Cosmological Collider Signatures from Right-Handed Neutrino Loops

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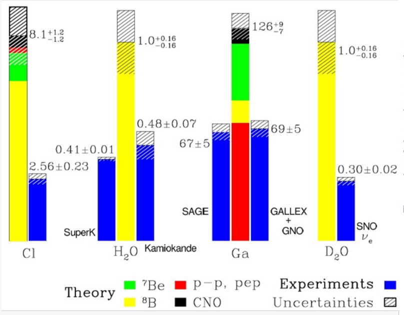
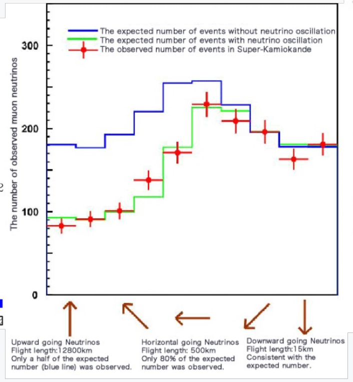
Neutrino masses point to very high scales

Why right-handed neutrinos?

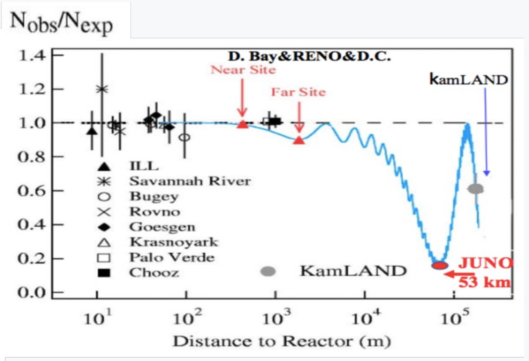
- Neutrino oscillations imply nonzero neutrino masses.
- The seesaw mechanism gives a natural explanation for small masses.



Solar Neutrino oscillations



Atmospheric Neutrino Oscillations



Reactor Neutrino Oscillations

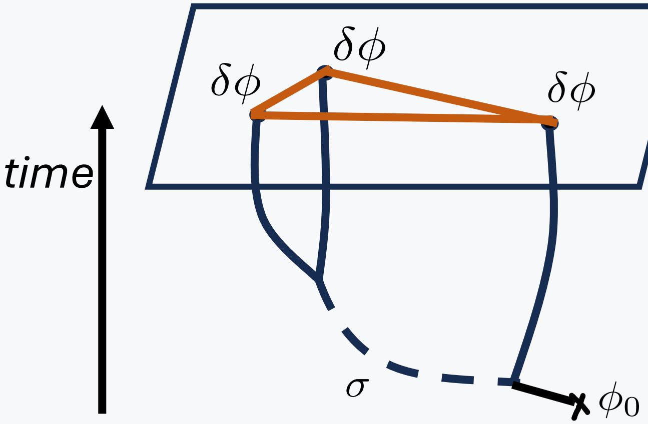
- It also connects naturally to leptogenesis and the baryon asymmetry.

If Yukawa couplings are O(1), the seesaw scale is typically M_R ~ 10^{13-14} GeV, far beyond laboratory reach.

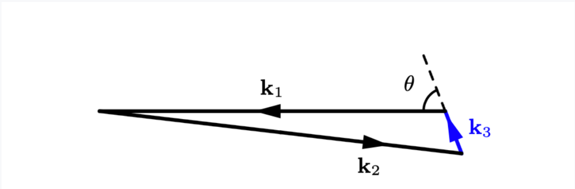
Cosmological collider physics

X. Chen and Y. Wang, JCAP 04 (2010)027
N. Arkani-Hamed and J. Maldacena, arXiv:1503.08043

Inflation can act as a high-energy collider sensitive to particles with mass ~ H.
Non-analytic features in the squeezed bispectrum encode the mass and spin of heavy fields.



