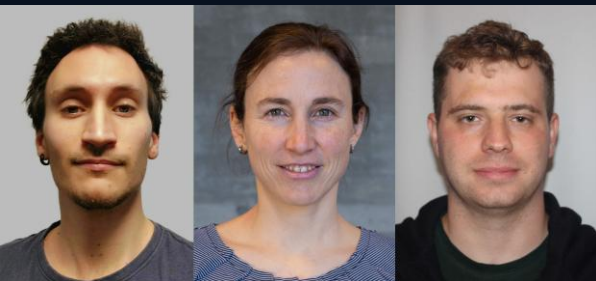
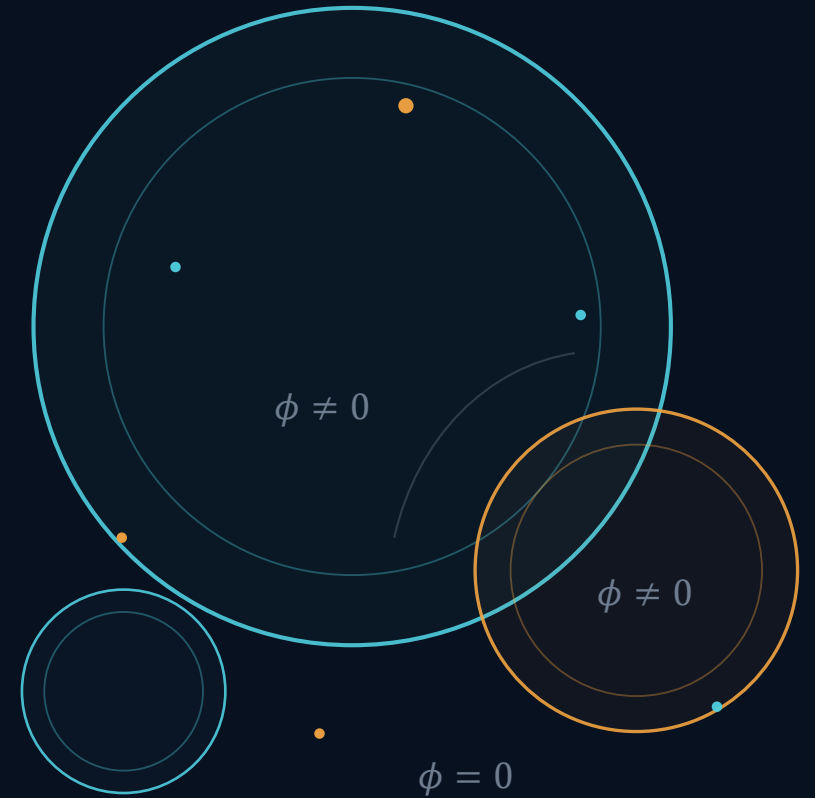


Dark transitions with a weak coupling

Marco Finetti · UAveiro, LIP-UMinho & U. Stavanger (NO)

MAP-Fis PhD Conference · 2026 October 2nd

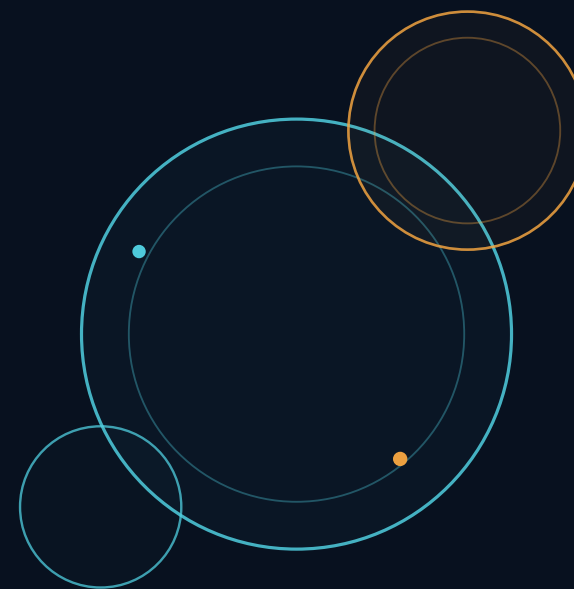
With Helena Kolečová & Daniil Krichevskiy
ArXiv 2610. $\alpha\beta\gamma\delta$ coming soon



01

Introduction

- 1st-order phase transitions (FOPTs)
- Stochastic Gravitational Wave Backgrounds
- Phase transitions in a dark sector



Intro

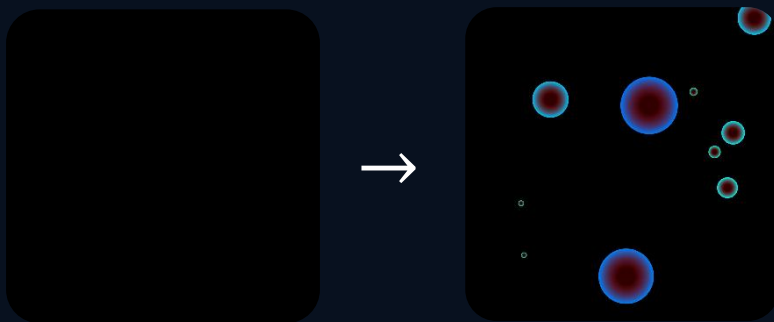
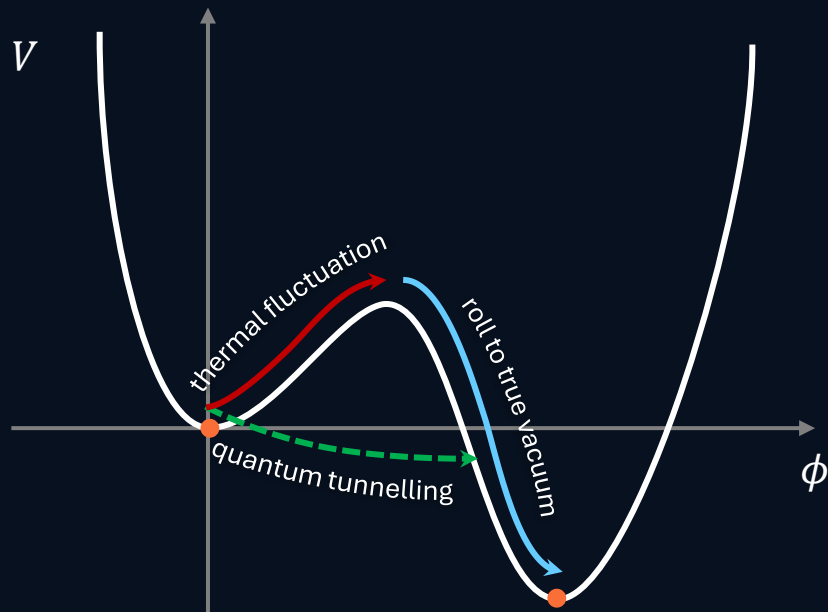
Regimes

