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Gravitational wave propagation beyond GR: waveform distortions and echoes

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Motivation

- LIGO/VIRGO gravitational wave (GW) detections give a strong constrain on gravity theory beyond GR
- Future: Einstein Telescope, Cosmic Explorer, LISA, TianQin, BBO, DECIGO, PTA
- It's the best era to test GR!

Motivation

- We study GW propagation if GWs interact with another field
- Homogenous and isotropic cosmological background (no interaction with scalar or vector DoF in linear theory, only tensor DoF)
- Parametrized equation of motion
- Theoretical Examples: massive bigravity, Yang-Mills theories, Abelian multi-gauge field, Multi-Proca theories (see also Jimenez et al. 2020 for details)

Equation of Motion

velocity

Mass

$$\left[\hat{I}\frac{\mathrm{d}^2}{\mathrm{d}\eta^2} + \hat{\nu}(\eta)\frac{\mathrm{d}}{\mathrm{d}\eta} + \hat{C}(\eta)k^2 + \hat{\Pi}(\eta)k + \hat{M}(\eta)\right]\begin{pmatrix} h \\ s \end{pmatrix} = 0$$

Friction

Chiral

h: GW field

s: Coupled tensor field

General Solution: two eigen propagation modes

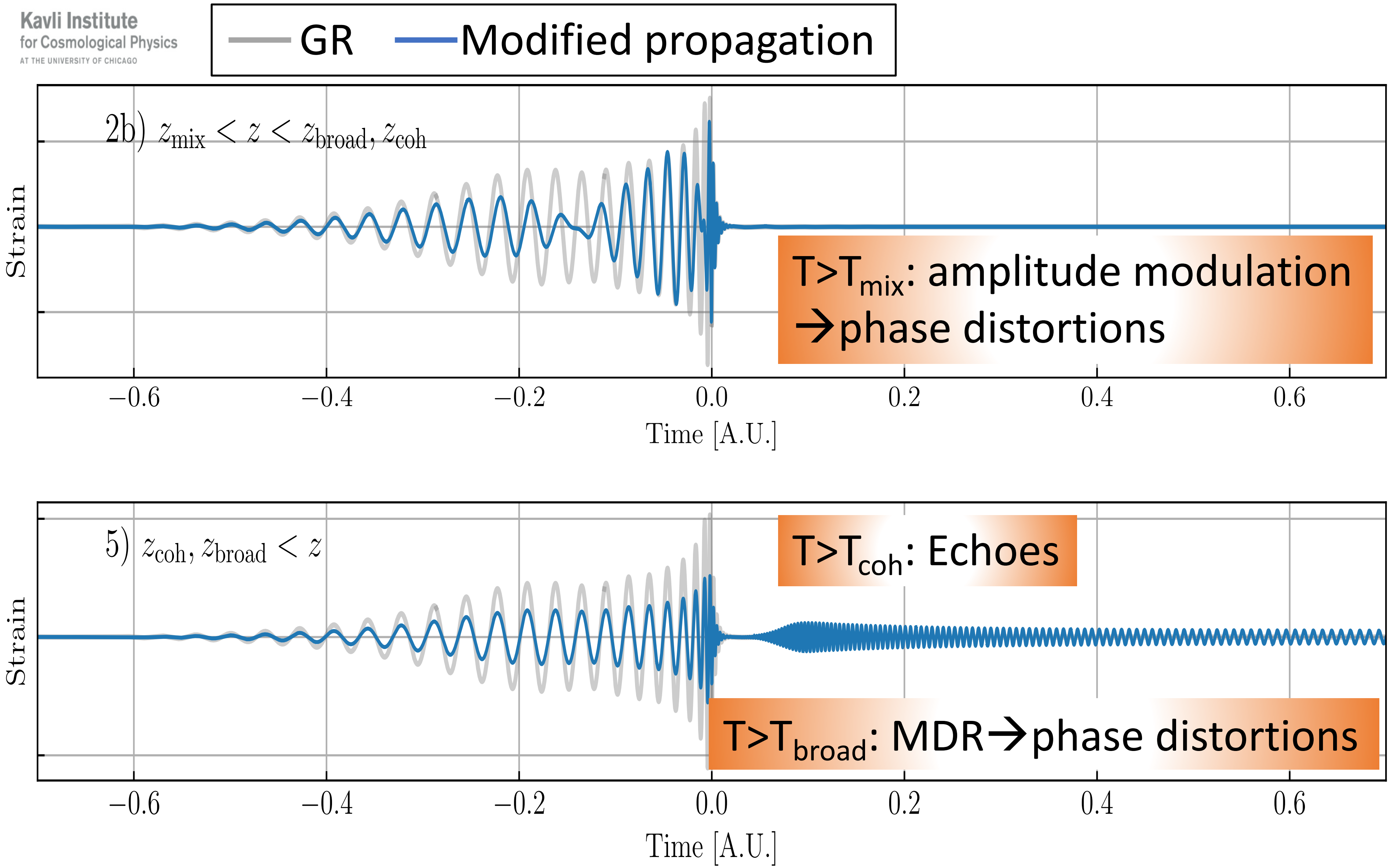
$$h(\eta, k) = \sum_A h_0(k)\, f_A(\eta, k)\, e^{-i\phi_A(\eta,k)}$$

$$\phi_A = \int \omega_A d\eta \qquad (\text{GR: } \omega_A = ck)$$

- Constant coefficients: exact analytical solution
- Time-dependent coefficients: WKB approximation
- Two eigenmodes propagate independently in high-k limit.
- The detected signal is the superposition of the two eigenmodes.