$$k_1 \sim k_2 \gg k_3$$



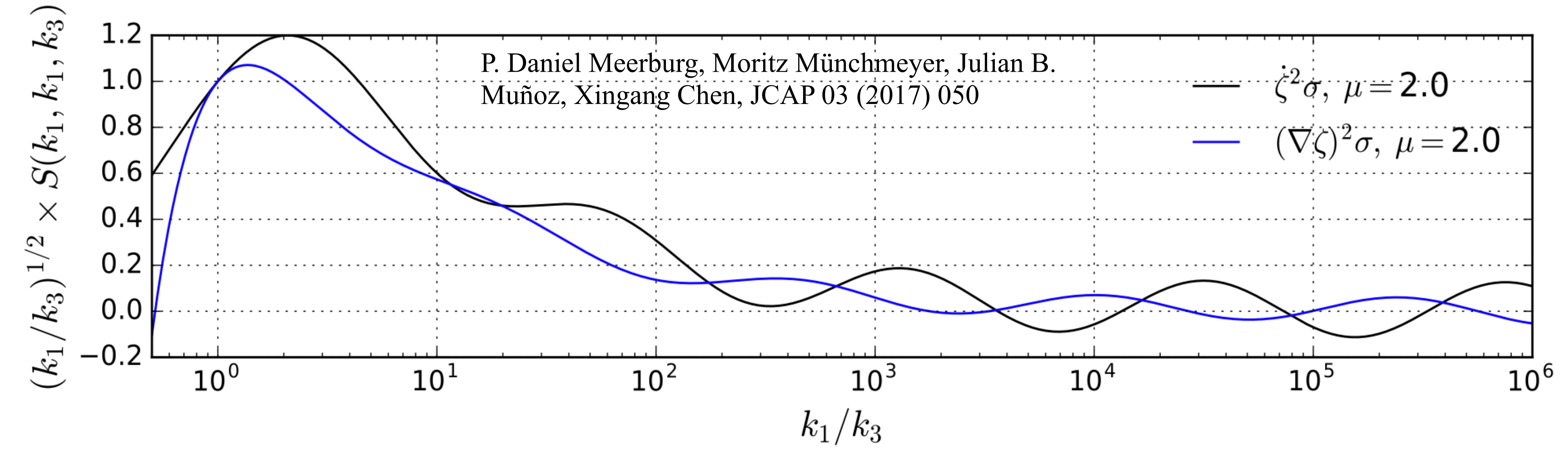
$$\langle \delta\phi_{\mathbf{k_1}} \delta\phi_{\mathbf{k_2}} \delta\phi_{\mathbf{k_2}} \rangle \sim e^{-\pi\mu} \cos(\mu \log \frac{k_3}{k_1} + \delta) P_s(\cos\theta) \qquad \mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

- The cosmological signal reflecting particle production and decay in the early universe
- Fields with m ~ H can leave oscillatory imprints.
- The signal becomes suppressed when the intermediate field is too heavy.

Cosmological collider physics

$$\langle \zeta^3 \rangle \equiv (2\pi)^3 \delta_D(\mathbf{k}_{123}) \frac{A^2}{(k_1 k_2 k_3)^2} S(k_1, k_2, k_3)$$