Hydro

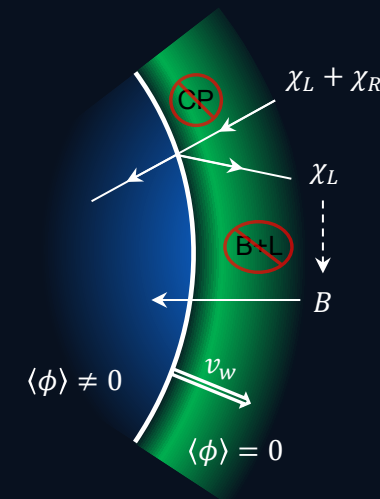
GWs

Summary

From Phase Transitions to Gravitational Waves



- FOPTs can occur in a QFT
 - typically, a thermal EFT
- Cosmological FOPTs are interesting because, if observed
 - signature of Beyond the Standard Model (BSM) effects
 - it provides a mechanism for anti/matter asymmetry through EW Baryogenesis
3rd Sakharov condition
- Strong FOPTs → SGWB
stochastic gravitational wave background
- Natural to consider FOPTs in a dark sector
- ? How does the coupling
DM ↔ SM
affect FOPTs and SGWB



Intro

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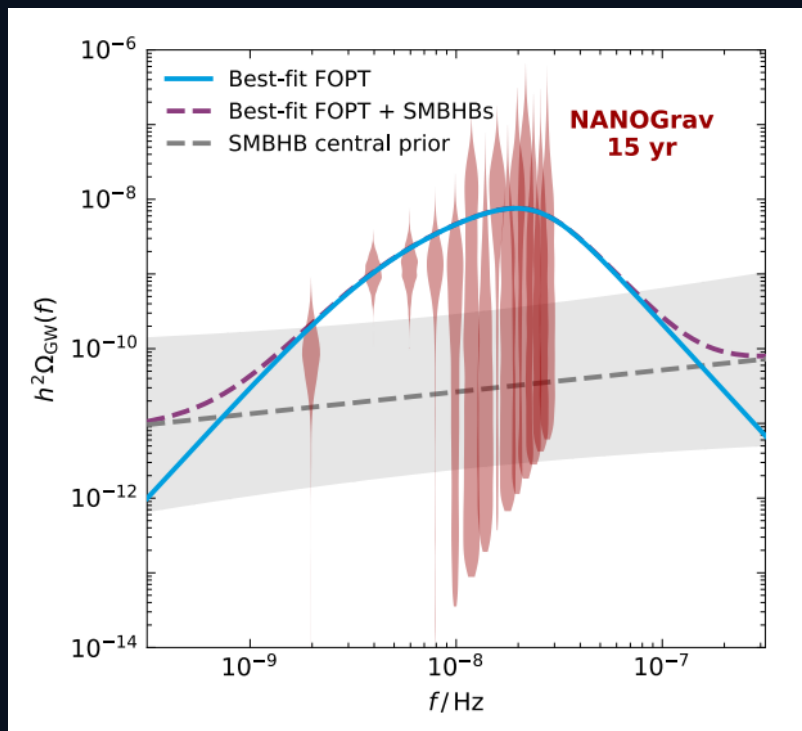
GWs

Summary

SGWB

Observation

- Pulsar Timing arrays



2602.09092

- Ground & Space based detectors

- LISA
- ET
- ...



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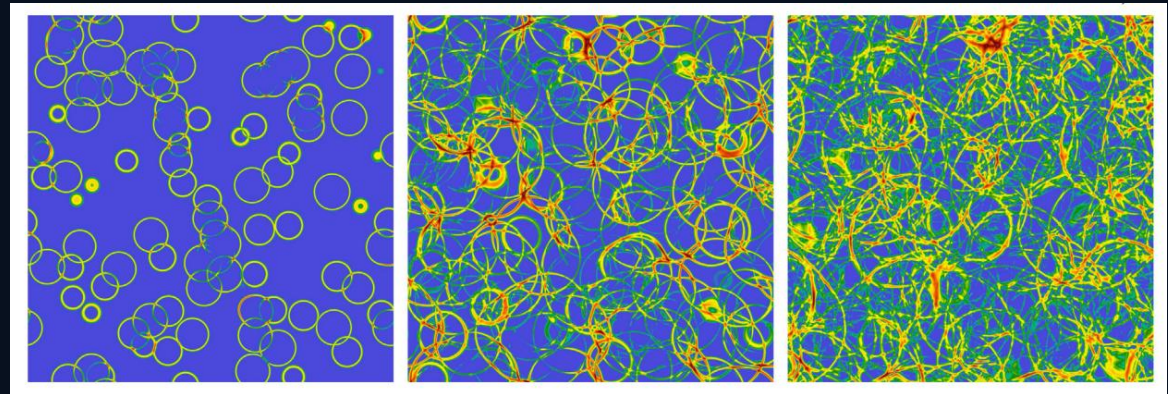
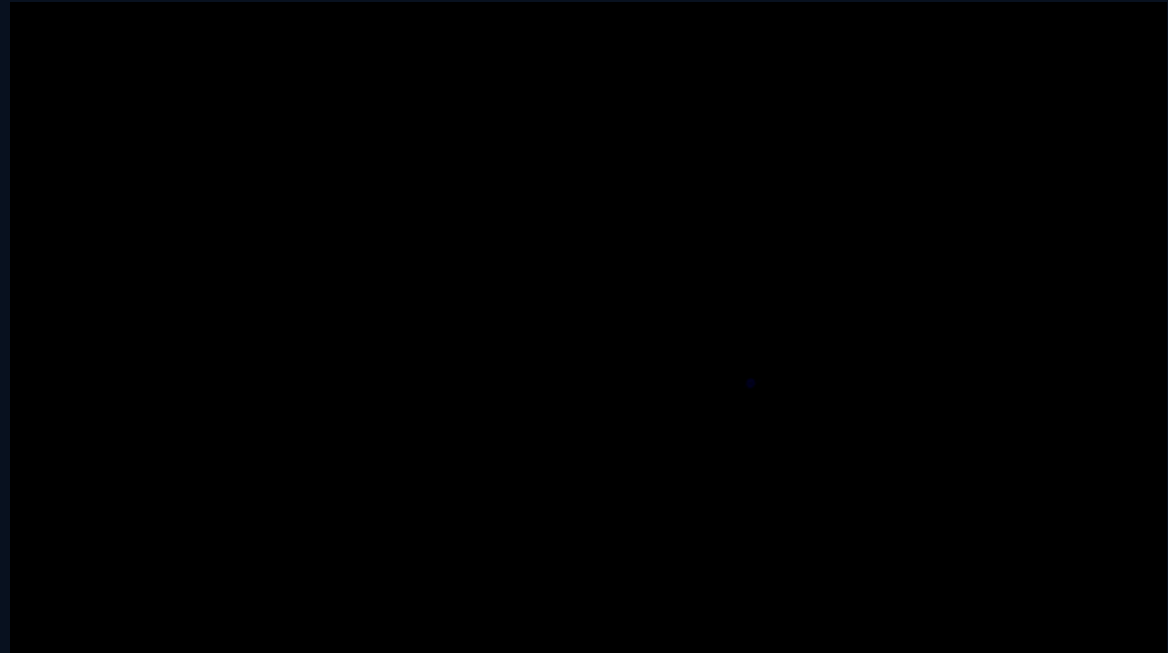
Summary

