How Does a Thermal Medium Affect Primordial Gravitational Waves?

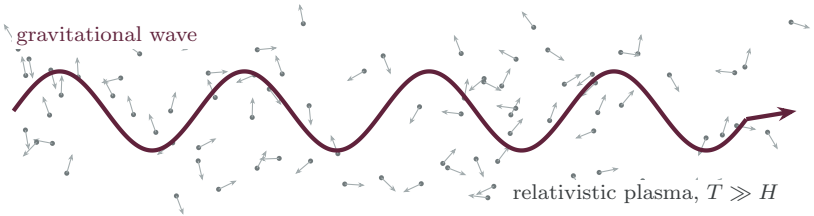
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Chongqing U.
Based on AO, arXiv:2510.22346 (revised 2026);
AO, H.-Y. Zhu, Y. Zhu, arXiv:2601.03631

November 7, 2026

A wave in a medium

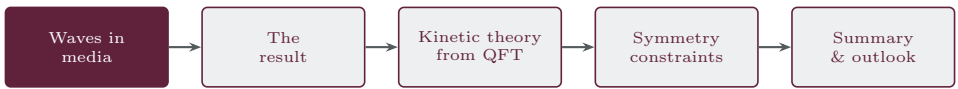
Question: What happens to a gravitational wave traveling through a medium?



- The early universe *was* a medium: a hot radiation plasma
- Every primordial GW we hope to detect (CMB B-modes, PTA, LISA, ET) crossed it

Roadmap

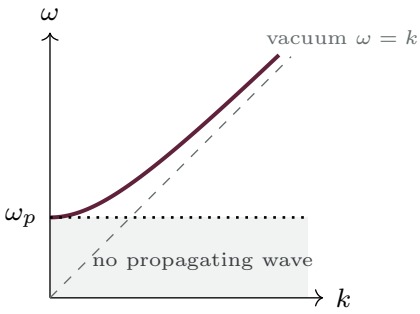
1. Waves in media: what plasma physics teaches us
2. The result: a graviton plasmon, no Landau damping, frozen superhorizon modes
3. Kinetic theory from QFT: the gravitational "HTL = Vlasov", in real time
4. Symmetry constraints: Ward identities on FLRW fix the response
5. Summary and outlook



Waves in media

Plasma physics has a clear answer for light. What about gravity?

Light in a plasma



Plasmon gap

$$\lim_{k\to 0} \omega^2 = \omega_p^2, \qquad \omega_p \sim eT$$

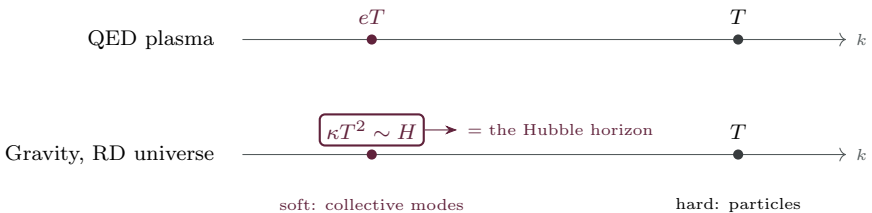
- Below ω_p: no propagation — this is why metals reflect light
- Gauge invariant: no mass in the Lagrangian, only in the dispersion

The plasma dresses the wave at the soft scale, where collective modes live.

[Braaten, Pisarski (1990); Le Bellac, *Thermal Field Theory*]

The gravitational version

Soft scale = coupling × temperature:



Friedmann: $H^2 = \kappa^2\rho/12 \sim \kappa^2 T^4 \;\Rightarrow\; \kappa T^2 \sim H$ ($\kappa^2 = 32\pi G$).

The graviton "plasmon gap" sits exactly at the Hubble horizon.

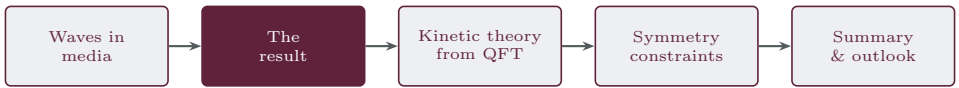
[Rebhan (1991); Brandt, Frenkel (1993)]

Taken literally, this is a paradox

- **Plasma intuition:** read the gap as a local mass
  $\Rightarrow$ superhorizon GWs decay on a Hubble time?
- **Standard cosmology:** superhorizon tensor modes exist and are frozen
  $\Rightarrow$ the basis of every inflationary prediction

[Weinberg (2003)]

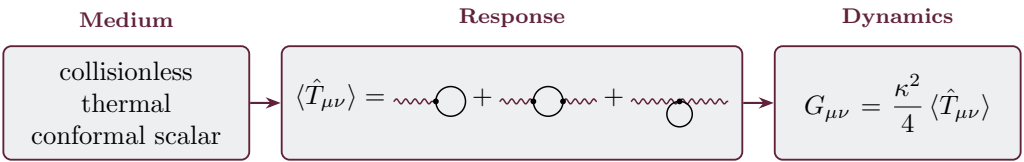
Are modes frozen or decaying? We need to know how the medium really responds — on a dynamical background.