$$P_\zeta(k) = A/k^3$$



Oscillation frequency only depends on the mass parameter

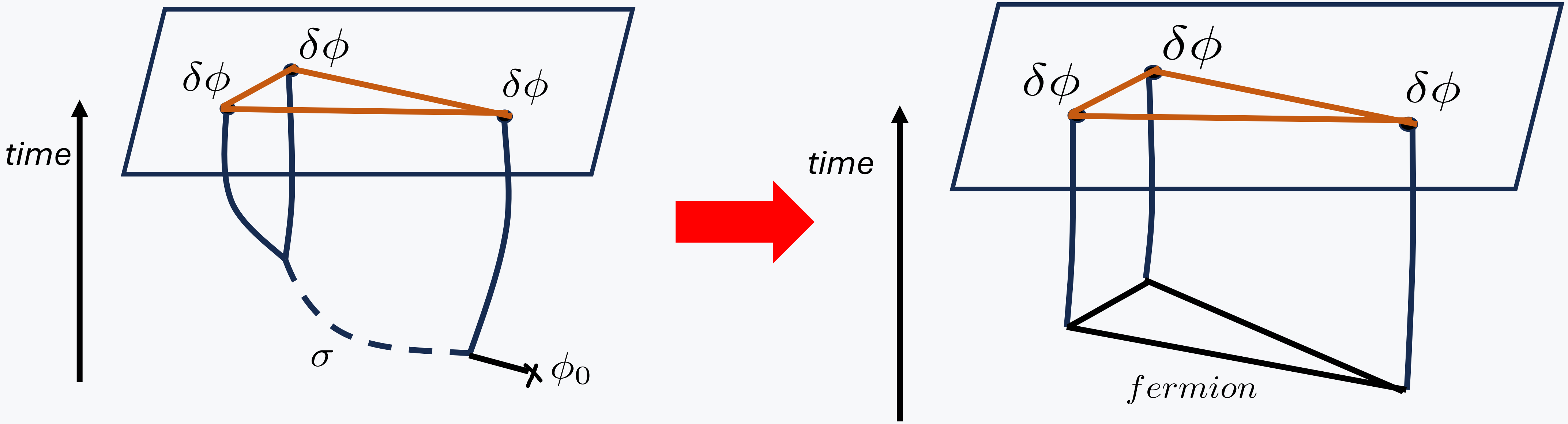
Can seesaw-scale RH neutrinos leave an observable signal?

Considering an interaction between inflaton and right-handed neutrino(respecting shift symmetry)

$$\frac{1}{\Lambda}\,\partial_\mu\phi\,N^\dagger\bar{\sigma}^\mu N$$

Providing a chemical potential for N, alleviate the suppression factor $e^{-\pi\mu} \to e^{-\pi\mu^2/\lambda}$

For fermions, the leading signal typically starts at loop level



Fermion-loop case is difficult

Compared with scalar or gauge-boson, fermion loops are technically harder and more strongly suppressed.

- The relevant cosmological collider signature first appears in loop diagrams.
- Mode functions and loop momentum integration both require careful treatment.

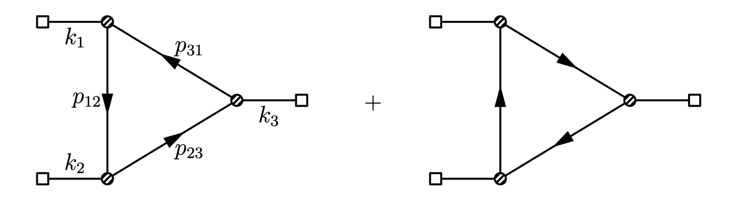
$$\tilde{N}_\alpha(\tau, x) = \int \frac{d^3\mathbf{k}}{(2\pi)^3} \sum_{s=\pm} \left[\xi_{s,\alpha}(\tau,\mathbf{k}) b_s(\mathbf{k}) e^{\mathrm{i}\mathbf{k}\cdot\mathbf{x}} + \chi_{s,\alpha}(\tau,\mathbf{k}) b_s^\dagger(\mathbf{k}) e^{-\mathrm{i}\mathbf{k}\cdot\mathbf{x}}\right]$$

$$\xi_{s,\alpha}(\tau,\mathbf{k}) = u_s(\tau,\mathbf{k})\, h_{s,\alpha}(\mathbf{k}), \qquad \chi_s^{\dagger\dot{\alpha}}(\tau,\mathbf{k}) = v_s(\tau,\mathbf{k})\, s\, h_{-s}^{\dagger\dot{\alpha}}(\mathbf{k}).$$

$$u_+(\tau,\mathbf{k}) = \tilde{m}\frac{e^{+\pi\tilde{\lambda}/2}}{\sqrt{-2k\tau}} W_{-\frac{1}{2}-\mathrm{i}\tilde{\lambda},\mathrm{i}\tilde{\nu}}(2\mathrm{i}k\tau),$$
$$u_-(\tau,\mathbf{k}) = \frac{e^{-\pi\tilde{\lambda}/2}}{\sqrt{-2k\tau}} W_{\frac{1}{2}+\mathrm{i}\tilde{\lambda},\mathrm{i}\tilde{\nu}}(2\mathrm{i}k\tau),$$