SGWB

Production Mechanisms

3 production mechanisms FOPT $\rightarrow$ SGWB

1. Bubble wall collisions
2. Compressional waves (*soundwaves*)
3. (M)HD Turbulence



PhysRevD.92.123009

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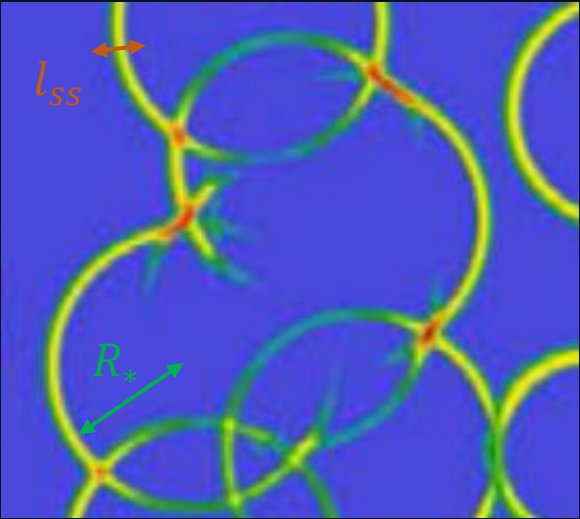
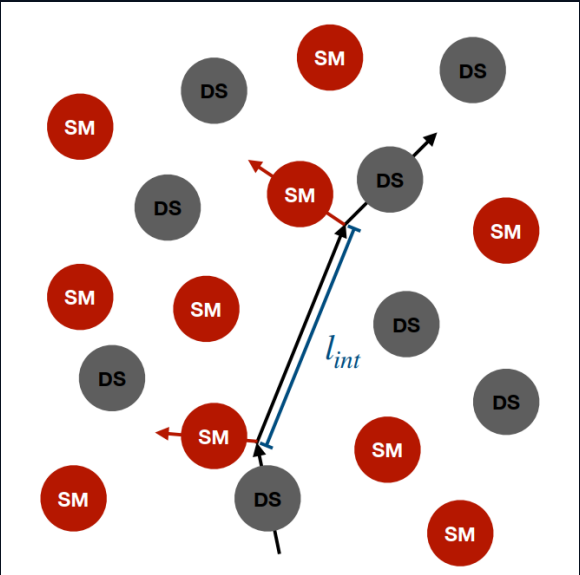
Summary

SGWB

Scales

Scale	Symbol	Value
Interaction	l_{int}	$\tau_{\text{int}} \sim \Gamma_{\text{int}}^{-1} \sim 1/(g^n T)$
Shell Thickness	l_{ss}	$1/m_\phi \sim R_* v_w - c_s /v_w$
Bubble radius	R_*	v_w/β
SW duration	τ_{SW}	$R_*/\sqrt{\Omega_K} \sim O(10)R_*$
Hubble	H_*^{-1}	

- Hard to perform lattice simulations!