The result

Compute the response on FLRW — here is what comes out.

What we compute



[AO (2025)]

Result 1: a collective mode — the graviton plasmon

Adiabatic dispersion relation

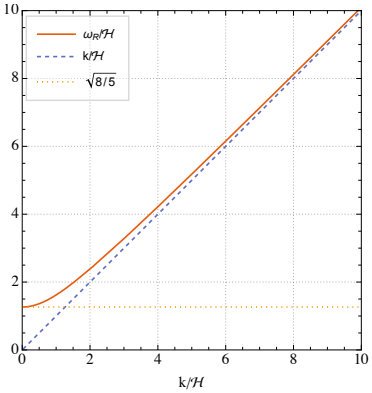
$v_{ij} = a h_{ij}^{\mathrm{TT}}$; $\mathcal{H} = a'/a \approx$ const; k, ω comoving

$$\omega^2 = k^2 + \mathcal{H}^2\,\mathcal{I}\left(\frac{\omega - i\mathcal{H}}{k}\right)$$

Superhorizon limit: a gap

$$\lim_{k\to 0} \omega^2 = \tfrac{8}{5}\,\mathcal{H}^2$$

Read as a local mass, it would make superhorizon modes decay — do they?



[AO (2025)]

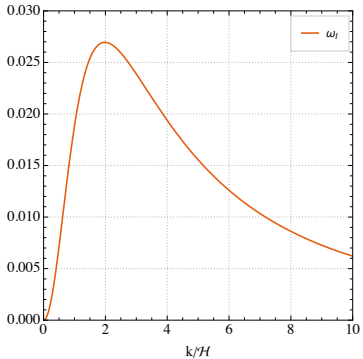
Result 2: is the graviton plasmon Landau damped?

Subhorizon pole of $v_{ij} = a h_{ij}^{\mathrm{TT}}$:

$$\omega_+ \simeq k + \frac{\mathcal{H}^2}{k} + i\frac{\mathcal{H}^3}{k^2} + \left(\cdots - \frac{3\pi i}{2}\right)\frac{\mathcal{H}^4}{k^3} + \cdots$$

- $i\mathcal{H}^3/k^2$: weaker Hubble damping — no instability
- $i\pi$: $\mathrm{Re}\,\omega > k$ — no particle surfs

As for the QED plasmon: no Landau damping



[AO (2025)]

Result 3: the gap is there, but a source cancels it

Full (Volterra, memory from τ_0)

$$h_{ij}'' + 2\mathcal{H}h_{ij}' + k^2 h_{ij} = -24\mathcal{H}^2 \int_{\tau_0}^{\tau} d\bar{\tau}\, K\big(k(\tau-\bar{\tau})\big)\, \partial_{\bar{\tau}} h_{ij}(\bar{\tau})$$

Leading gradient ($k \ll \mathcal{H}$: memory localized)

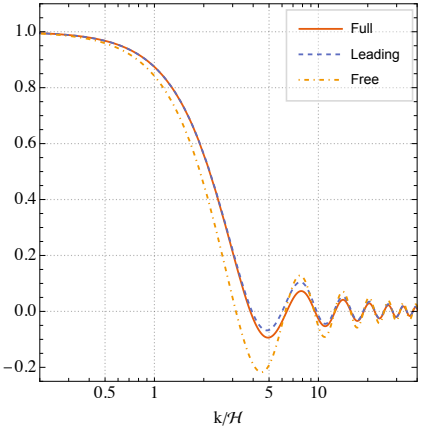
$$h_{ij}'' + 2\mathcal{H}h_{ij}' + k^2 h_{ij} + \underbrace{\tfrac{8}{5}\mathcal{H}^2 h_{ij}}_{\text{gap}} \underbrace{- \tfrac{8}{5}\mathcal{H}^2 h_{ij}(0)}_{\text{time-boundary source}} = 0$$

- Superhorizon: gap and source cancel $\Rightarrow h_{ij} = h_{ij}(0)$, frozen
- The source comes from τ_0: the medium responds only to *changes* of h_{ij}

[AO (2025); Weinberg (2004)]

