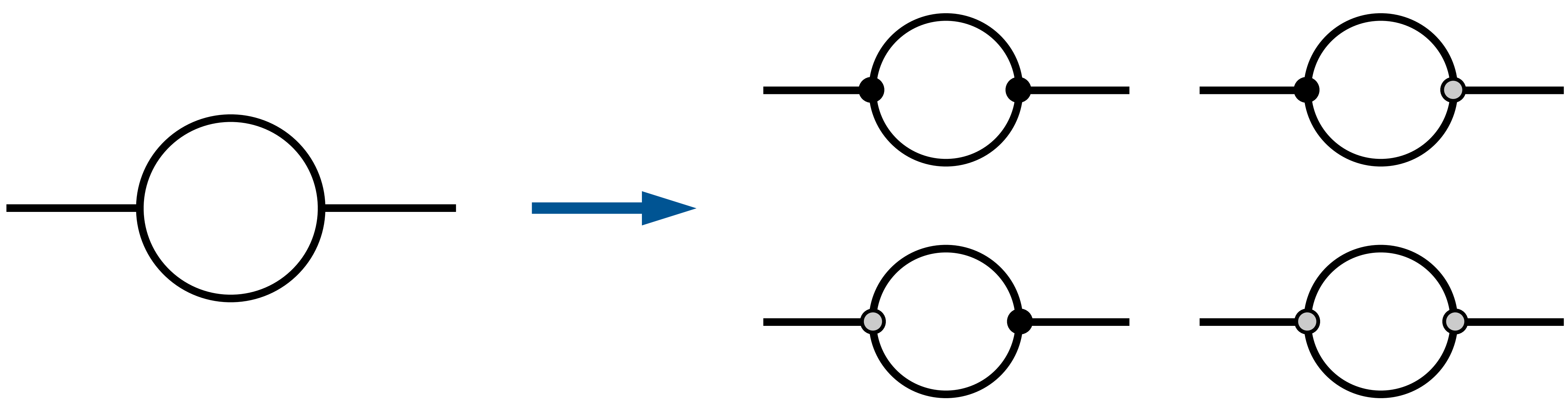
$$\longrightarrow \quad m^2 \sim \lambda\langle\phi^2\rangle \sim \sqrt{\lambda}H^2$$

Loop corrections

- Two ways of loop computation:

  1. Schwinger-Keldysh formalism 2. Wick rotation

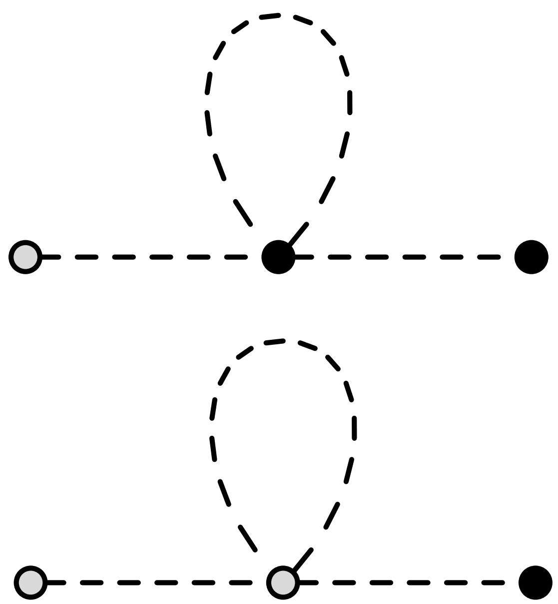
- Schwinger-Keldysh: $\langle \mathrm{in}|\cdots|\mathrm{in}\rangle = \sum_{\mathrm{out}} \langle \mathrm{in}|\cdots|\mathrm{out}\rangle\langle \mathrm{out}|\cdots|\mathrm{in}\rangle$



Loop corrections: SK amplitude

- Example: $\lambda\phi^4$; 2-point SK amplitude. Tree-level: $\dfrac{H^2}{2k^3}$

- 1-loop correction:



$$= \frac{\lambda H^2}{6(2\pi)^2 k^3}\left(\frac{1}{\epsilon} + \frac{3H^2}{2m^2} + \log\frac{\mu}{H}\right)\log(-2k\tau)$$

dimensional regularization

subtracted by local counterterm

leading term in small mass limit

IR divergent when $m \to 0$

leading term in late-time limit

resummation via dynamical RG

Loop corrections: SK amplitude

- Example: $\lambda\phi^4$; 2-point SK amplitude. Tree-level: $\dfrac{H^2}{2k^3}$

- Dynamical renormalization group resummation: Burgess et al., 0912.1608
  An analogy with RG improvement in ordinary loop calculation

$$\frac{H^2}{2k^3} + \frac{H^2}{2k^3} \cdot \frac{\lambda H^2}{2(2\pi)^2 m^2} \log(-k\tau) + \cdots \longrightarrow \frac{H^2}{2k^3}(-k\tau)^{\lambda H^2/2(2\pi m)^2}$$

- A light massive mode at late-time limit,

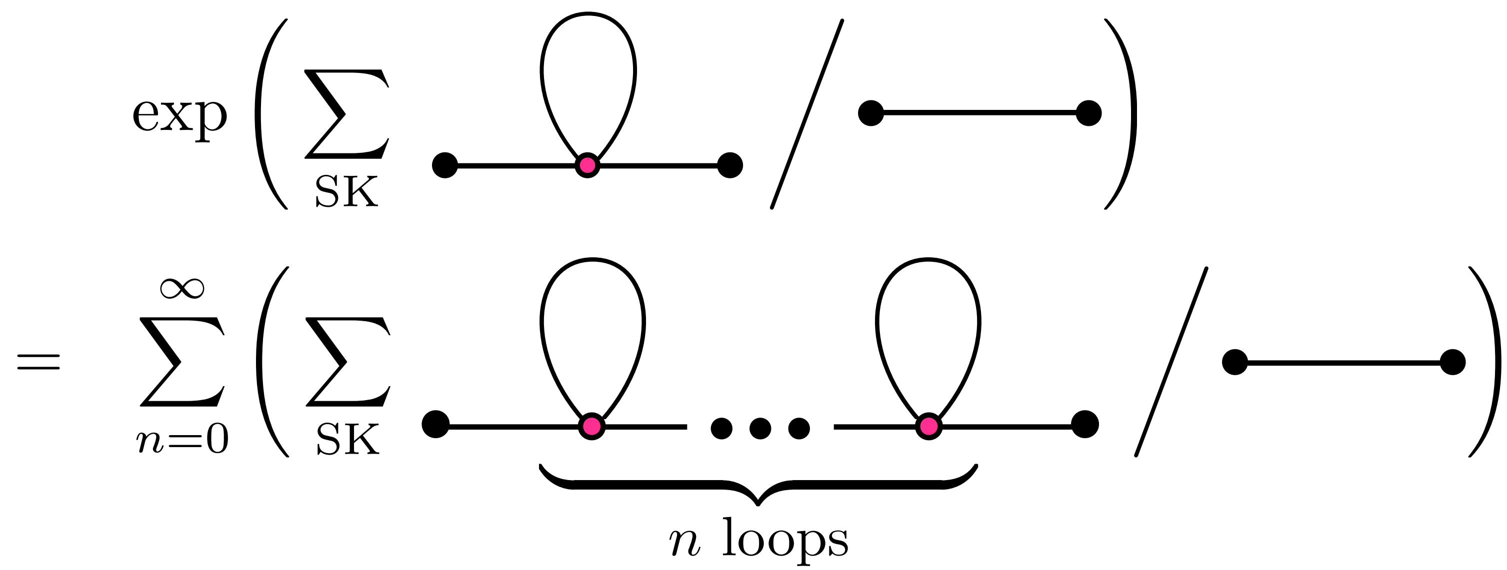
$$\left|(-\tau)^{3/2} H_\nu^{(1)}(-k\tau)\right|^2 \longrightarrow (-k\tau)^{3-2\nu} \simeq (-k\tau)^{2m^2/3H^2}$$