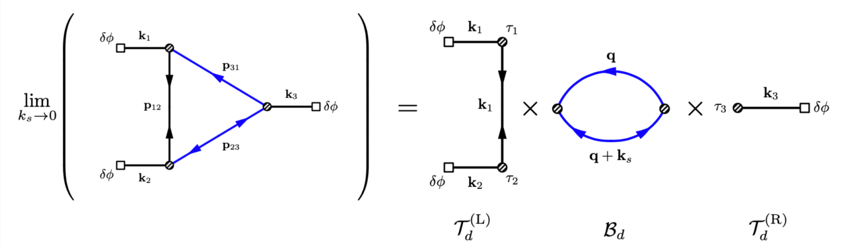
$$v_+(\tau,\mathbf{k}) = \frac{e^{+\pi\tilde{\lambda}/2}}{\sqrt{-2k\tau}} W_{\frac{1}{2}-\mathrm{i}\tilde{\lambda},\mathrm{i}\tilde{\nu}}(2\mathrm{i}k\tau),$$
$$v_-(\tau,\mathbf{k}) = \tilde{m}\frac{e^{-\pi\tilde{\lambda}/2}}{\sqrt{-2k\tau}} W_{-\frac{1}{2}+\mathrm{i}\tilde{\lambda},\mathrm{i}\tilde{\nu}}(2\mathrm{i}k\tau),$$

Previous work calculate the contribution of the following diagrams



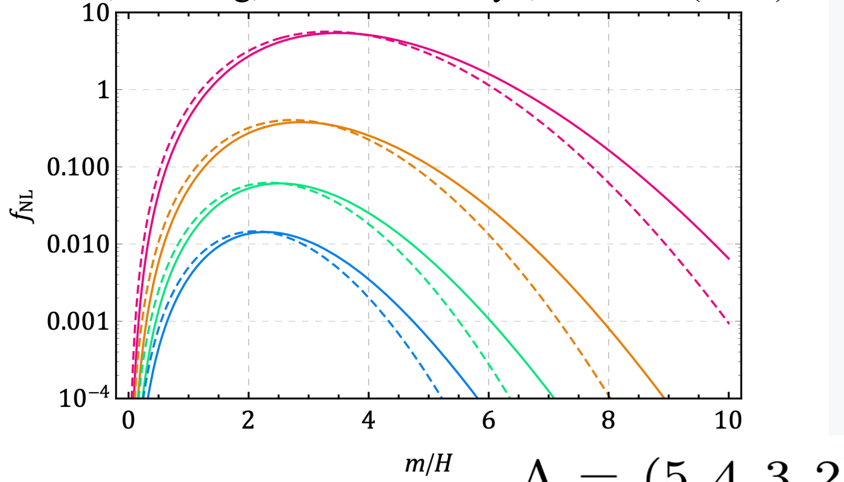
X. Chen, Y. Wang, and Z.-Z. Xianyu, JHEP 09 (2018) 022
A. Hook, J. Huang, and D. Racco, JHEP 01 (2020) 105

The squeezed signal only emerges in specific soft limits, which can be factorized.



- The T_L was estimated with a saddle-point approximation.
- The bubble subdiagram was approximated using a typical loop momentum k_s instead of the full integration.
- Under those assumptions, the loop signal looked potentially observable.