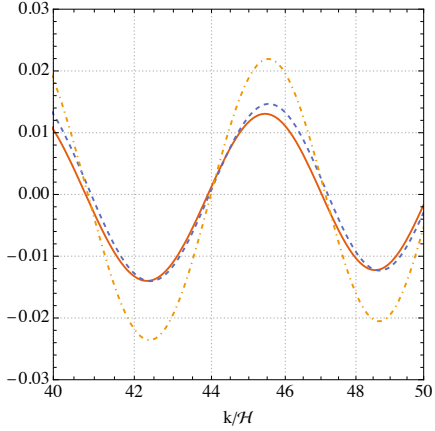
Real-time evolution: Full vs Leading vs Free

Horizon entry



Leading already tracks Full: gap + source

Deep inside

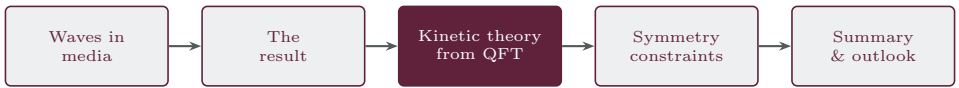


$\sim 40\%$ below free; memory adds a further suppression

[AO (2025)]

The result at a glance

Question	Answer
Is there a gap?	Yes: $\omega_p^2 = \frac{8}{5}\mathcal{H}^2$, a collective mode of the radiation
Superhorizon modes?	Frozen: the time boundary of the retarded response protects them
Suppression?	$\sim 40\%$: mostly gap + time boundary, the rest from memory
Next: the details	
Relation to kinetic theory?	Real-time HTL on FLRW = Weinberg's kinetic equation
Is it consistent?	Ward identities on FLRW hold; no local state response allowed



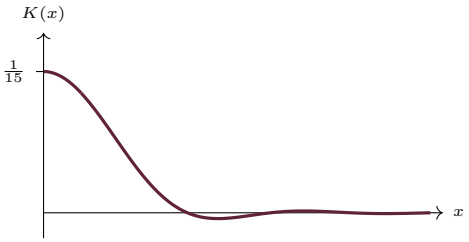
Kinetic theory from QFT

The gravitational counterpart of "HTL = Vlasov" — in real time, on FLRW.

The equation is known from kinetic theory

$$h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = -24\mathcal{H}^2 \int_{\tau_0}^{\tau} d\bar{\tau}\, K\big(k(\tau - \bar{\tau})\big)\, \partial_{\bar{\tau}} h_{ij}(\bar{\tau})$$

- Weinberg (2004): from the collisionless Boltzmann equation of free-streaming radiation (neutrinos)
- $K(x) = j_2(x)/x^2$: the memory of free streaming
- Coefficient 24: all radiation free-streams ($24 f_\nu$ for a fraction f_ν)



This work: the same equation from QFT — how?

[Weinberg (2004); Watanabe, Komatsu (2006)]

The response has three pieces, not one

All pieces add up to the full stress tensor:

$$\begin{aligned}\langle \hat{T}_{\mu\nu} \rangle &= \bar{T}_{\mu\nu} + T^R_{\mu\nu} + T^C_{\mu\nu} \\ &= \langle \hat{T}^I_{\mu\nu} \rangle + i \int dy^0 \, \Theta(x^0 - y^0) \left\langle \left[\hat{H}_{\rm int}(y^0), \hat{T}^I_{\mu\nu}(x) \right] \right\rangle + \int d^4y \, h^{\rho\sigma}(y) \left\langle \frac{\delta \hat{T}_{\mu\nu}(x)}{\delta h^{\rho\sigma}(y)} \right\rangle_{\chi, \pi_\chi}\end{aligned}$$



$\bar{T}_{\mu\nu}$: tadpole — background stress of the plasma



$T^R_{\mu\nu}$: retarded response — history of the plasma (nonlocal)



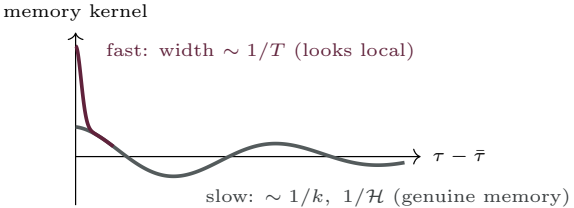
$T^C_{\mu\nu}$: contact response — explicit metric dependence, at fixed χ, π_χ

[Kubo (1957); Schwinger (1959); AO (2025)]

Two time scales in the retarded response



$T^R_{\mu\nu}$: retarded response



- **Fast** $(1/T)$: the plasma reacts almost instantly — a local term $-2\mathcal{H}^2 h_{ij}$
- **Slow** $(1/k,\ 1/\mathcal{H})$: the genuine memory of the medium
- **Schwinger terms**: non-covariant, from ∂_0 vs Θ; cancelled by T^C, and both vanish for TT

A local term from a nonlocal diagram — what removes it?