- Compare the time dependence: $m^2 = \dfrac{\sqrt{3\lambda}H^2}{4\pi}$

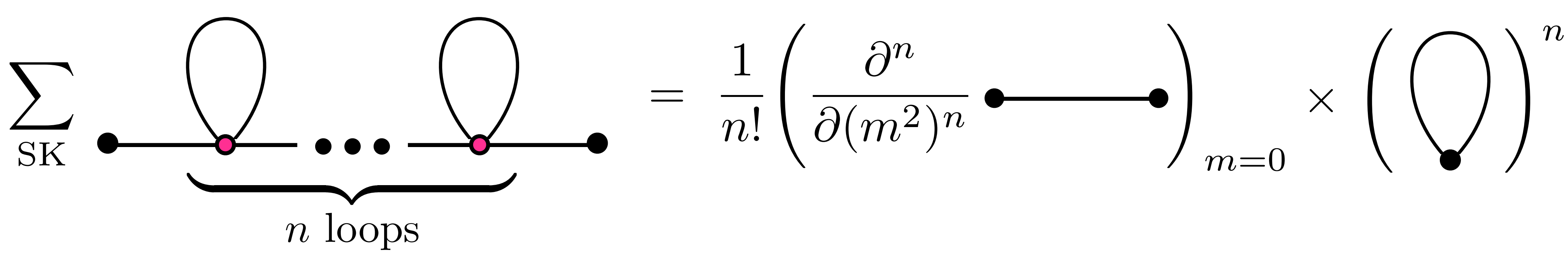
Loop corrections: SK amplitude

- Which loop diagrams does DRG resum?

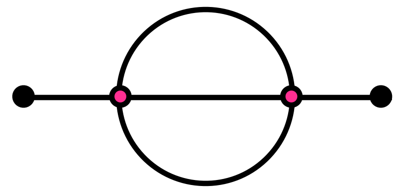
- A direct proof of DRG ansatz in simple cases:

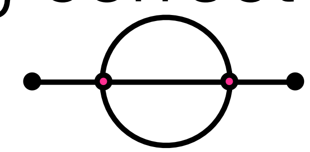


- The key identity for the proof:

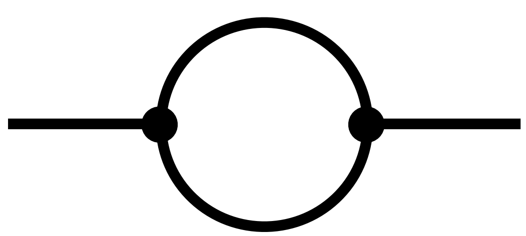


Loop corrections: SK amplitude

- Diagrams like  are not included in DRG

- A partial resummation, giving correct semi-quantitative result
  — But exact in large N limit:  is suppressed

- Further problems with real-time calculation:
  space-time asymmetric (gauge condition) / regularization



$$\sim \int_{-\infty}^{\tau} \mathrm{d}\tau_1 f_1(\tau_1) \int_{-\infty}^{\tau_1} \mathrm{d}\tau_2 f_2(\tau_2) e^{\pm \mathrm{i}k(\tau_1-\tau_2)} \times \int \frac{\mathrm{d}^3 q}{(2\pi)^3} H_\nu^{(1)}(-q\tau_1) H_\nu^{(2)}(-q\tau_2) H_\nu^{(2)}(-p\tau_1) H_\nu^{(1)}(-p\tau_2)$$

- Alternative method: Wick rotation

Loop corrections: Wick rotation

- Highly nontrivial in curved space!
  — coordinate dependent / not always sensible

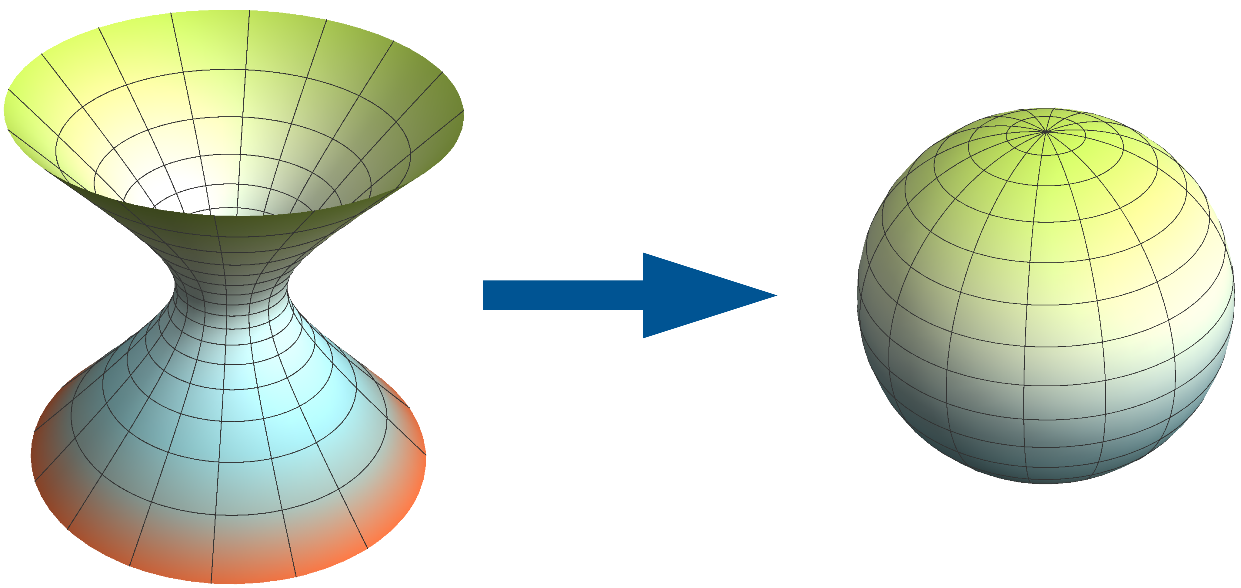
$$\mathrm{d}s^2 = -\mathrm{d}t^2 + e^{2Ht}\mathrm{d}\mathbf{x}^2 \quad \longrightarrow \quad \mathrm{d}s^2 = \mathrm{d}t_E^2 + e^{2\mathrm{i}Ht_E}\mathrm{d}\mathbf{x}^2$$