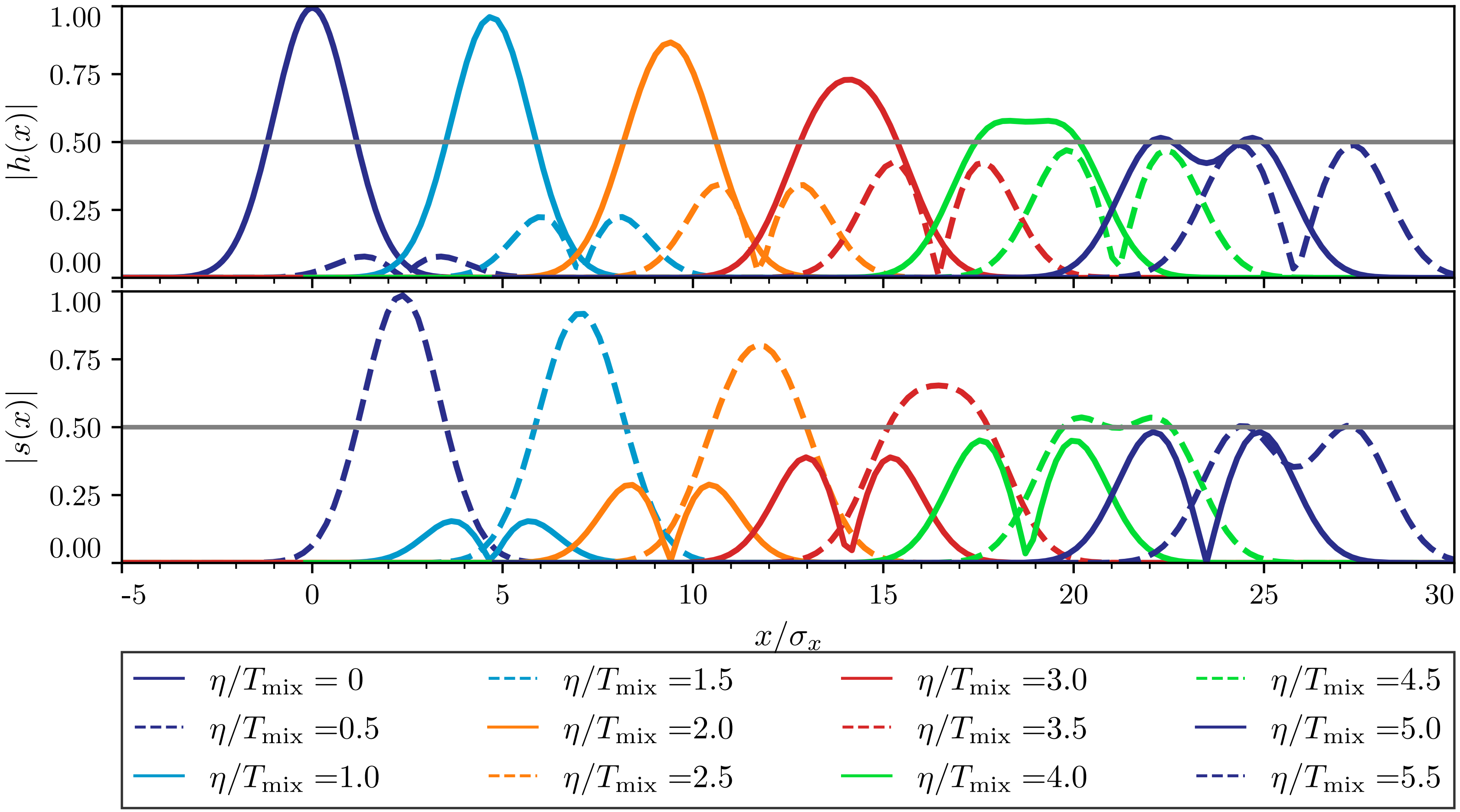
Phenomenon highlights

- Three timescales: mixing, coherence, broadening
- Observational implication:
  - Echoes
  - Phase distortion



GR
Modified propagation
2b) $z_{\rm mix} < z < z_{\rm broad}, z_{\rm coh}$
Strain
T>T$_{mix}$: amplitude modulation
→phase distortions
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
Time [A.U.]
5) $z_{\rm coh}, z_{\rm broad} < z$
Strain
T>T$_{coh}$: Echoes
T>T$_{broad}$: MDR→phase distortions
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
Time [A.U.]