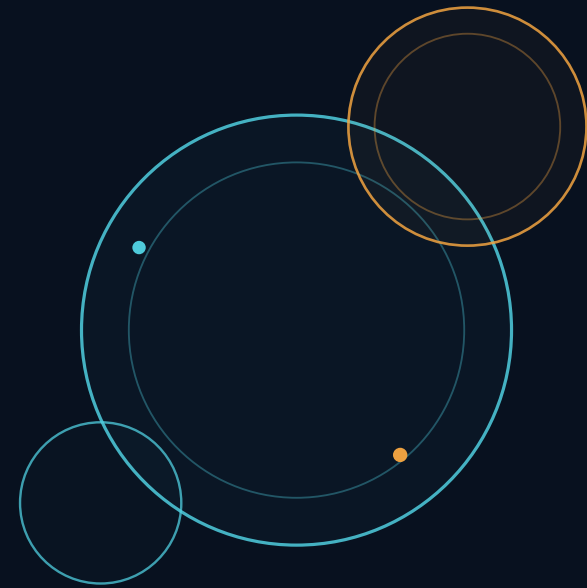
PhysRevD.92.123009

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02

Regimes

- Fully secluded/Fully coupled
- Intermediate → weak coupling



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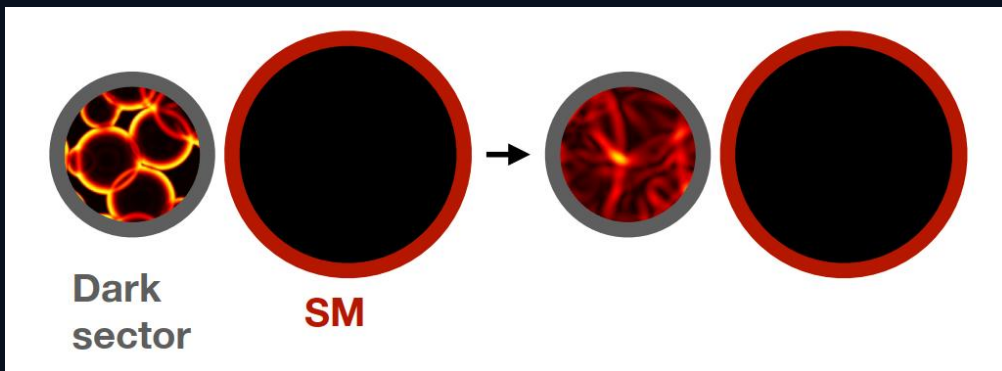
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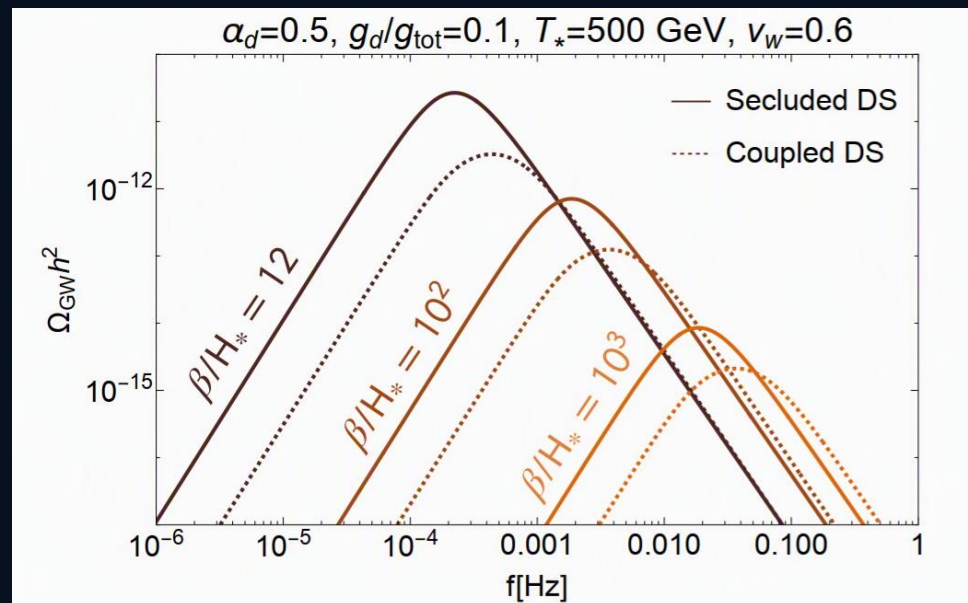
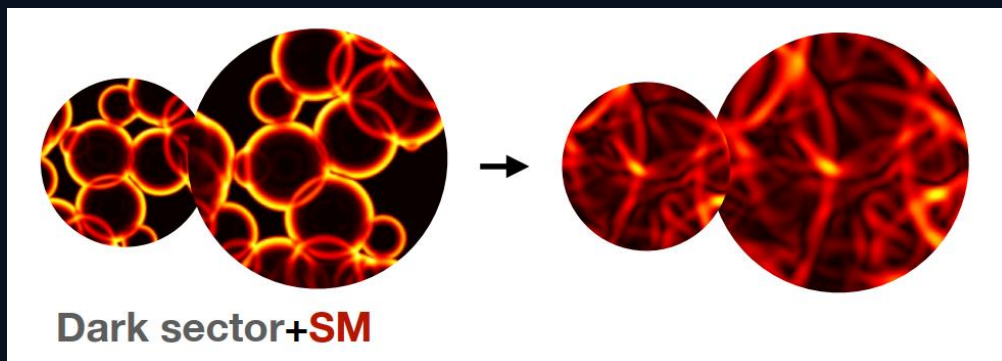
Summary

Fully secluded/coupled Dark Sector

- Fully secluded: $l_{\text{int}} \gg l_{\text{sw}}$



- Fully coupled: $l_{\text{int}} \ll l_{\text{ss}}$



Based on 2409.03651, plotted with CosmoGW

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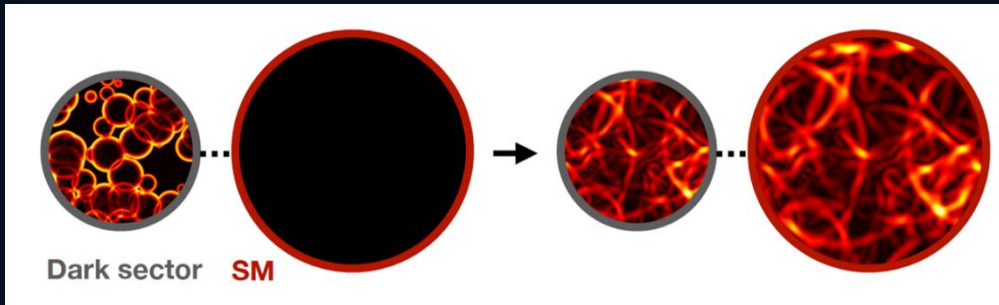
GWs

Summary

Intermediate regime

Weak coupling $\text{DM} \leftrightarrow \text{SM}$

- Weak coupling: $R_* \ll l_{\text{int}} < l_{\text{sw}}$



- Weak coupling yet unexplored
- This regime leaves the bubble expansion unaltered!

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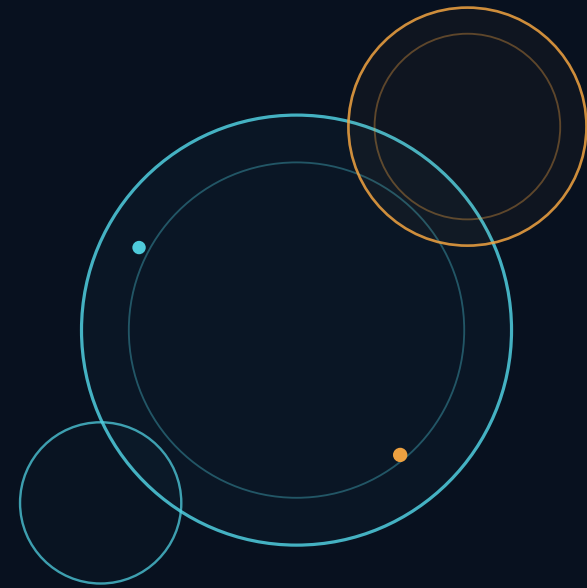
GWs

Summary

03

Hydrodynamics

- EMT Conservation: transport equation
- Linearized wave equations
- Mode evolution