- An appropriate Wick rotation of inflation background:
  Wick rotation in imbedding space ~ global coordinates

$$-T^2 + \sum_{i=1}^{4} X_i^2 = H^{-2}$$

$$\Big\downarrow \; T \Rightarrow \mathrm{i}T_E$$

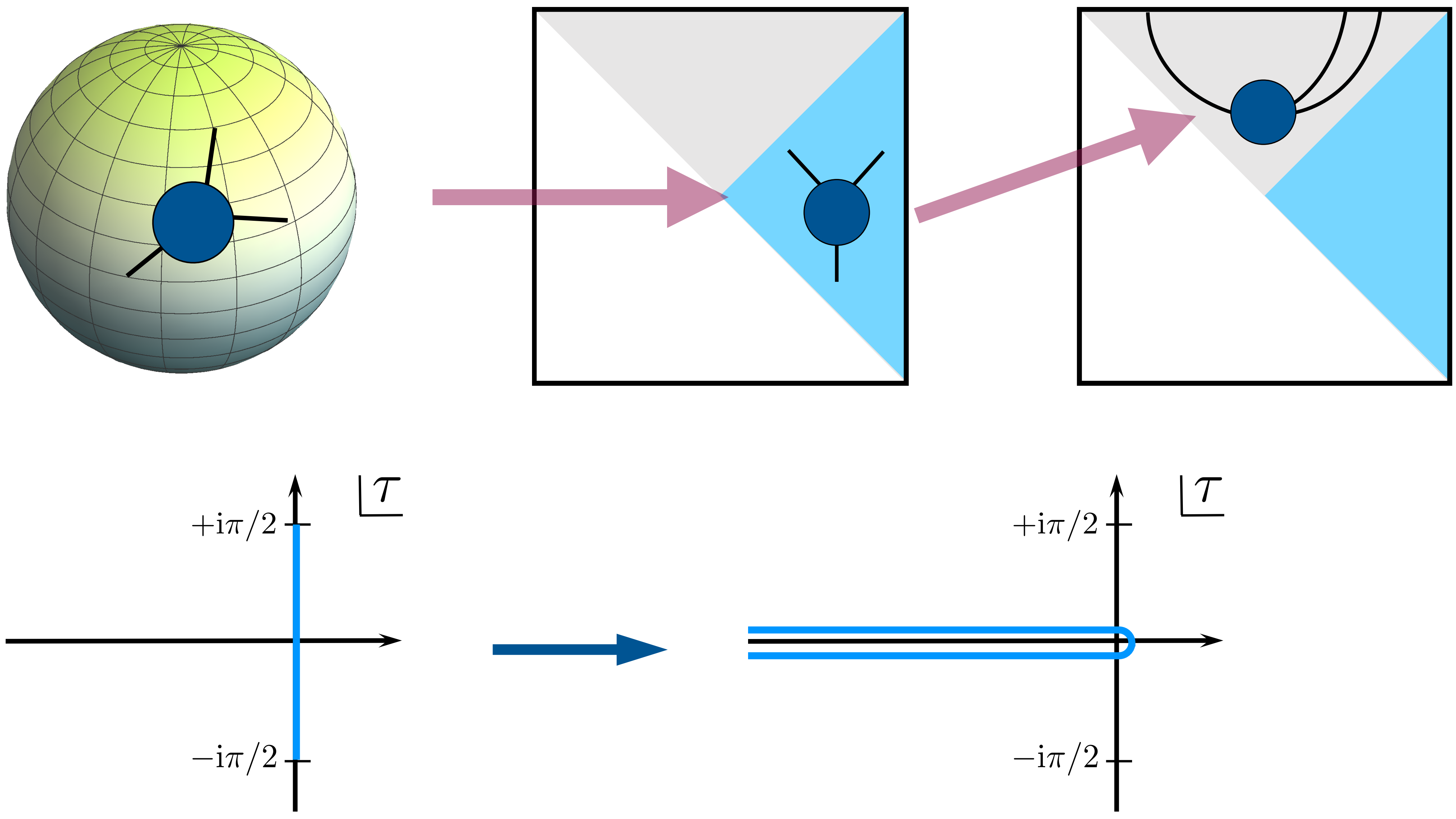
$$+T_E^2 + \sum_{i=1}^{4} X_i^2 = H^{-2}$$



Loop corrections: Wick rotation

Higuchi, Marolf, Morrison, 1012.3415

- The equivalence between
  Euclidean dS amplitude & SK amplitude in Poincaré patch



Loop corrections: Wick rotation

- Fun with spherical harmonics

$$\Box Y_{\vec{L}}(x) = -H^2 L(L+d) Y_{\vec{L}}(x)$$

$S^2: \; j(j+1)$

"total angular momentum"

- A scalar of mass m : $(\Box - m^2)\phi = 0$

- Propagators in terms of harmonics

$$= \sum_{\vec{L}} \frac{H^{d+1}}{\lambda_L} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x')$$

$$\lambda_L = L(L+d) + (m/H)^2$$

- The zero mode ($L = 0$) is divergent as $m \to 0$

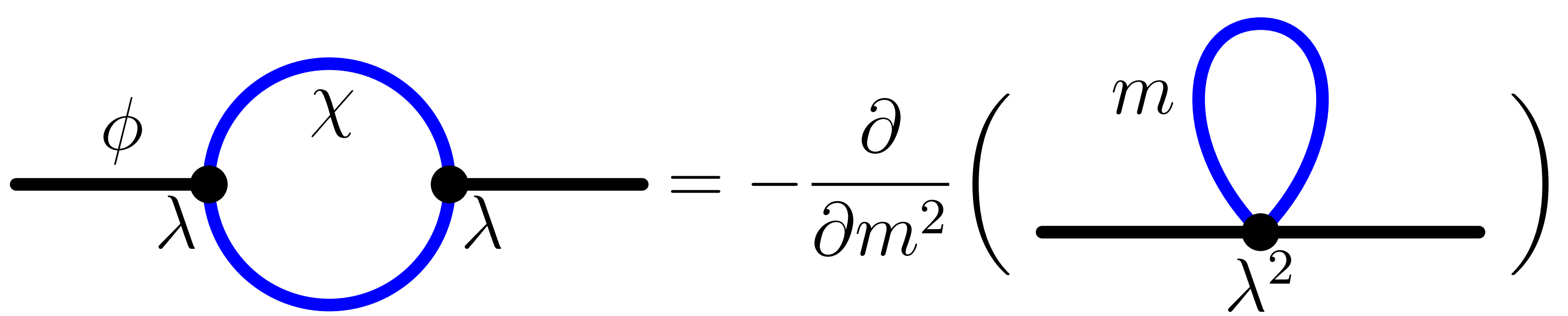
Loop corrections: Wick rotation

- Example 0: two scalars: ϕ and χ, with cubic int. $\lambda\phi\chi^2$

- 1-loop mass correction to ϕ from χ:

$$\int_{x,x'} G(x,x')^2 = \sum_{L,M} \int_{x,x'} \frac{1}{\lambda_L \lambda_M} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x') Y_{\vec{M}}(x') Y^*_{\vec{M}}(x)$$

$$= \sum_{L} \int_{x} \frac{1}{\lambda_L^2} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x) = -\frac{\partial}{\partial m^2} \int_x G(x,x)$$



Loop corrections: Wick rotation

- Example 0: two scalars: ϕ and χ, with cubic int. $\lambda\phi\chi^2$

$$-\frac{\partial}{\partial m^2}\int_x G(x,x)$$

- UV divergence readily removed by dimensional regularization

- In small mass M_χ limit: $\delta M_\phi^2 = \boxed{\frac{3\lambda^2 H^4}{8\pi^2 M_\chi^4}} + \mathcal{O}(M_\chi^0)$

zero mode!