Echoes: from coherence to decoherence



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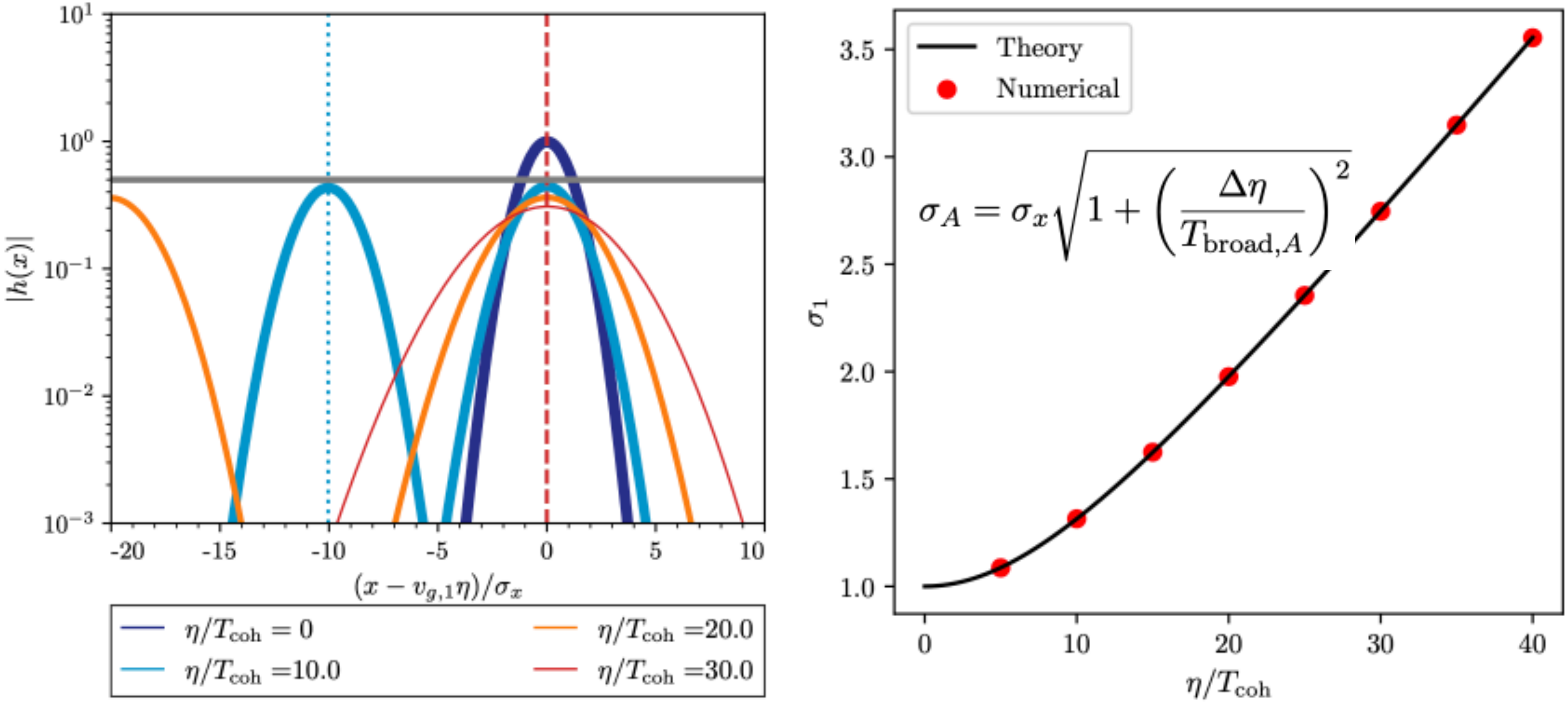
Broadening



Real waveforms: k-dependent group velocity → phase distortion

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Summary

- We study GW propagation if GW field interacts with another tensor field, obtain general WKB solution
- Three timescales: mixing, coherence, broadening
- Observational implication:
  - Echoes
  - Phase distortion
- Other interesting phenomena in the paper (see arxiv:2108.10872)
  - Apparent luminosity distance change
  - Polarization oscillations and amplitude/phase birefringence
  - Broadening prevents decoherence

BACKUP

Typical timescales

- Dispersion relation:

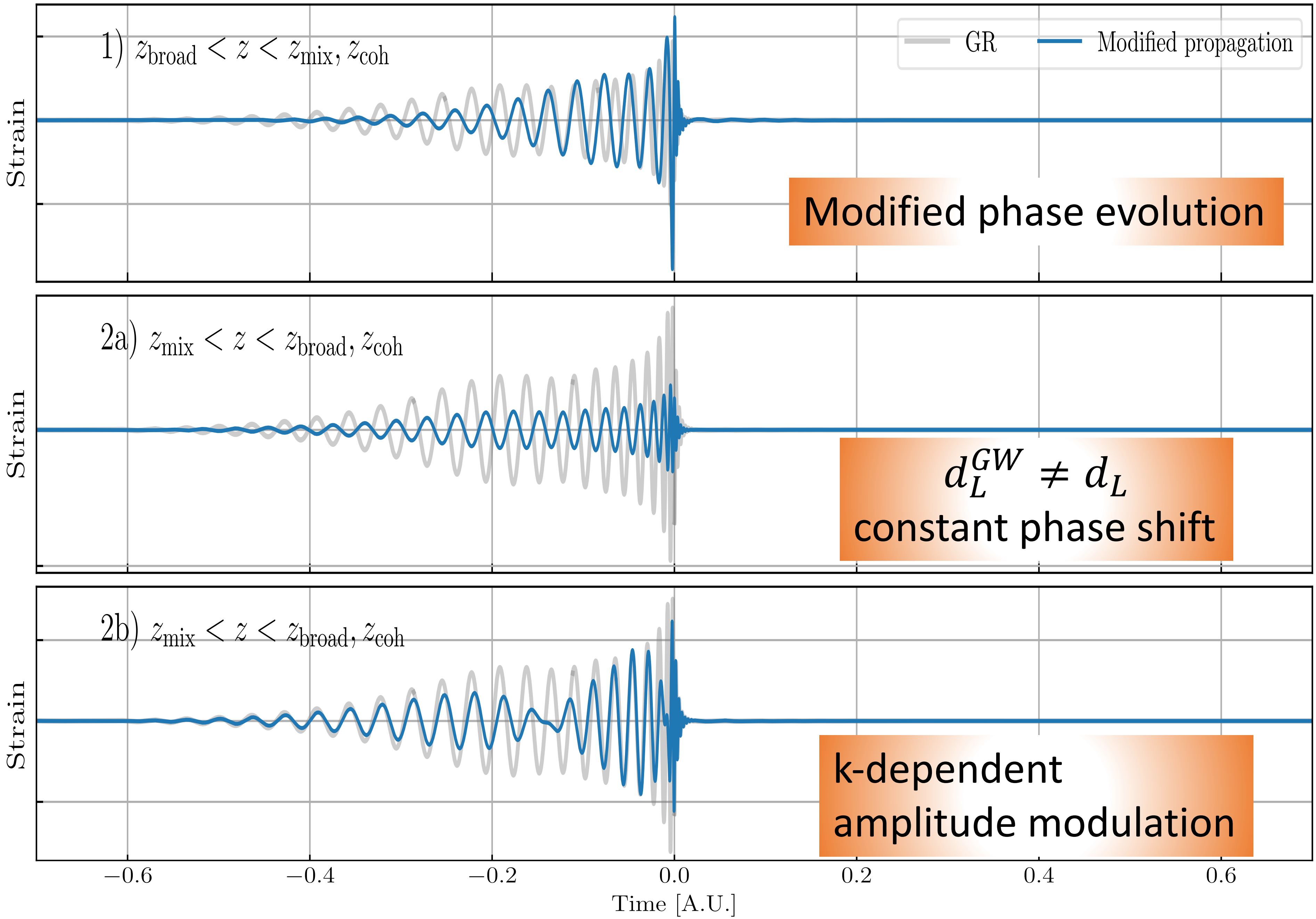
$$\omega_A(k) = \omega_A(k_0) + \frac{\partial \omega_A}{\partial k}(k - k_0) + \frac{1}{2}\frac{\partial^2 \omega_A}{\partial k^2}(\mathrm{k} - \mathrm{k}_0)^2 + \cdots$$