[AO (2025)]

Weinberg's equation from QFT

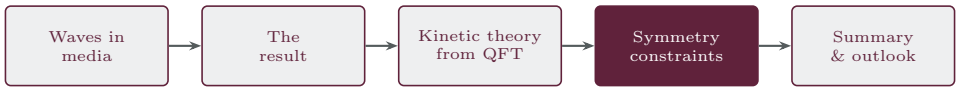
TT projection of the full response in a radiation universe:

$$\underbrace{-2\mathcal{H}^2 h_{ij}}_{\text{fast}} + \underbrace{24\mathcal{H}^2 K(k\tau)\,\sigma_{ij}}_{\text{boundary}} + \underbrace{24\mathcal{H}^2 \int_{\tau_0}^{\tau} d\bar{\tau}\, K\big(k(\tau-\bar{\tau})\big)\,\partial_{\bar{\tau}} h_{ij}}_{\text{slow memory}}$$

- On-shell projection: the background pressure gives $+\frac{1}{2}\kappa^2 a^2 \bar{P}\, h_{ij} = +2\mathcal{H}^2 h_{ij}$
- Fast + pressure $= 0$; boundary $= 0$; the slow memory is Weinberg's kernel

The background pressure eats the fast part — what is left is exactly kinetic theory.

[AO (2025); Weinberg (2004)]



Symmetry constraints

Ward identities on FLRW test the response: $\delta_\xi \Gamma = 0$ *fix the state.*

On FLRW, diffeomorphism and Weyl are entangled

Schematically (indices suppressed):

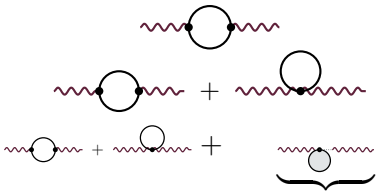
$$\partial \cdot (a^4 \bar{\Pi}) \;=\; \underbrace{\partial\,(a^2 \bar{T})}_{\text{background stress}} \;-2\,(\partial \ln a)\; \underbrace{\left[\bar{T} - \tfrac{1}{2}\,\mathrm{tr}\,\bar{\Pi}\right]}_{\text{the Weyl identity}}$$

- The bracket vanishes for conformal matter — it *is* the Weyl identity
- So a response that violates Weyl invariance violates the diffeomorphism identity as well
- On an expanding background the two symmetries become one test

That entanglement is what makes the check sharp and sensitive to the state.

[AO (2025)]

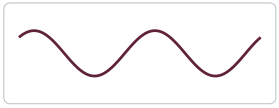
Verdict: which construction passes?

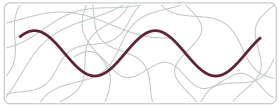


✗ retarded only: non-covariant Schwinger terms survive

✓ **this work**: Weyl and diffeomorphism identities both hold

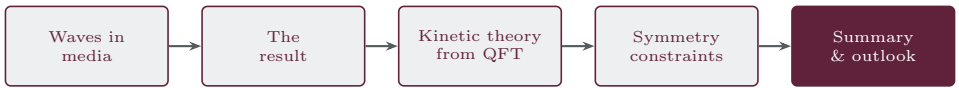
✗ a perturbed state, such as local Gibbs, is not allowed


one wave in empty space


one wave among many

A local state response cannot be introduced: local Gibbs is ruled out.

[AO (2025)]



Summary and outlook

So, what happens to a gravitational wave in a medium?

Summary

The result

- A collective mode: the graviton plasmon, $\lim_{k\to 0} \omega^2 = \frac{8}{5}\mathcal{H}^2$
- Its $\mathrm{Im}\,\omega$ only weakens the Hubble damping — not Landau damping
- Real time: the gap is cancelled by the time-boundary source $\Rightarrow$ superhorizon modes frozen; $\sim 40\%$ suppression inside

How it is built

- Tadpole + retarded + contact, on shell: real-time HTL on FLRW = Weinberg's equation
- FLRW Ward identities fix the response *and* the state: no local state response is allowed

Outlook: spinning fields (spin blind), non-thermal and resonant media, scalar and vector sectors.

A gravitational wave in the early universe is a plasma wave whose gap is the horizon.

Thank you for your attention.

References

- A. Ota, *Collective properties of gravitational perturbations in thermal environments on a dynamical background*, arXiv:2510.22346 (revised 2026).
- A. Ota, H.-Y. Zhu, Y. Zhu, *Real-time gravitational wave response in thermal spinning fields*, JHEP 06 (2026) 216, arXiv:2601.03631.

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