- Only zero modes are important in small mass limit
  Can be calculated by setting loop momentum to zero

Loop corrections: Wick rotation

- Example 1: Higgs boson with tree-level mass M_{H0}

- Loop correction dominates when $M_{H0} \ll H$ due to zero modes — can be calculated non-perturbatively   Rajaraman, 1008.1271

$$\frac{H^D}{M_H^2}\left|Y_{\vec{0}}\right|^2 = \langle h_0^2 \rangle = \frac{\int \mathrm{d}^N h_0 \, h_0^2 e^{-V_D(\frac{1}{2}M_{H0}^2 h_0^2 + \frac{1}{4}\lambda h_0^4)}}{\int \mathrm{d}^N h_0 \, e^{-V_D(\frac{1}{2}M_{H0} h_0^2 + \frac{1}{4}\lambda h_0^4)}}$$

loop-corrected mass

#fields, N=4 for SM Higgs

Volume of S^D

- Finite correction when $M_{H0} = 0$:

$$M_H^2 = \sqrt{\frac{6\lambda}{\pi^3}} H^2$$

Loop corrections: Wick rotation

- Example 1: Higgs boson with tree-level mass M_{H0}

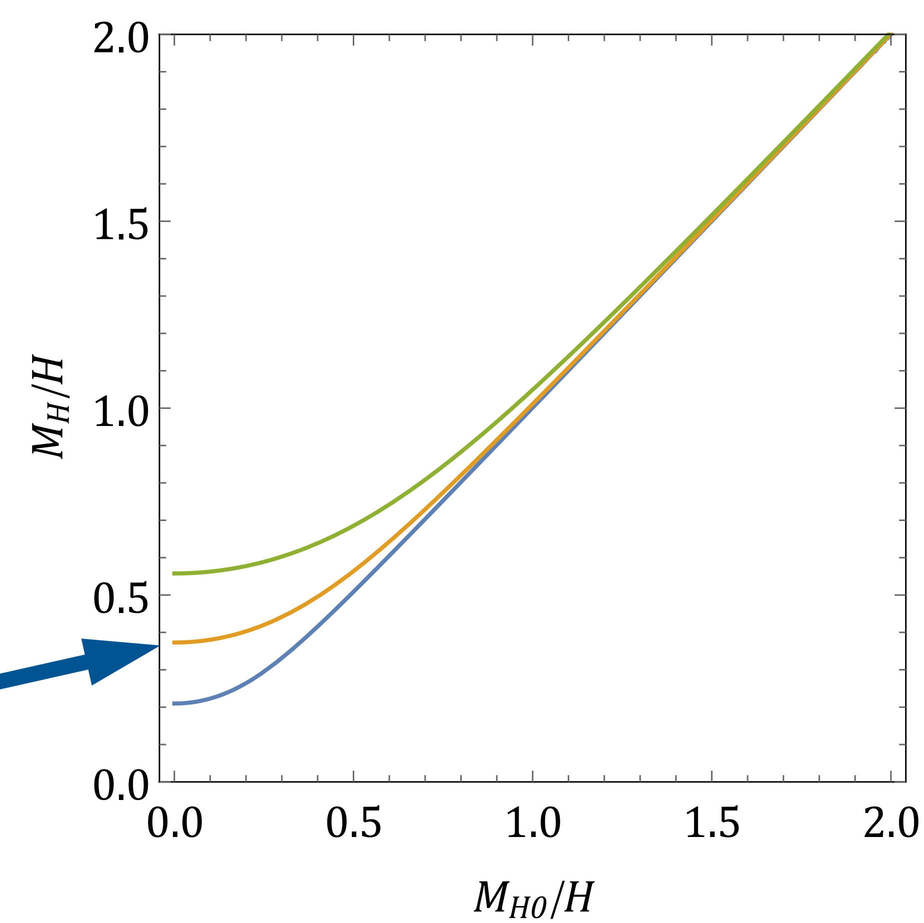
- Loop correction dominates when $M_{H0} \ll H$ due to zero modes — can be calculated non-perturbatively Rajaraman, 1008.1271

- Generally, when $M_{H0} \neq 0$:

- $M_H \gtrsim \mathcal{O}(H)$

- Lighter Higgs needs fine tuning

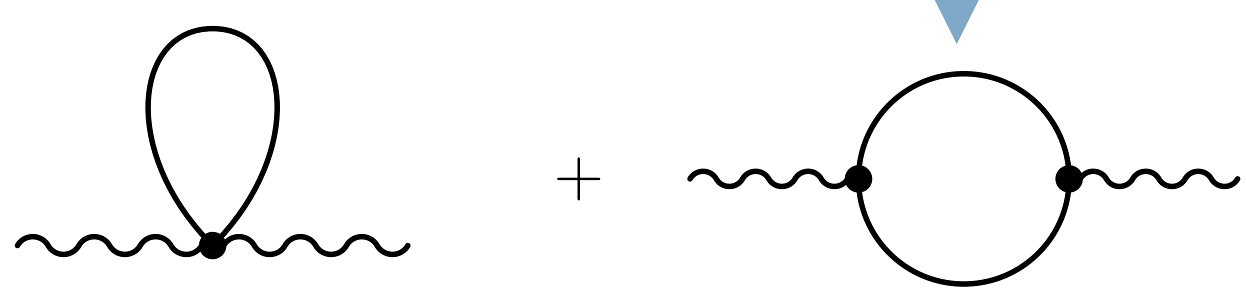
$$M_H^2 = \sqrt{\frac{6\lambda}{\pi^3}} H^2$$



Loop corrections: Wick rotation

- Example 2: Gauge boson

$$
\begin{aligned}
S &= -\int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |\mathrm{D}_\mu\Phi|^2 + m^2\Phi^\dagger\Phi\right] \\
&\supset -\int \mathrm{d}^4x\,\sqrt{-g}\left[\boxed{\frac{1}{2}e^2A^2(\pi^2+\phi^2)} + \boxed{eA^\mu(\phi\partial_\mu\pi - \pi\partial_\mu\phi)}\right]
\end{aligned}
$$



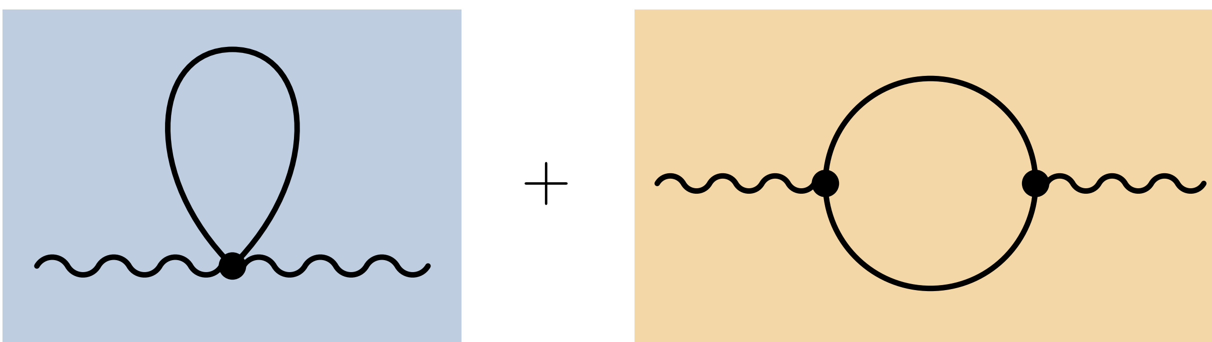
Zero-mode-only approximation:

$$\boxed{\delta M_A^2 = \frac{3e^2H^4}{4\pi^2 m^2}}$$

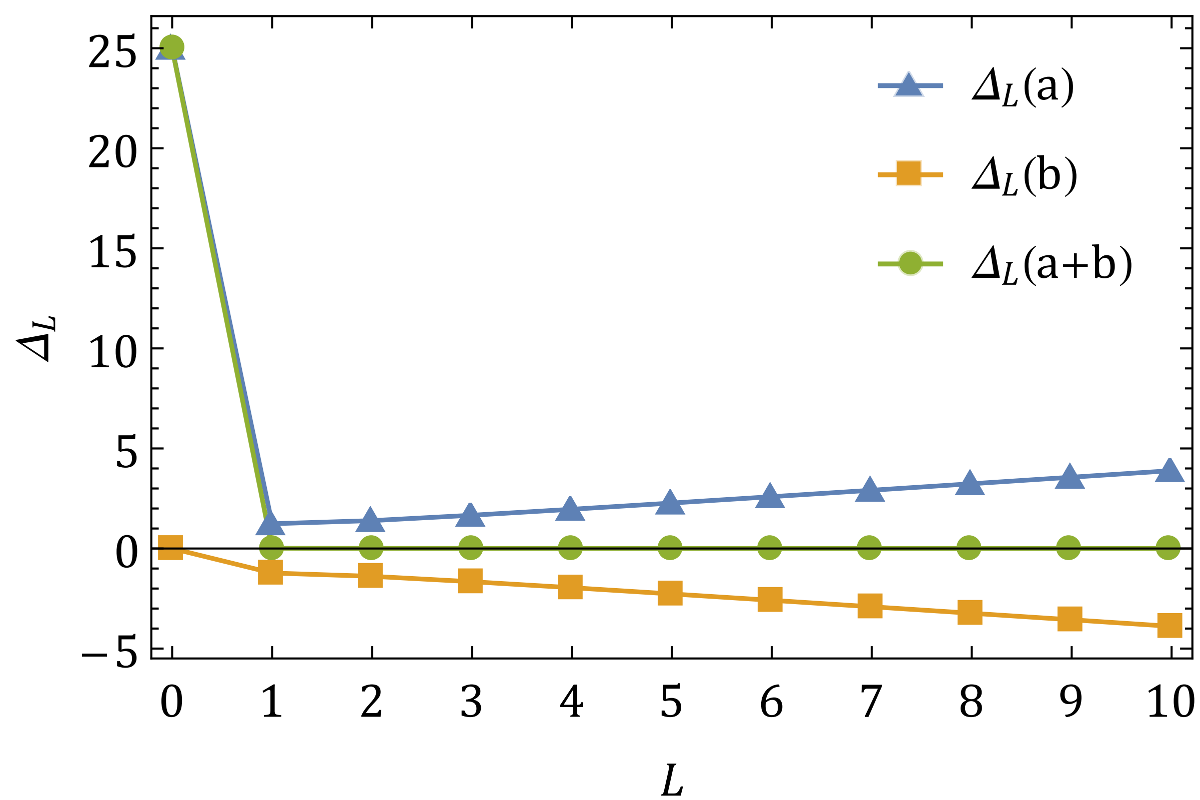
= 0, due to derivatives

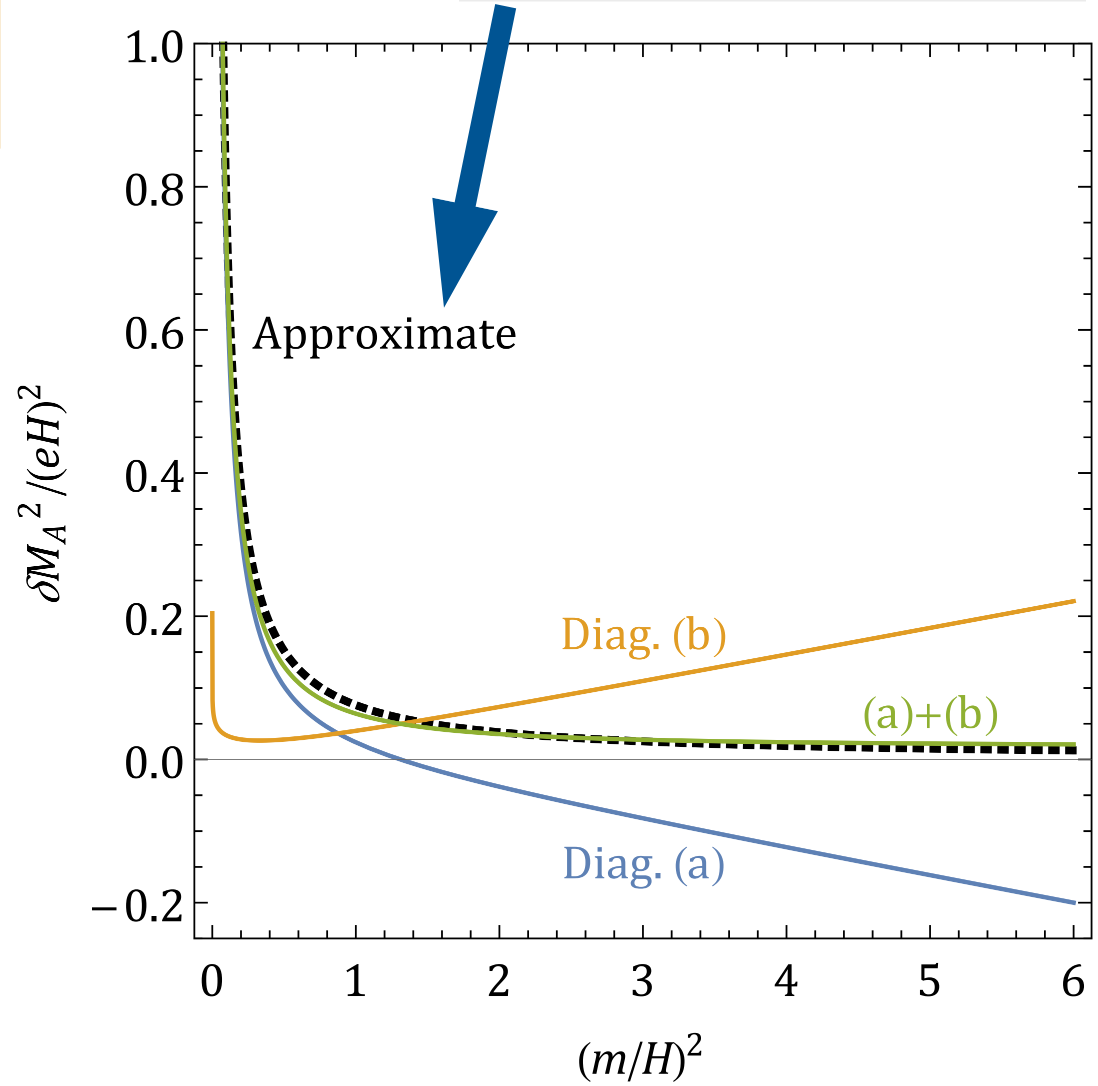
Loop corrections: Wick rotation

- Example 2: Gauge boson
  Possible to keep all modes / compute full 1-loop



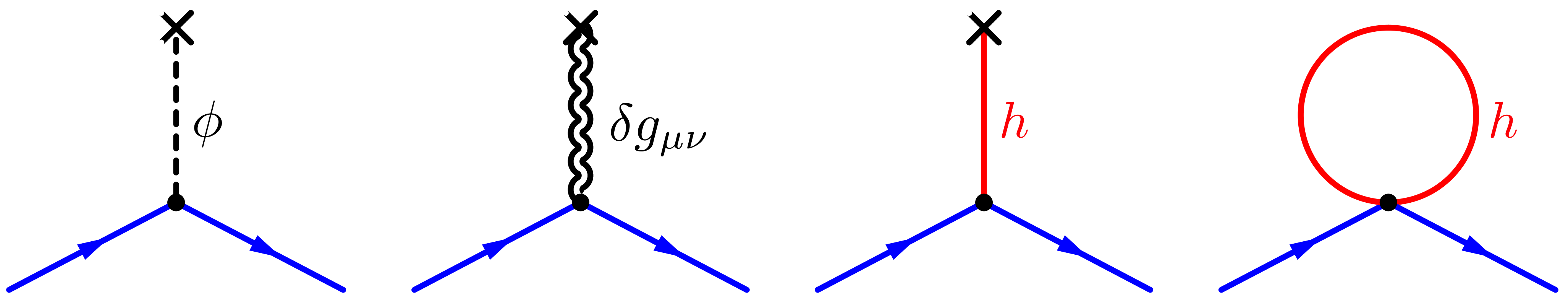
$$\delta M_A^2 = \frac{3e^2 H^4}{4\pi^2 m^2}$$