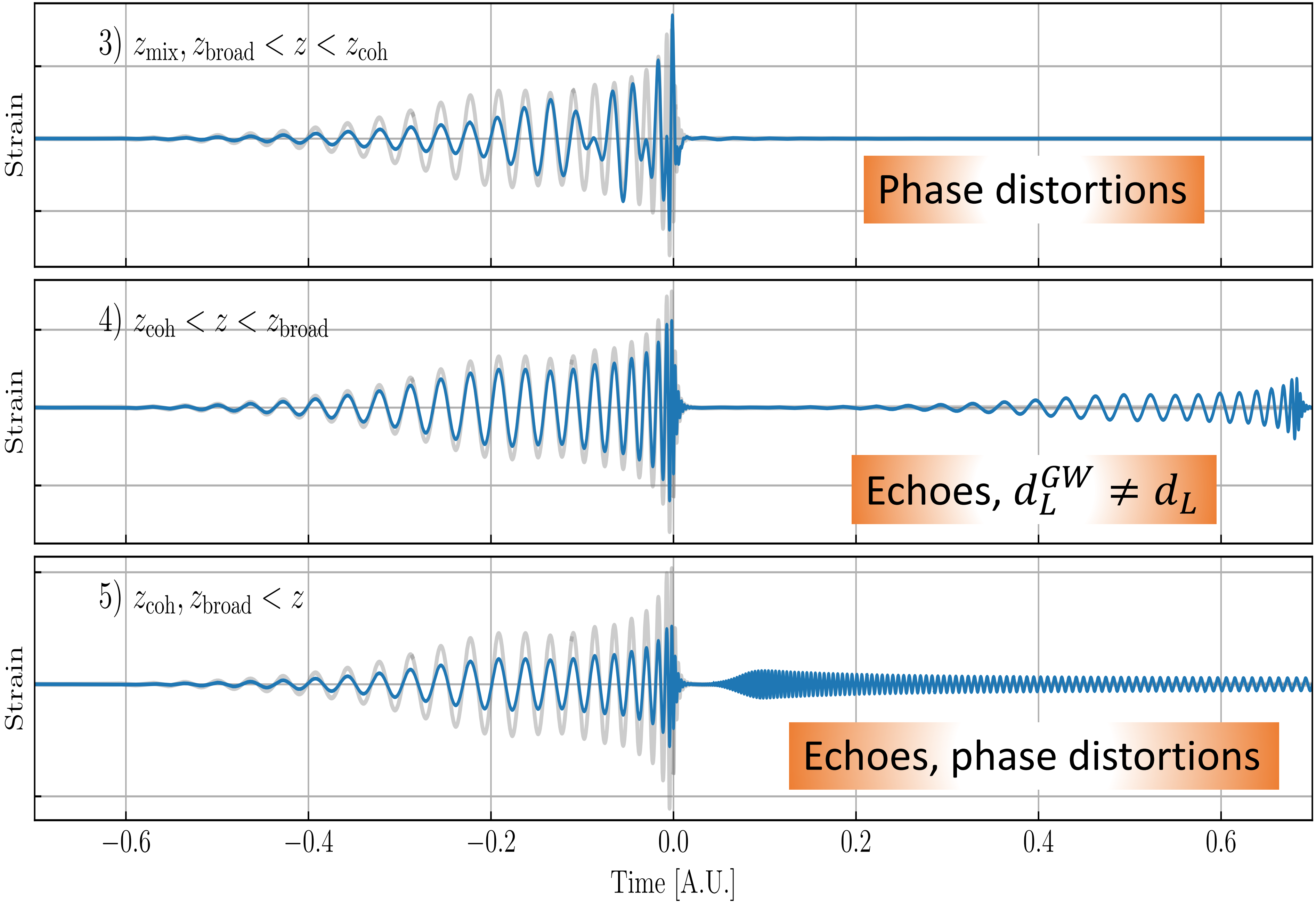
- Mixing: $T_{mix}|\omega_1 - \omega_2| \sim 2\pi$
  - $T > T_{mix}$: oscillations due to mixing
- Coherence: $T_{coh}|v_{g1} - v_{g2}| \sim \sigma_A,\ v_{g,A} = \frac{\partial \omega_A}{\partial k}$
  - $T > T_{coh}$: echoes
- Broadening: $T_{broad,A}\left|\frac{\partial^2 \omega_A}{\partial k^2}\right| \sim \sigma_x^2$
  - $T > T_{broad}$: phase distortions

Observation: for real binary coalescence signal

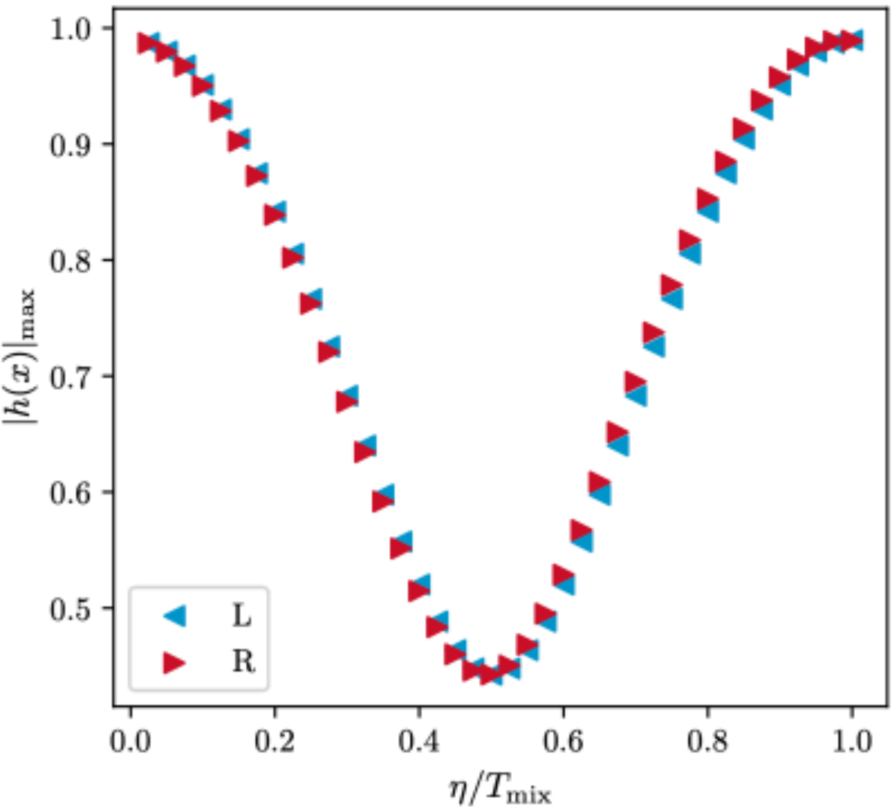
	Regime	Observables
0)	$z \ll z_{\rm mix}, z_{\rm broad}, z_{\rm coh}$	Unmodified waveform
1)	$z_{\rm broad} < z \ll z_{\rm mix}, z_{\rm coh}$	Single event with modified phase evolution
2a) 2b)	$z_{\rm mix} < z < z_{\rm broad}, z_{\rm coh}$	Single event with $d_L^{\rm GW} \neq d_L$ and constant phase shift, or frequency-dependent amplitude modulation with phase distortions
3)	$z_{\rm mix}, z_{\rm broad} < z < z_{\rm coh}$	Single event with modified phase evolution
4)	$z_{\rm coh} < z < z_{\rm broad}$	Echoes with different arrival times and $d_L^{\rm GW}$
5)	$z_{\rm coh}, z_{\rm broad} < z$	Echoes with different arrival times and phase distortions