X. Chen, Y. Wang, and Z.-Z. Xianyu, JHEP 09 (2018) 022



$$\Lambda = (5,4,3,2)\dot{\phi}_0^{1/2}$$

Previous picture: promising, but based on strong approximations

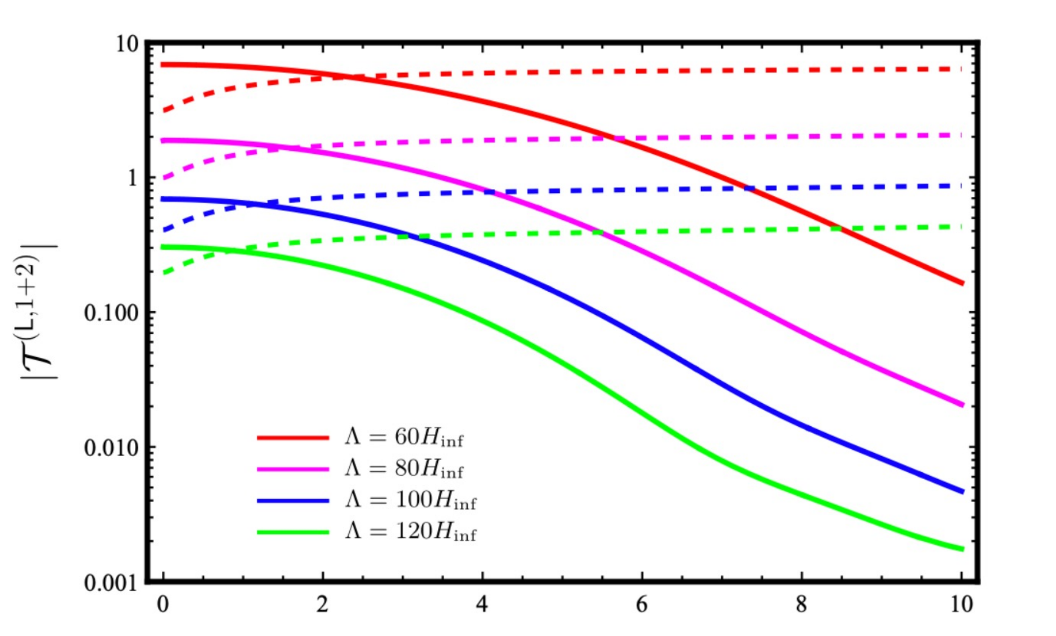
What needed to be checked

- How accurate is the saddle-point estimate for T_L across the parameter space?
- Does the full loop-momentum integral introduce extra suppression?
- Are there additional diagrams of the same order that were not yet included?

Our strategy: replace approximations with controlled calculation

- Compute the factor T_L analytically rather than by saddle point.

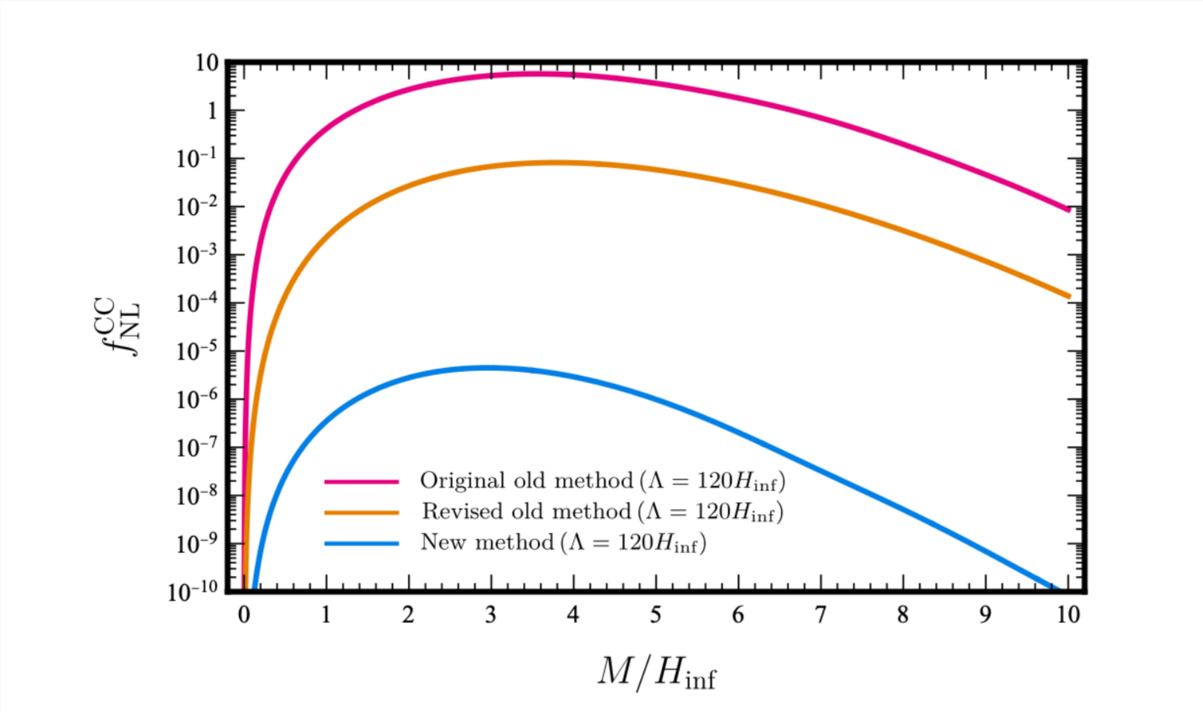
- Evaluate the bubble contribution through the full loop-momentum integration.