Standard Model mass spectrum

- Combining all corrections: Classical input + quantum correction



- For non-Higgs inflation:
  - Higgs mass arbitrary, generally $\gtrsim \mathcal{O}(H)$
  - Gauge bosons get mass: due to Higgs zero-mode
  - Fermions remain massless, if classically so

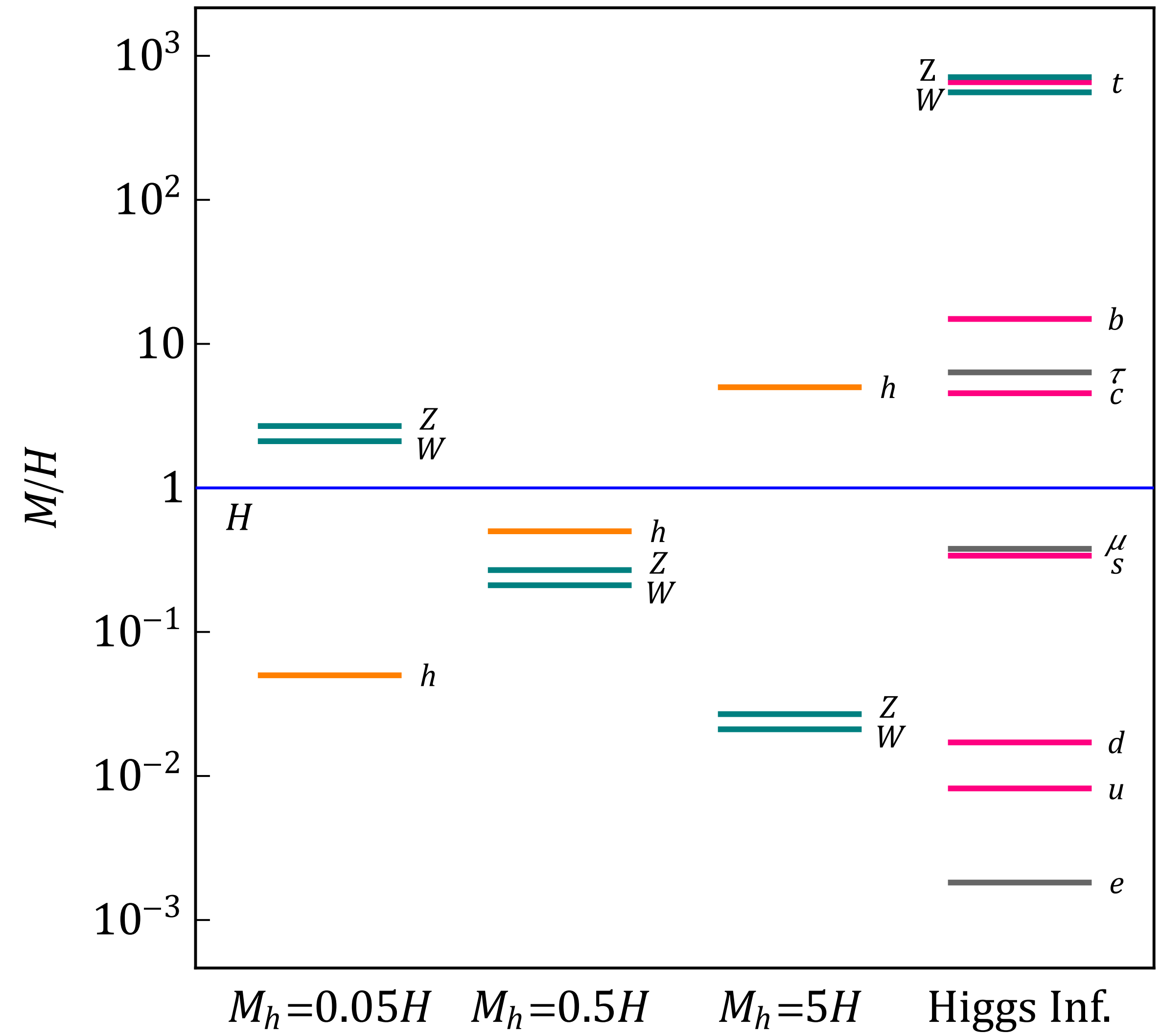
Standard Model mass spectrum

- Non-Higgs inflation SM spectrum: In general very arbitrary

- Calibration limit: SM mass spectrum not "polluted" by inflaton couplings

- Higgs inflation:

  SM spectrum uplifted from electroweak scale to inflation scale, except the Higgs boson itself