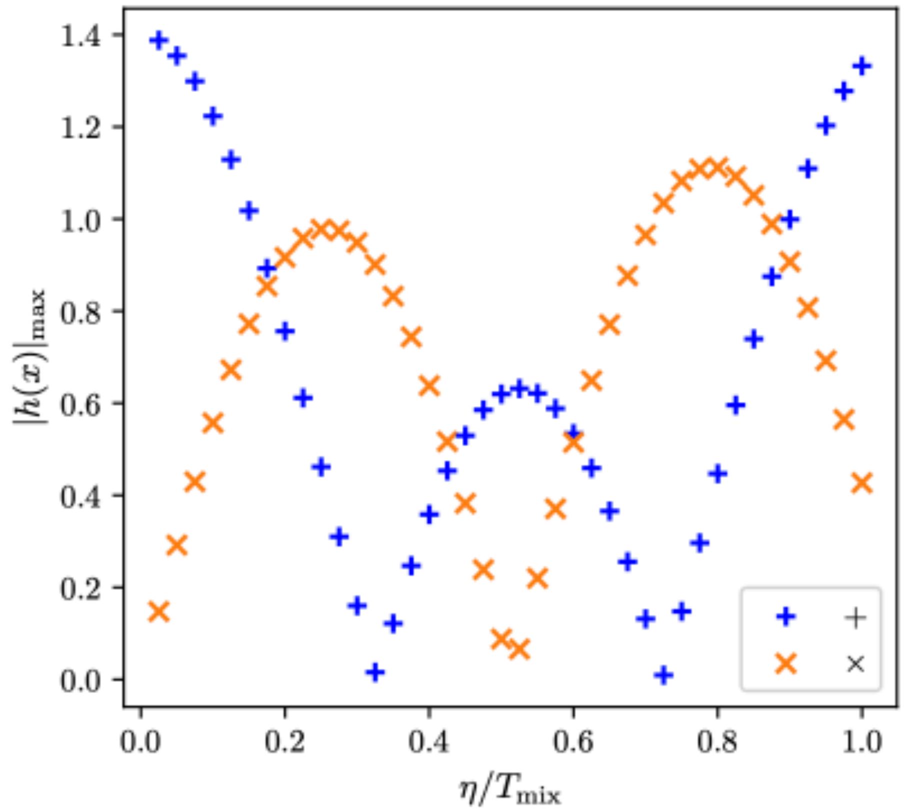
Main effects: echoes, phase distortions, oscillations and birefringence


1) $z_{\rm broad} < z < z_{\rm mix}, z_{\rm coh}$
GR
Modified propagation
Modified phase evolution
Strain
2a) $z_{\rm mix} < z < z_{\rm broad}, z_{\rm coh}$
$d_L^{GW} \neq d_L$
constant phase shift
Strain
2b) $z_{\rm mix} < z < z_{\rm broad}, z_{\rm coh}$
k-dependent
amplitude modulation
Strain
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
Time [A.U.]


3) $z_{\rm mix}, z_{\rm broad} < z < z_{\rm coh}$
Phase distortions
4) $z_{\rm coh} < z < z_{\rm broad}$
Echoes, $d_L^{GW} \neq d_L$
5) $z_{\rm coh}, z_{\rm broad} < z$
Echoes, phase distortions
Strain
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
Time [A.U.]