First corrected result: the previously considered signal is much smaller

What changes numerically?

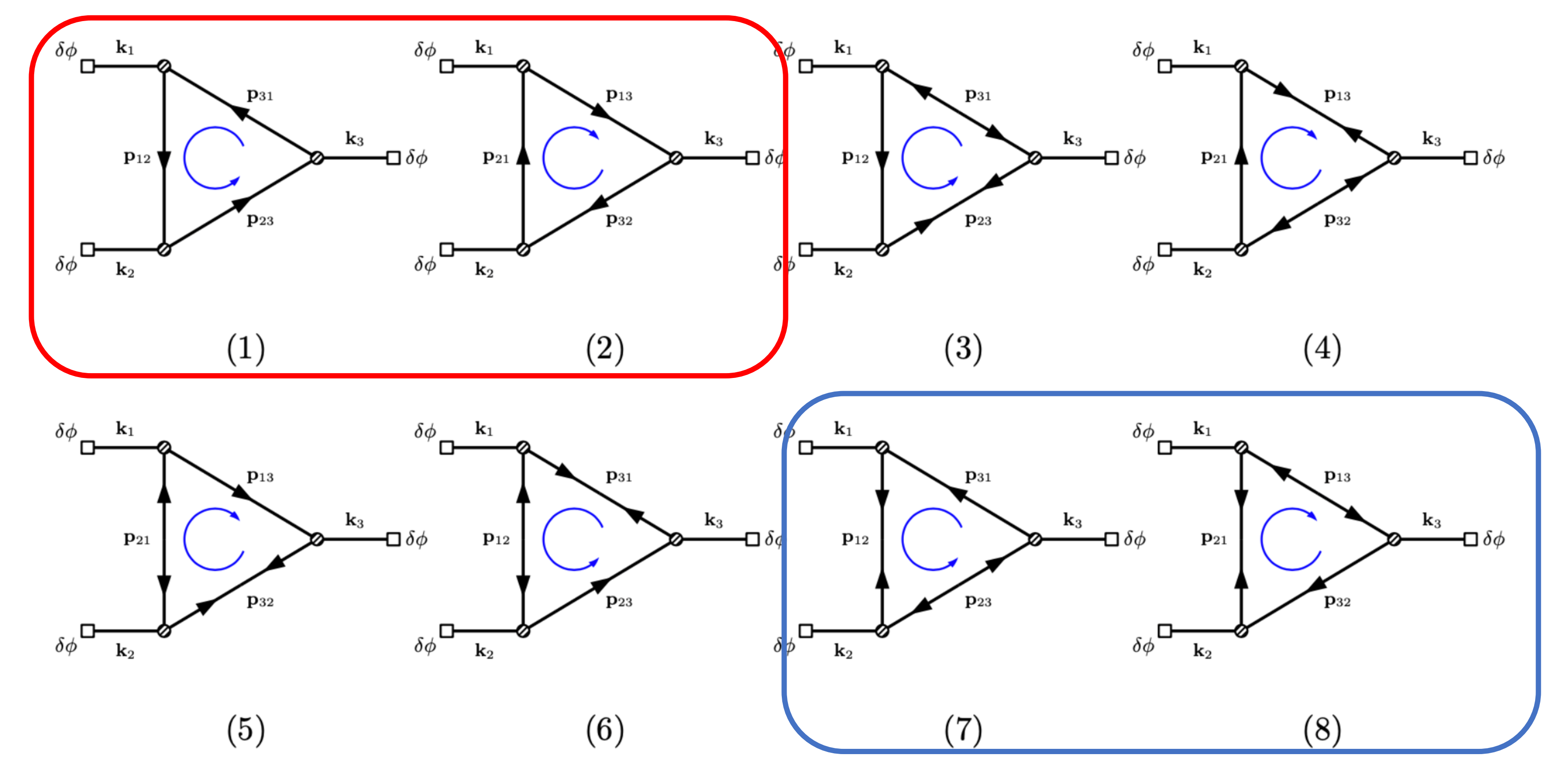
- The saddle-point approximation can differ substantially from the exact result in some mass ranges.
- The full loop integration brings an additional suppression factor of order 10^{-4}.
- Together, the old estimate can be too large by roughly six orders of magnitude.