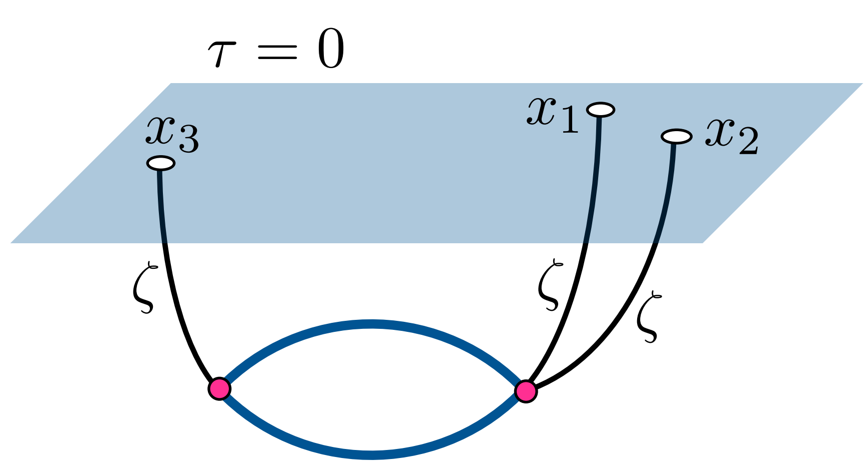
Chen, Wang, ZZX, 1610.06597

SM background in cosmological collider

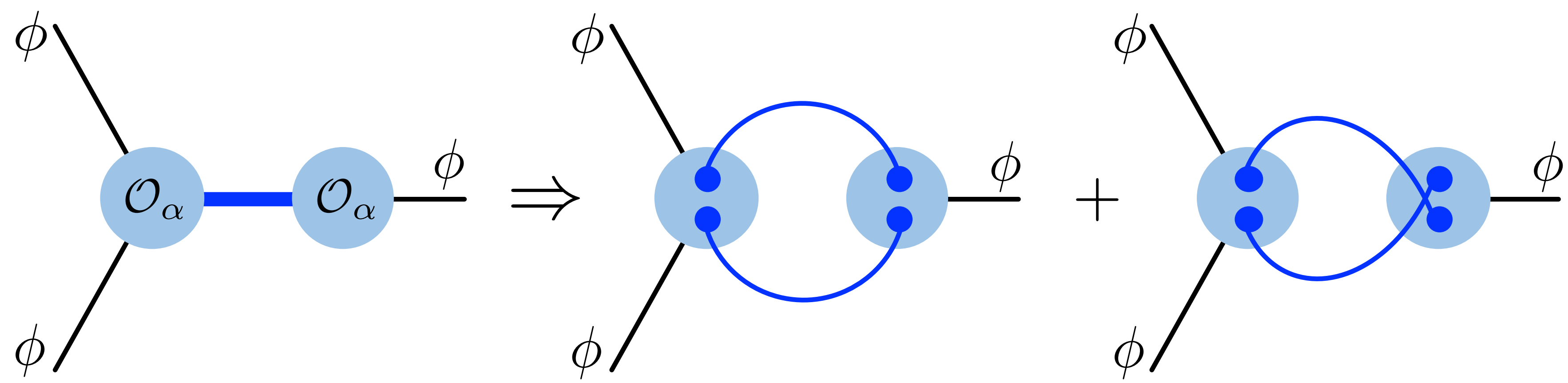
- How to reveal SM spectrum in cosmological collider?
  — always produced in pairs

$$\mathscr{L} \supset -f_H(X)\mathbf{H}^\dagger\mathbf{H} - f_{DH}(X)|\mathrm{D}_\mu\mathbf{H}|^2$$
$$- f_{\Psi_i}(X)\overline{\Psi}_i \not{D}\Psi_i - \frac{1}{4}f_{A_a}(X)F_{a\mu\nu}F_a^{\mu\nu},$$

- —1-loop diagrams at leading order



SM background in cosmological collider

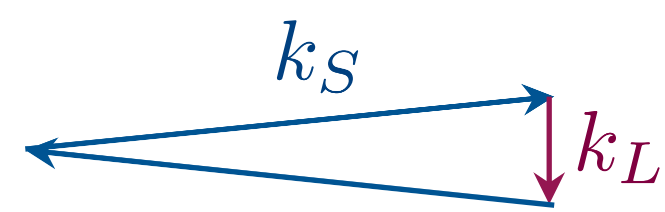


- Discovering channel: loops lines stretched far beyond horizon
- Non-local effect, free of UV divergence
- Oscillating/scaling behavior in squeezed limit:
  — Late-time expansion as an approximation

SM background in cosmological collider

- Dimensionless non-Gaussianity

$$\mathscr{L} \supset -f_H(X)\mathbf{H}^\dagger\mathbf{H} - f_{DH}(X)|\mathrm{D}_\mu\mathbf{H}|^2$$
$$-f_{\Psi_i}(X)\bar{\Psi}_i \not{D}\Psi_i - \frac{1}{4}f_{A_a}(X)F_{a\mu\nu}F_a^{\mu\nu},$$



$$S_H = \left[\frac{f'_H(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{\dot{\phi}_0^2}{2\pi^4}\left[C_H(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$

$$S_{DH} = \left[\frac{f'_{DH}(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{H^4\dot{\phi}_0^2}{8\pi^4}\left[C_{DH}(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$

$$S_\Psi = \left[\frac{f'_\Psi(X_0)}{1+f_\Psi(X_0)}\right]^2 \frac{H^4\dot{\phi}_0^2\mu_{1/2}^2}{2\pi^4}\left[C_\Psi(\mu_{1/2})\left(\frac{k_L}{k_S}\right)^{1+2\mathrm{i}\mu_{1/2}} + \mathrm{c.c.}\right]$$

$$S_A = \left[\frac{f'_A(X_0)}{1+f_A(X_0)}\right]^2 \frac{27H^8\dot{\phi}_0^2}{16\pi^4 M_A^4}\left[C_A(\mu_1)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_1} + (\mu_1 \to -\mu_1)\right]$$

SM background in cosmological collider

$$S_H = \left[\frac{f'_H(X_0)}{1+f_{DH}(X_0)}\right]^2 \frac{\dot{\phi}_0^2}{2\pi^4}\left[C_H(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right]$$

$$C_H(\mu) \simeq (2-\mu)(3-2\mu)\cos(\pi\mu)\sin^3(\pi\mu)$$
$$\times\,\Gamma(-4+4\mu)\Gamma^2(\mu)\Gamma^2(\frac{3}{2}-\mu)\Gamma^2(2-2\mu)$$

- Very model dependent in general
- But consistency relation still exists in most general case:

$$\frac{d\ln\tan^2\theta_W}{d\ln k} = \frac{\pi(1-n_s-\frac{1}{4}r)}{3\sqrt{3P_\zeta}\sin^2\theta_W}\left[\frac{M_W^2}{H^2}\sqrt{\frac{f_{NL}^W}{N_W|C_A(\mu_W)|}} - \frac{M_Z^2}{H^2}\sqrt{\frac{f_{NL}^Z}{N_Z|C_A(\mu_Z)|}}\right]$$

SM background in cosmological collider

- Signal strength?

- $f_{NL} \sim 1$ requires $f'^{\,2}_H(X_0) \sim \dot{\phi}_0^{-2}$

$$f'^{\,2}_{DH}(X_0),\ f'^{2}_{\Psi}(X_0),\ f'^{2}_{A}(X_0) \sim H^{-4}\dot{\phi}_0^{-2}$$

— can be relaxed — Calibrating limit (Part 2)

- Calibrating limit in summary:

$$f_{DH}(X_0),\ f_{\Psi_i}(X_0),\ f_{A_a}(X_0) \ll 1$$
$$f'^{\,2}_H(X_0) \sim \dot{\phi}_0^{-2}$$
$$f'^{\,2}_{DH}(X_0),\ f'^{2}_{\Psi}(X_0),\ f'^{2}_{A}(X_0) \sim H^{-4}\dot{\phi}_0^{-2}$$

- Not technically natural as EFT, but can be realized in a model?

Example

- More concrete predictions can be made for specific models
- Example: original Higgs inflation
- Heavy fields are suppressed by Boltzmann factor;
  Light fields (fermions) are suppressed by small Yukawa couplings
- SM background is negligibly small
- More examples?