Polarization: chiral mixing





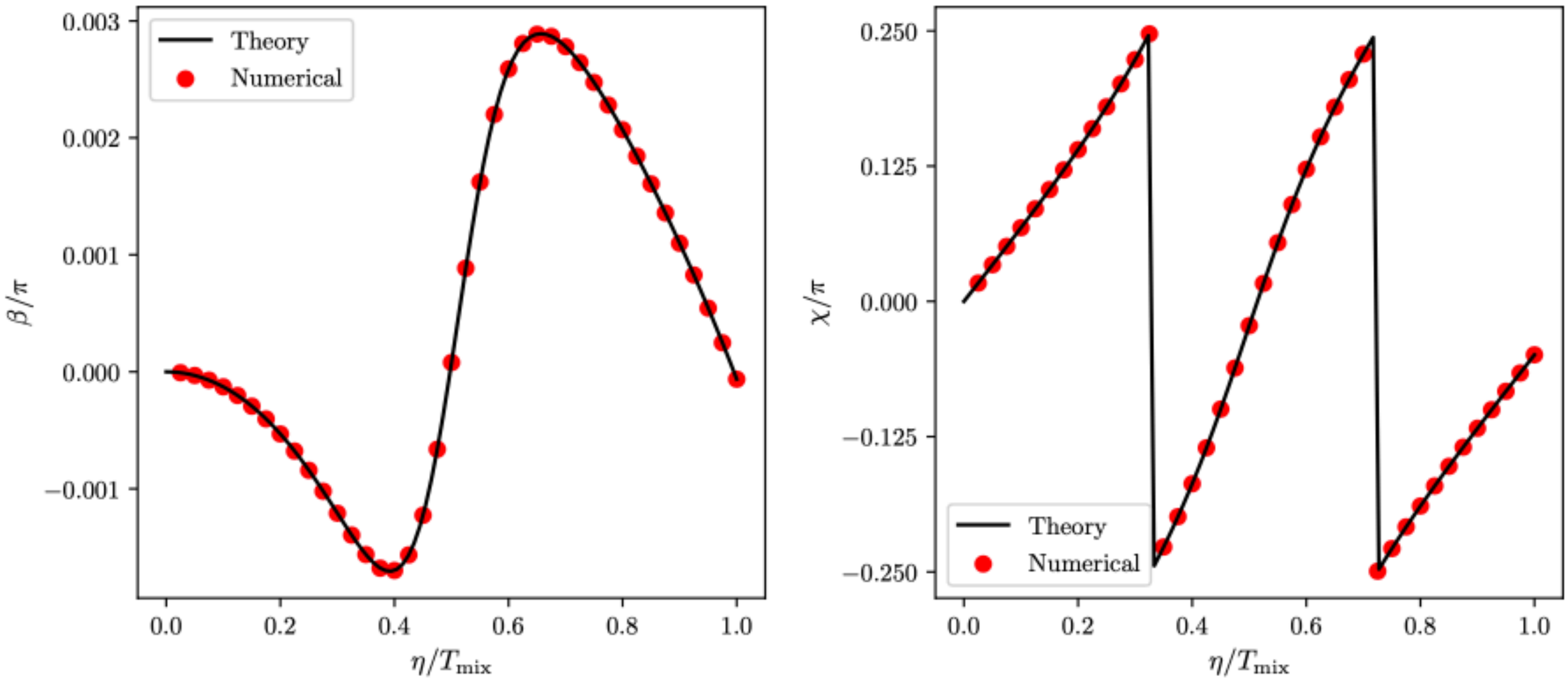
Initial: pure + polarization

Propagation: oscillate between + and X

$$h_+ = \frac{1}{\sqrt{2}}(h_L + h_R)$$

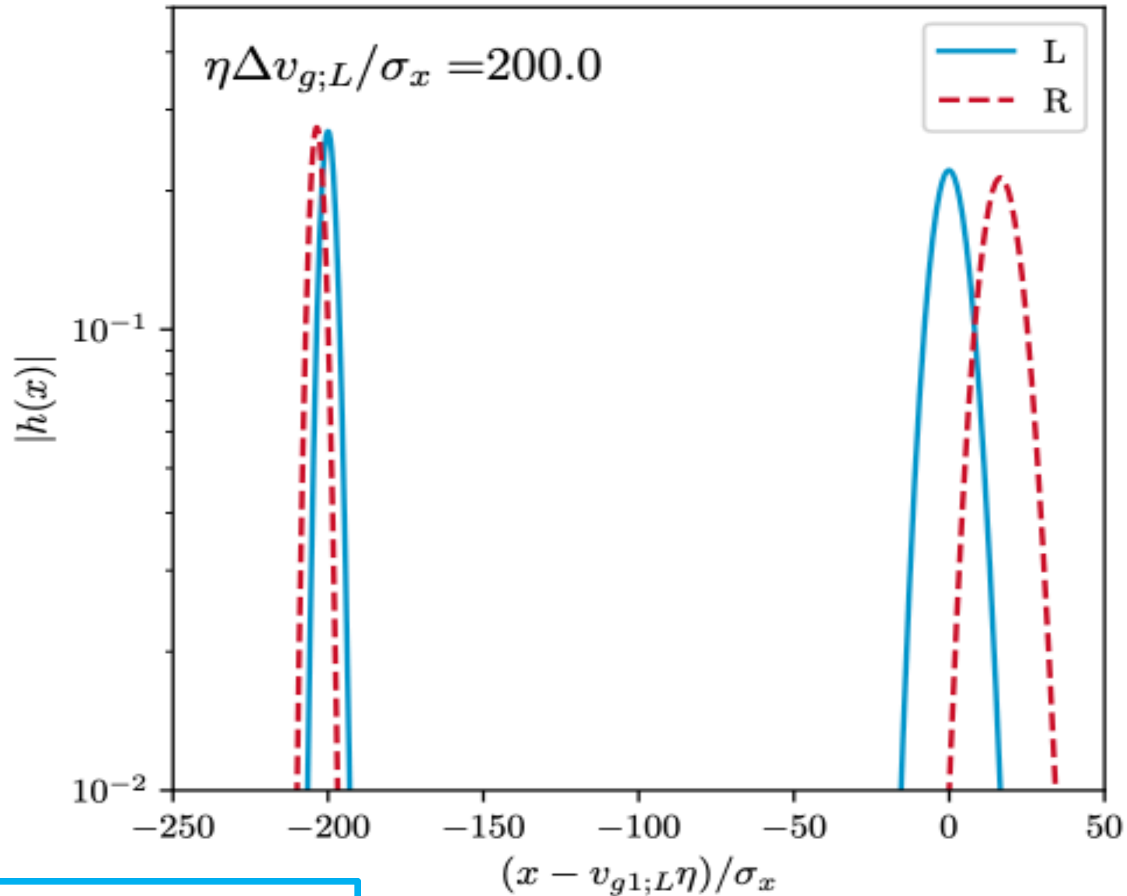
$$h_\times = \frac{i}{\sqrt{2}}(h_L - h_R)$$