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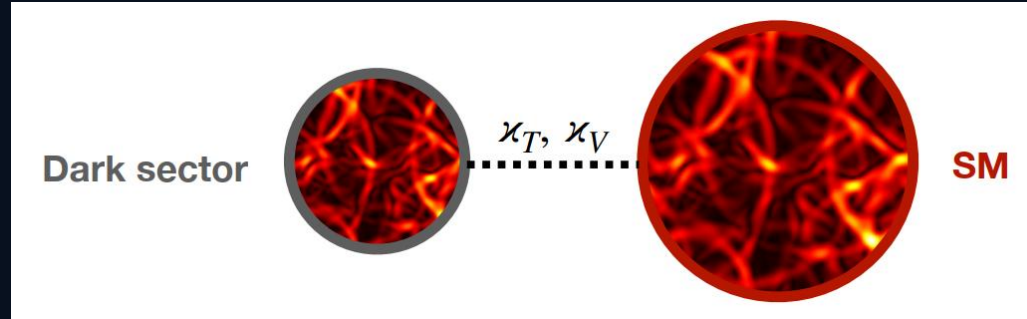
Hydro

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Summary

2-fluid Model

EM Tensor



- Soundwave propagation
- Perfect fluids

$$T_s^{\mu\nu} = w_s u^\mu u^\nu + p_s g^{\mu\nu}, \quad s = \{d, v\}$$

$$\nabla_\mu T^{\mu\nu} = 0 \rightarrow \begin{cases} \nabla_\mu T_d^{\mu\nu} = Q^\nu \\ \nabla_\mu T_v^{\mu\nu} = -Q^\nu \end{cases}$$

- @1st order in near-equilibrium expansion, the transport equation is

$$Q^\nu = \chi_T \frac{\Delta T}{\bar{T}} \bar{u}^\nu + \chi_V \Delta u^\nu$$

$$\Delta \equiv \partial_v - \partial_d$$

- from Lorentz invariance
- $\chi_{T,V}$ are phenomenological parameters
 - model-dependent
 - derivable, in principle, from collision integral

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Linearized wave equations

Wave equations

- Energy density fluctuations

$$\lambda_s \equiv \frac{\delta e_s}{\bar{w}_s}$$

- $\Rightarrow$ 4 equations for v_s and λ_s
 $s \equiv \{d, v\}$

$$\begin{cases} \lambda'_s + \partial_j v_s^j = \frac{(-)^{\delta_{sd}+1}}{3\bar{w}_s} \chi_T(\bar{T}) \Delta \lambda \\ (v_s^i)' + c_s^2 \partial_i \lambda_s = \frac{(-)^{\delta_{sd}+1}}{\bar{w}_s} \chi_T(\bar{T}) \Delta v^i \end{cases}$$

- Solved in Fourier space

Solution

- Undamped *collective* mode

$$V_q(\tau) \equiv \frac{\bar{w}_d}{\bar{w}_v} v_{d,q}(\tau) + v_{v,q}(\tau)$$

$$\Omega_{+,\pm} = \pm i\omega, \quad \omega \equiv c_s k$$

- Decaying *relative* mode

$$U_q(\tau) \equiv v_{d,q}(\tau) - v_{v,q}(\tau)$$

$$\begin{aligned} \Omega_{+,\pm} &= -\Gamma_{\text{int}} \pm \omega \sqrt{-1 + \left(\frac{\delta\Gamma}{\omega}\right)^2} \\ &= \underbrace{-\Gamma_{\text{int}}}_{\text{LO}} \pm i\omega + \mathcal{O}\left(\frac{\delta\Gamma}{\omega}\right)^2 \end{aligned}$$

$$\Gamma_{\text{int}} \equiv \left(\frac{\chi_T}{3} + \chi_V\right) \frac{\bar{w}_d + \bar{w}_v}{2\bar{w}_d \bar{w}_v}$$

$$\delta\Gamma \equiv \left(\frac{\chi_T}{3} - \chi_V\right) \frac{\bar{w}_d + \bar{w}_v}{2\bar{w}_d \bar{w}_v}$$

Modes' evolution

- Initial conditions

$$\begin{pmatrix} v_q \\ \lambda_q \end{pmatrix}_d = \begin{pmatrix} v_{q,0} \\ \lambda_{q,0} \end{pmatrix}, \quad \begin{pmatrix} v_q \\ \lambda_q \end{pmatrix}_v = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

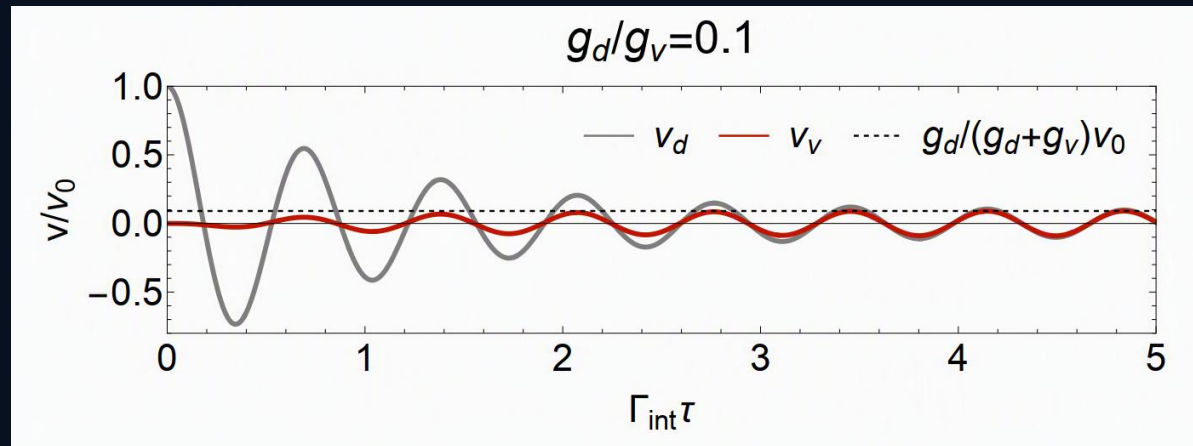
- Fluids approach the same velocity in stationary regime

$$\begin{Bmatrix} v_{d,q}(\tau) \\ v_{v,q}(\tau) \end{Bmatrix} \xrightarrow{\tau \gtrsim l_{int}} \frac{\bar{w}_d}{\bar{w}_d + \bar{w}_v} v_{d,q}^{\text{free}}(\tau)$$

- This leads to suppression of the EMT perturbations

$$\delta T \xrightarrow{\tau \gtrsim l_{int}} \frac{\bar{w}_d}{\bar{w}_d + \bar{w}_v} \delta T_d^{\text{free}}(\tau)$$