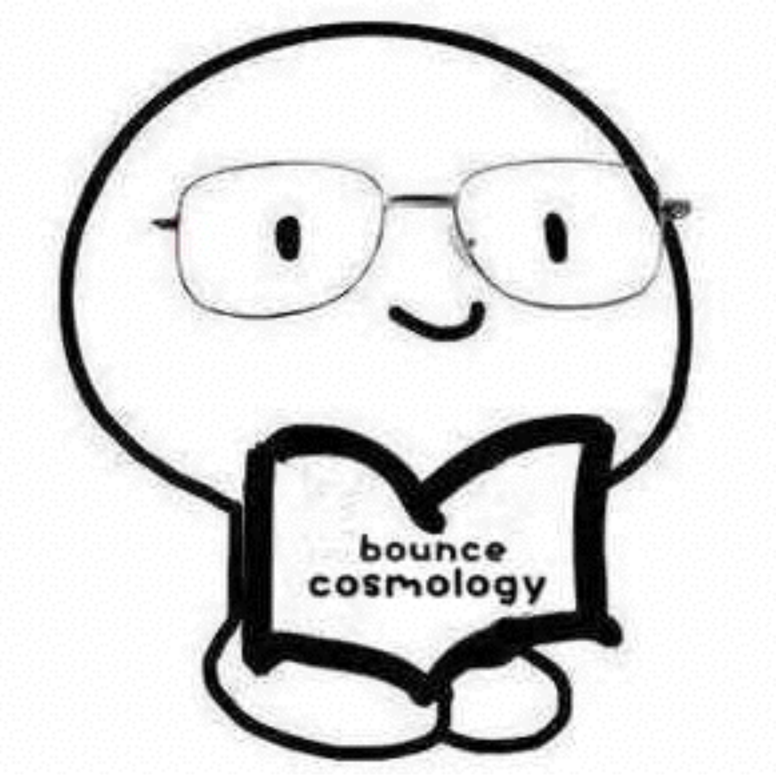
Summary

- SM particles present a novel mass spectrum during inflation, in contrast to ordinary case
- The SM spectrum in inflation is potentially observable from the squeezed limit of the inflaton bispectrum
- A detection of a heavy particle in squeezed bispectrum does not necessarily tell a new particle beyond SM
- The spin structure in bispectrum does not necessarily tell the spin of the massive particle
- Loops are relevant!

Outlook: Beyond Inflation Paradigm

- Spectator fields in alternative-to-inflation scenarios?
  —Primordial standard clocks Chen, Namjoo, Wang, 1411.2349, 1509.03930

- Generated at low scales in typical bouncing models
  Anything interesting about pre-history of universe to be learnt from non-G? e.g. Li, 1306.0191; Cai et al., 0903.0631



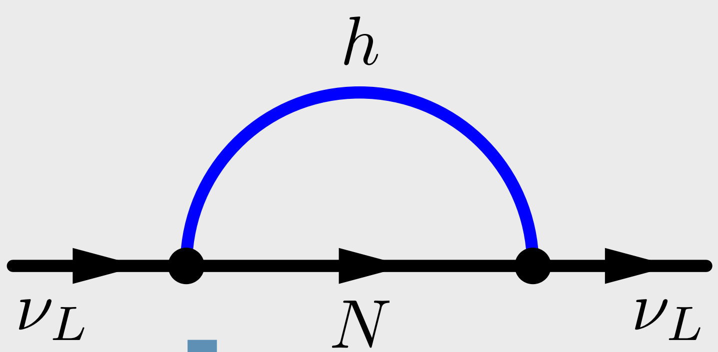
Outlook: Beyond SM

- Spin-0: Axions / moduli?
- Spin-1/2: Neutrinos: seesaw mechanisms?
  Chen, Wang, ZZX, Xu, in progress
- Spin-1: Gauge symmetry breaking?
- Spin-3/2: Supersymmetry?
  Delacretaz, Gorbenko, Senatore, 1610.04227
- Spin ≥ 2: Higher spin particles / string states?
  Lee, Baumann, Pimentel, 1607.03735
- Missing energy?

Beyond SM: Neutrino mass

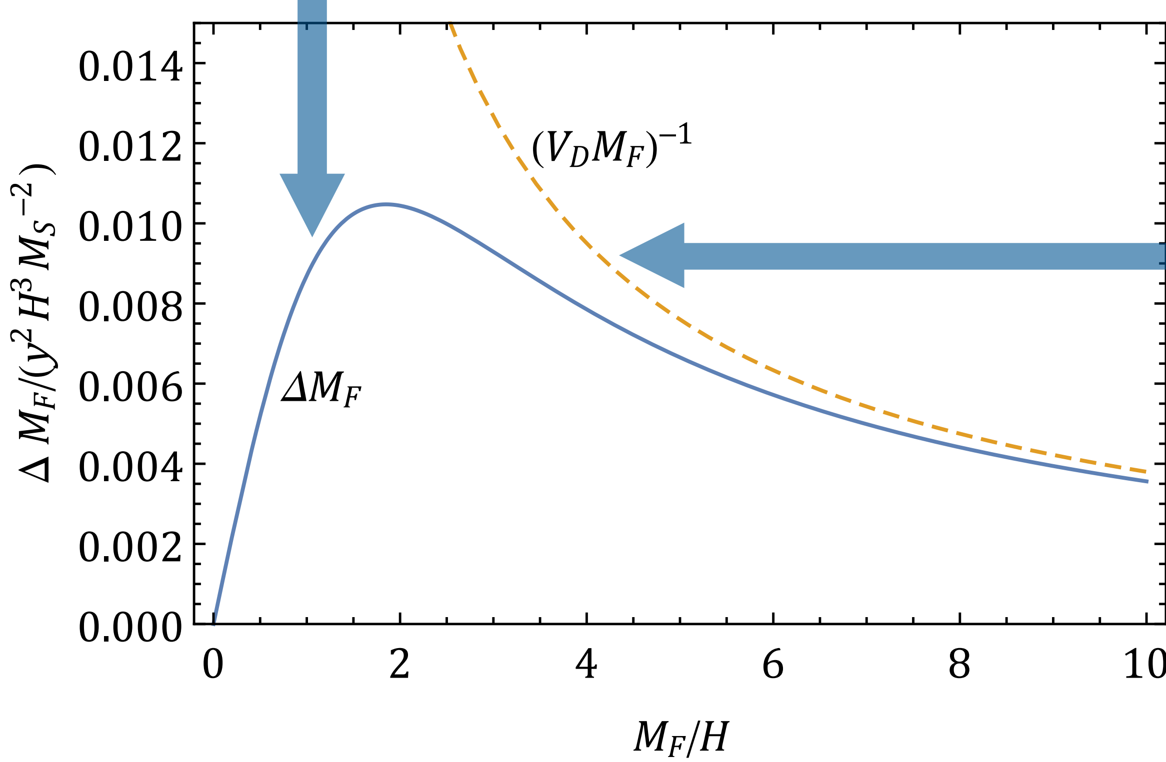
- Example: Type I seesaw

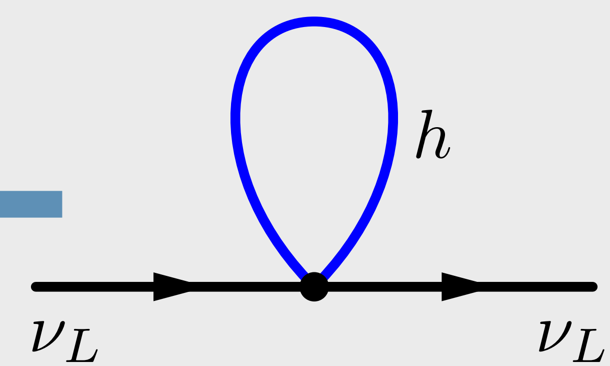
Chen, Wang, ZZX, Xu, in progress



$$\Delta M_\nu = \frac{3y^2H^2M_2}{140\pi^2M_h^2}\Gamma(2-\frac{\mathrm{i}M_N}{H})\Gamma(2+\frac{\mathrm{i}M_N}{H}) \times {}_3F_2\Big(2-\frac{\mathrm{i}M_N}{H}, 2+\frac{\mathrm{i}M_N}{H}, \frac{5}{2}; 3, \frac{9}{2}; 1\Big).$$

large M_N limit: Weinberg operator





$$\Delta M_\nu \simeq \frac{3y^2H^2}{140\pi^2M_h^2M_N}$$

Thank you!