Polarization: chiral mixing



β: degree of circular polarization (amplitude birefringence)
χ: orientation of elliptical polarization (phase birefringence)

Broadening prevents decoherence



Criteria for ever decoherence: RHS>1

$$\frac{\int_{\eta_0}^{\eta_0+\Delta\eta} \Delta v_g(k_0) d\eta}{\sigma_A} \rightarrow \frac{\Delta v_g(k_0) T_{\mathrm{broad,A}}(k_0)}{\sigma_x}$$

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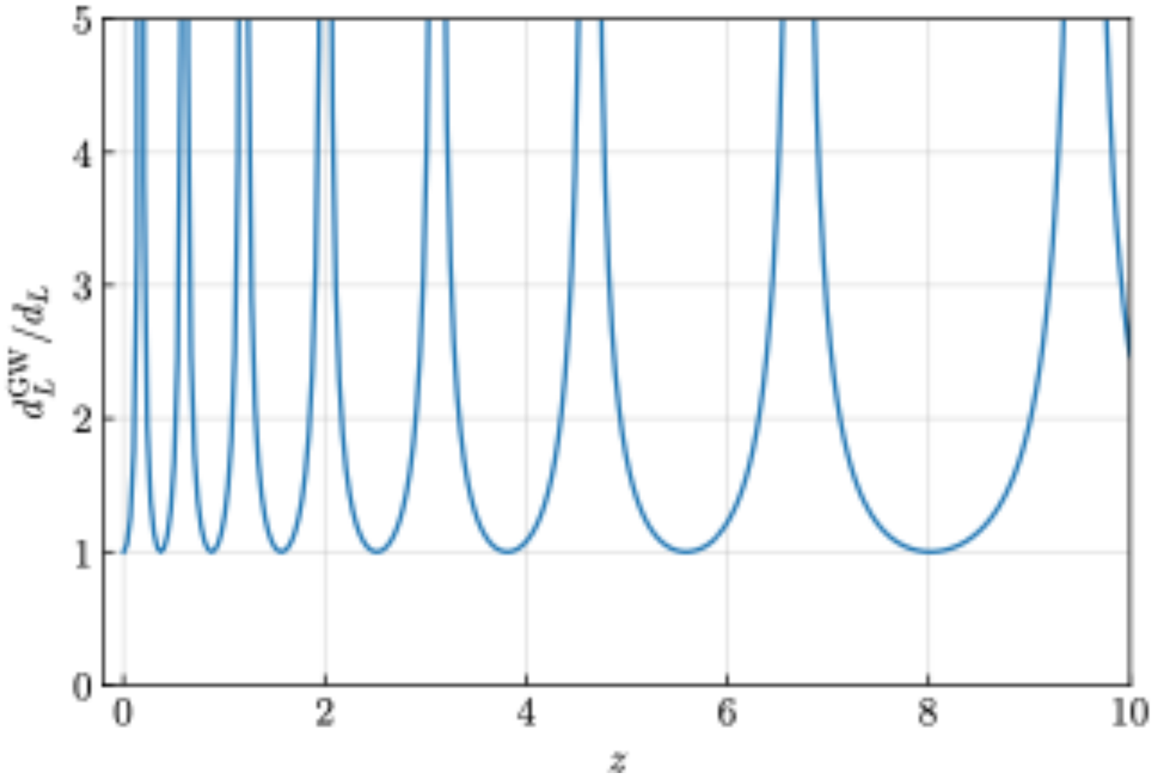
Observation: apparent luminosity distance (friction mixing)



Observation: birefringence (chiral mixing)