- $\Rightarrow$ SWGB too



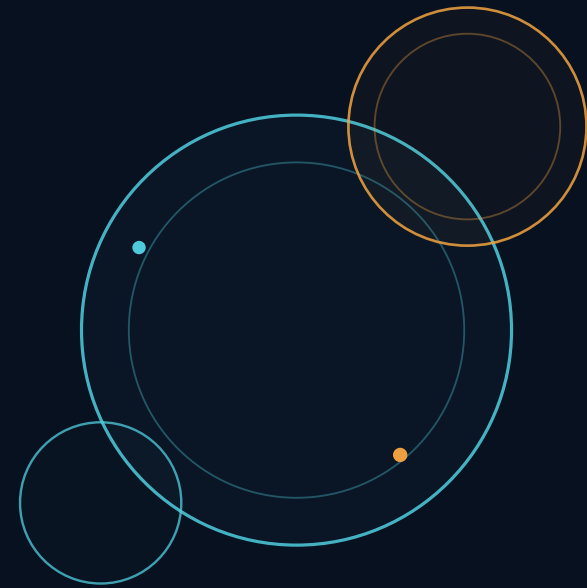
g_s effective number of relativistic d.o.f.

$$\frac{g_d}{g_v} = \frac{w_d}{w_v}$$

04

Gravitational Waves

- Sound Shell Model
- Suppression factor
- Full GW spectrum results



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Sound Shell Model

PhysRevLett.120.071301, JCAP 12 (2019) 062

- Aims to capture the *linear regime* of EMT perturbations
- Ansatz:
Self-similar fluid shells around the bubbles persist long after the transition completed (aka, in the true vacuum phase)
- 2-point correlation function of the velocity field given by superposition of randomly-placed fluid shells
where the size distribution is given by the nucleation rate

$$F(\tau) \equiv \frac{\bar{w}_d}{\bar{w}_d + \bar{w}_v} \left(1 + \frac{\bar{w}_v}{\bar{w}_d} e^{-2\Gamma_{int}(\tau - \tau_*)} \right)$$

$$\begin{aligned} \Omega_{\text{GW}}(k) &\approx 3k \underbrace{\mathcal{T}_{\text{GW}}}_{\text{redshift}} \int_{\tau_*}^{\tau_{fin}} \frac{d\tau_1}{\tau_1} \int_{\tau_*}^{\tau_{fin}} \frac{d\tau_2}{\tau_2} E_{\Pi}(\tau_1, \tau_2, k) \cos[k(\tau_0 - \tau_1)] \cos[k(\tau_0 - \tau_2)] F(\tau_1) F(\tau_2) \\ &= 3 \frac{\bar{w}_d^2}{\bar{\rho}^2} k^3 \mathcal{T}_{\text{GW}} \int_{-1}^1 dz (1 - z^2)^2 \int_0^\infty dp \frac{p^2}{\tilde{p}^4} E_{kin}(p) E_{kin}(\tilde{p}) \Delta(\tau_{sw}, k, p, \tilde{p}) \end{aligned}$$

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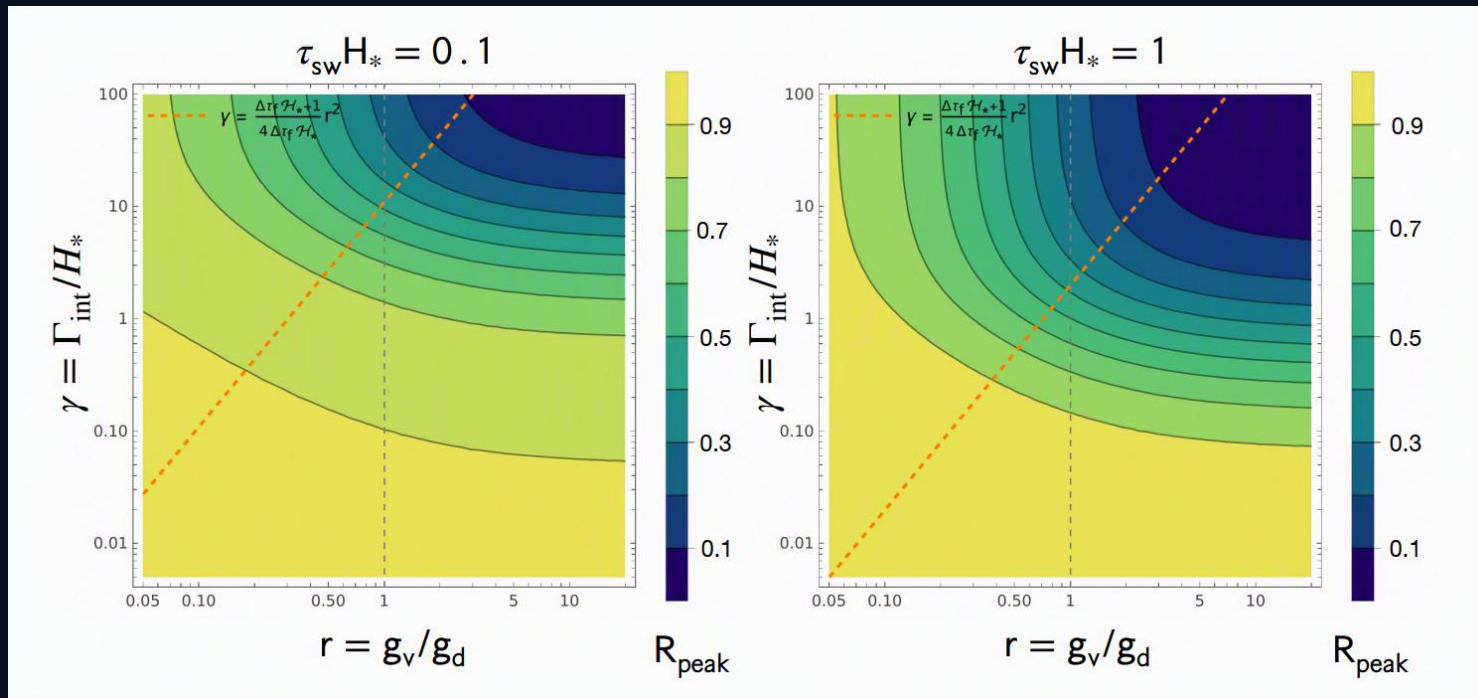
GWs