Seems hopeless to see the seesaw signal

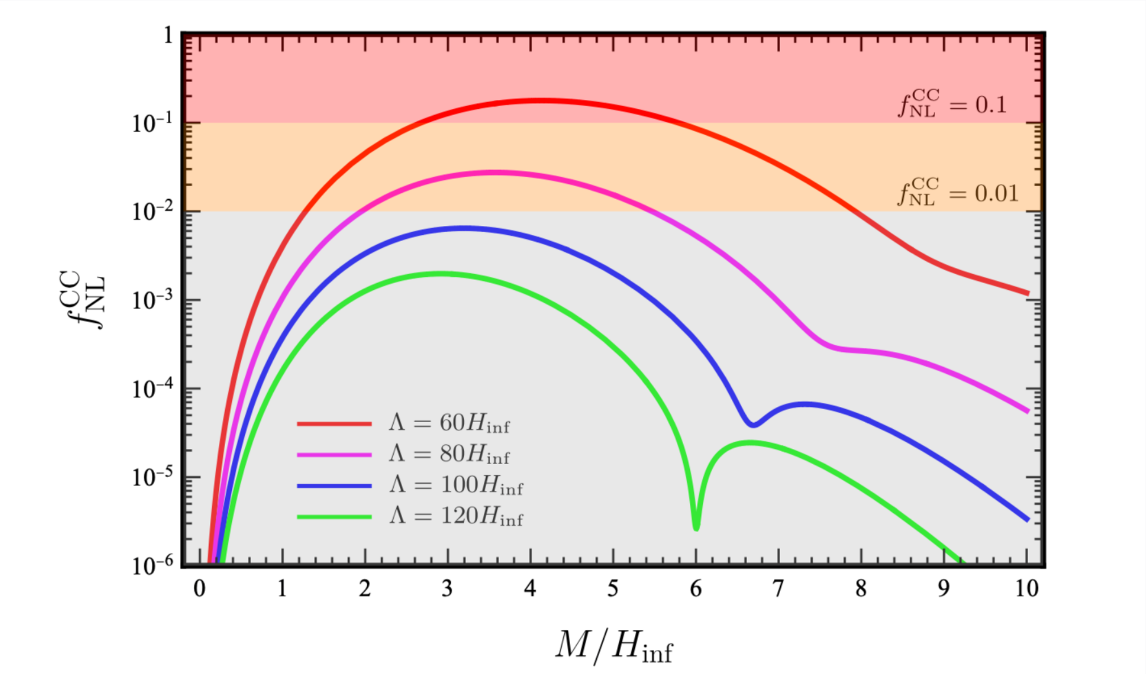
But that is not the full answer: many diagrams were missing

The old literature evaluated only a subset of diagrams



Full result: the observable window reappears after summing all diagrams

- New diagrams can dominate over the older benchmark piece.
- In part of parameter space, the total RH-neutrino loop signal reaches an observable level.



Summary

- Right-handed neutrinos are motivated by neutrino masses and leptogenesis, but their natural scale is extremely high
- In the relevant cosmological-collider setup, fermionic signals arise only from loops, so quantitative control matters
- RH-neutrino loops can still generate an observable nonlocal bispectrum in part of parameter space