Summary

Suppression factor

- For $k\tau_{sw} \gg 1$, we obtain an overall suppression factor

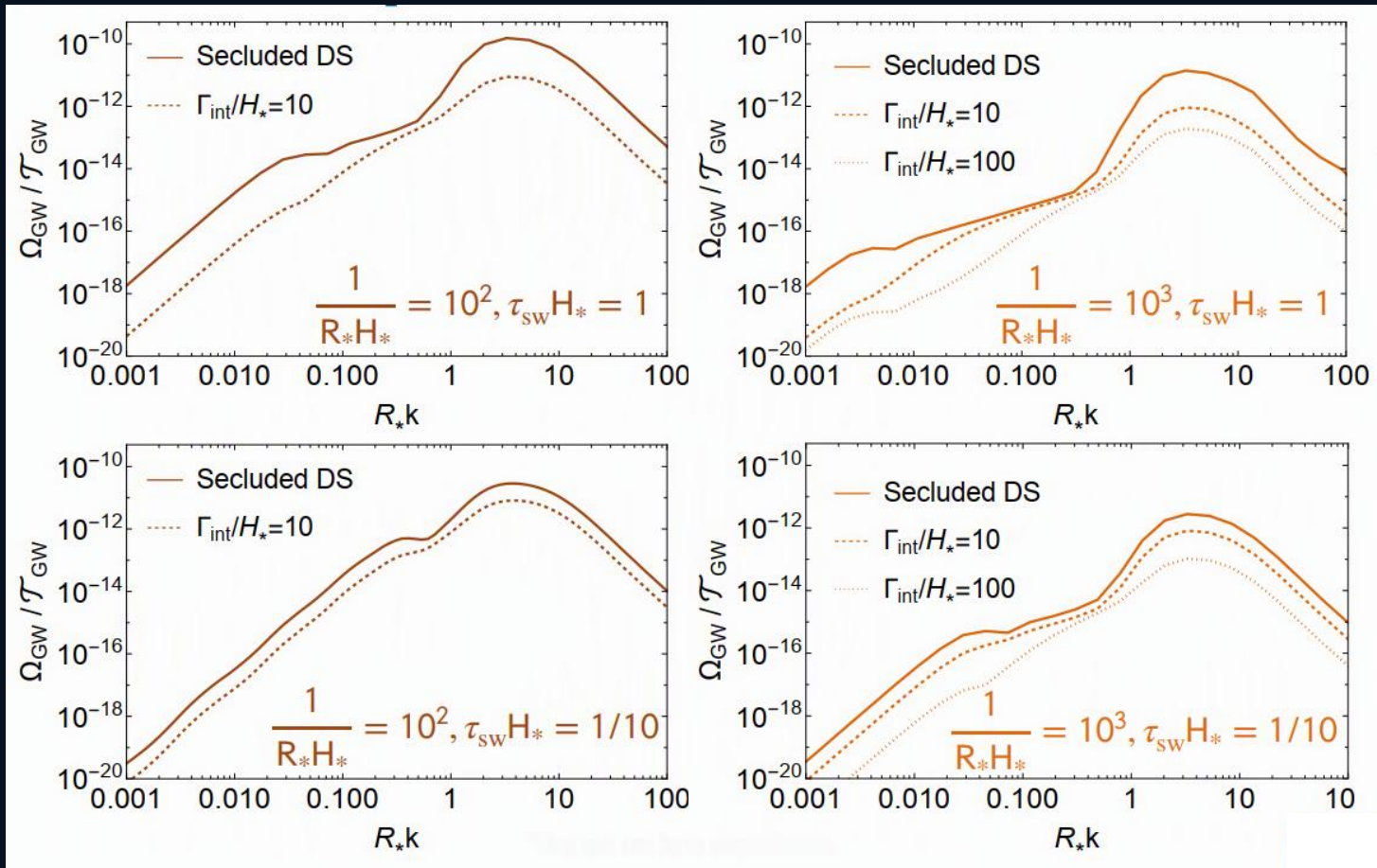
$$R \equiv \frac{\Upsilon^{2f}}{\Upsilon} = \frac{\int_{\tau_*}^{\tau_{fin}} \frac{d\tau}{\tau^2} F(\tau)^2}{\int_{\tau_*}^{\tau_{fin}} \frac{d\tau}{\tau^2}}$$



SGWB

Results

- LO GW spectra for varying R_* and τ_{sw}



$$\alpha = 0.1$$

$$\frac{g_d}{g_v} = 0.1$$

$$v_w = 0.9$$

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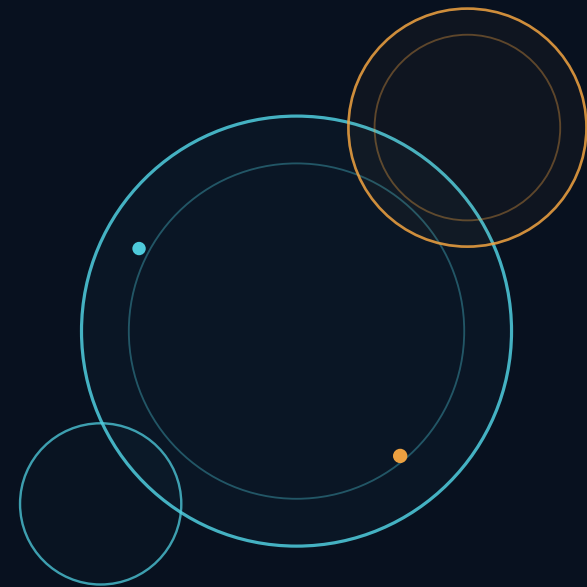
GWs

Summary

Summary

- SGWB signals from a dark sector with a weak coupling to the visible sector are suppressed!
- Besides the suppression, the SGWB spectral shape may vary at low and intermediate momenta $k\tau_{sw} \lesssim 1$, depending on the parameters
- Further directions
 - Computing Γ_{int} in specific PP models
 - Is the source duration $\tau_{sw} \sim \tau_{nl}$ affected by the coupling?
 - For stronger interactions, how is bubble dynamics affected?
 - What if soundwaves do not propagate in a relativistic plasma?

Looking forward to your feedback!



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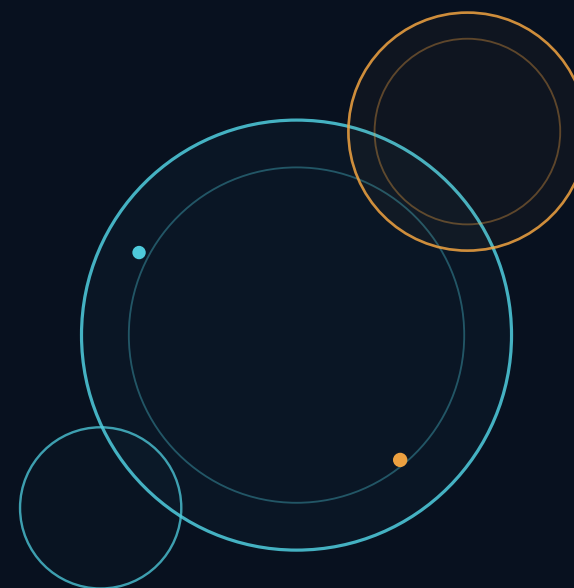
GWs

Summary

05

Extra

- 1st-order phase transitions (FOPTs)
- Stochastic Gravitational Wave Backgrounds
- Phase transitions in a dark sector



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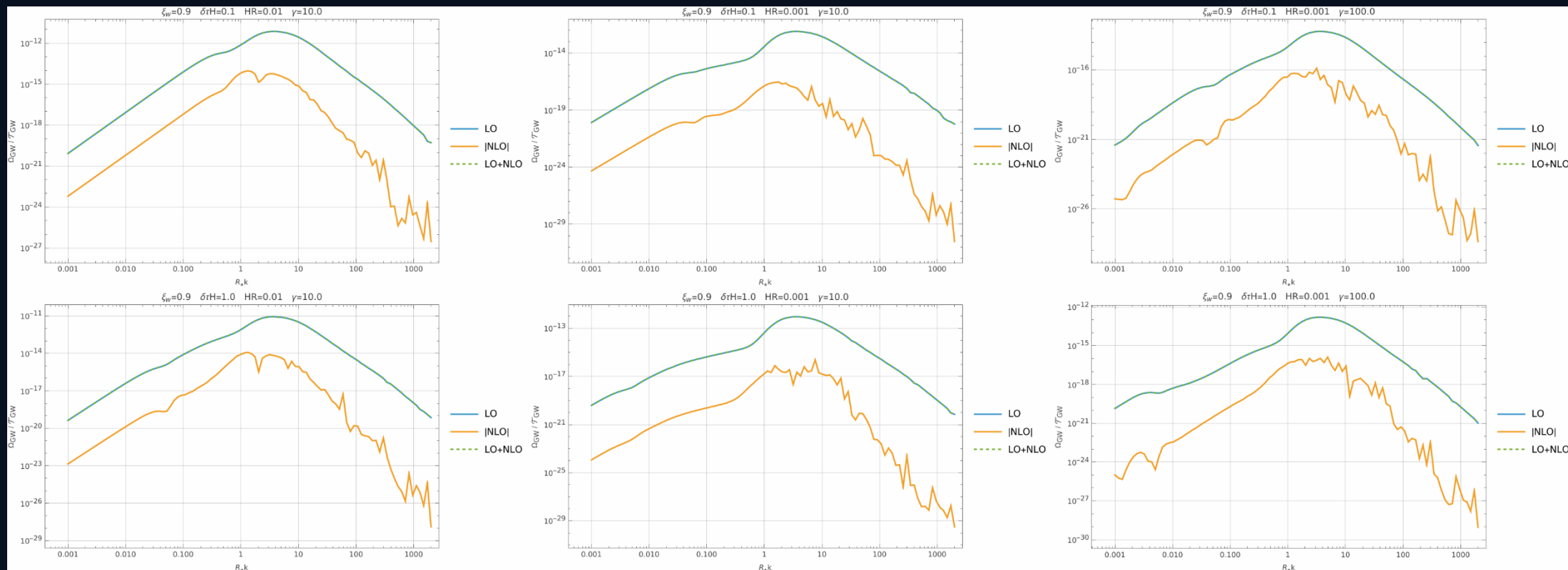
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Summary

NLO Corrections

Amplitude



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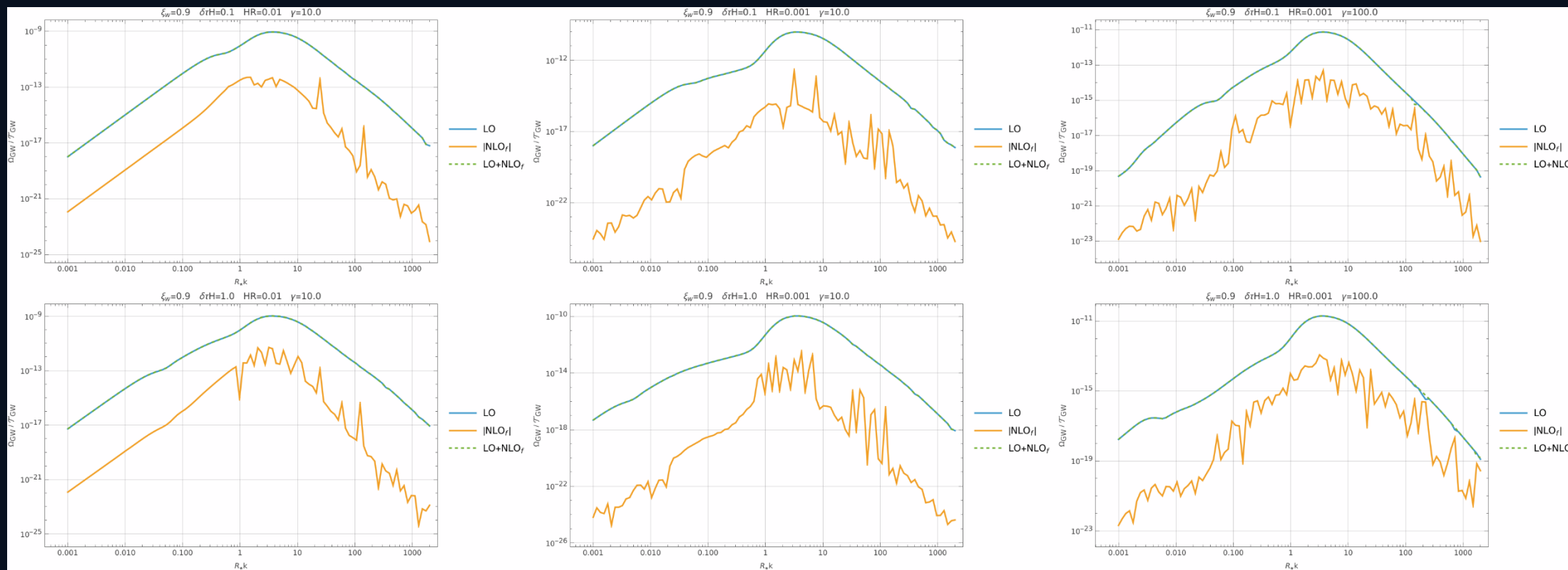
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