

Gravitational wave signals from area metric gravity

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Outline

- a) Area metrics
- b) Modified Plebanski Gravity
- c) Area metric gravity dynamics
- d) Gravitational wave signals

Area vs Length metric

[Schuller et al 05+: Area metrics]

Length metric $g_{\mu\nu}$:

- Measuring length of tangent vectors and angles between vectors
- **10 independent components**

Area metric $A_{\mu\nu\rho\sigma}$:

- Measuring areas of parallelograms and angles between parallelograms
- require cyclicity (as for Riemann tensor): $A_{[\mu\nu\rho\sigma]} = 0$ (for mathematical and physical reasons)
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Each length metric induces a (cyclic) area metric:

$$A_{\mu\nu\rho\sigma} = g_{\mu\rho}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\rho}$$

Area metric configuration space (quantum) extends length configuration space.



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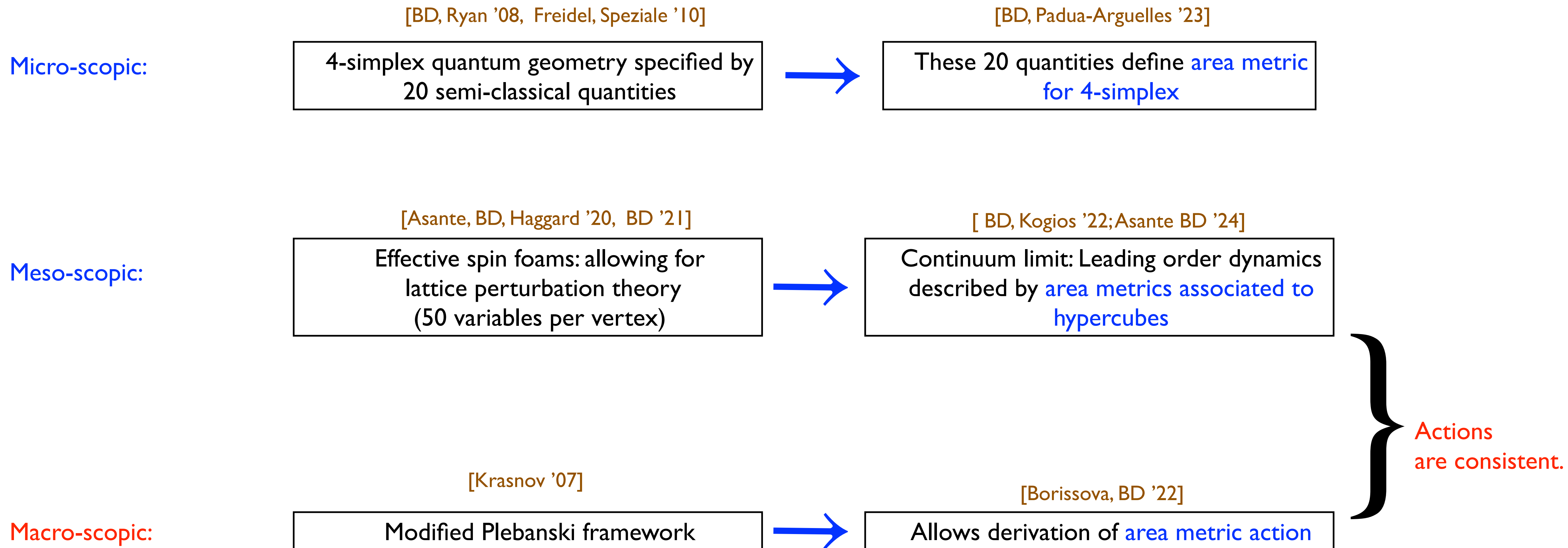
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Area metrics have been motivated from **Loops/Spin foams** [Borissova, BD, Kogios, Padua-Arguelles],
Strings [Schuller et al] and **AdS/CFT** [Bhattacharya et al '25].



Area metrics from spin foams: three different ways



Plebanski action for Gravity

- Quantizing non-trivial phase spaces is often “simpler” if one embeds it into a larger phase space and then constrains back to the original one.
- Example: replace length metric with triads (3D) or tetrads (4D).
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BF action: “easy part”

Can be quantized exactly.

Same structure as spin foams.

Discretization independent.

Defines a topological field theory.

No gravitons.

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 Can be quantized exactly.
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 No gravitons.
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Simplicity constraints - very involved.
 Need to be imposed to regain GR.
 But a quantum anomaly appears:
 cannot be imposed sharply.
 Are imposed ‘weakly’ in spin foams.

A simple two form:
 $B = \star e \wedge e$

$$\hat{B}^{ij} \sim \epsilon^{ijk} J_k$$

Angular momentum operators
 do not commute

Effective continuum dynamics for spin foams

Can one derive an area metric action directly in the continuum?

- Spin foams derived from quantization of Plebanski action:
but part of the constraints only implemented weakly
- Modified Plebanski actions: replace constraints by mass terms for constrained dof's
- Chiral version: leads to (“deformed version of”) GR
- Non-chiral version (used in spin foams): leads to bi-metric theory of gravity

[Kransov 08+]

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[Borissova, BD 2022:]

- To mimic split of simplicity constraints into sharply and weakly imposed sets, replace only weakly imposed constraints by potential terms
- Leads to an action in terms of area metrics
- Integrate out non-length metric degrees of freedom:

$${}^{(2)}\mathcal{L}(h) = {}^{(2)}\mathcal{L}_{EH}(h) - {}^{(1)}C_{\mu\nu\rho\sigma}(h) \frac{1}{p^2 + M^2} {}^{(1)}C^{\mu\nu\rho\sigma}(h)$$

Consistent with continuum limit of effective spin foams!

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Found a very special class of modified gravity theories from spin foams: no additional poles.

General linearized area metric actions

[Borissova, BD, Krasnov 2023]

Deriving area metric actions from scratch.

Linearized area metric perturbations:

$$a_{\mu\nu\rho\sigma} \rightarrow h_{\mu\nu}, \chi_{\mu\nu}^{\pm} \quad (\chi_{\mu\nu}^{\pm} = p^{-2} \mathbb{P}_{\mu\nu\rho\sigma}^{\pm ab} p^{-2} p^{\rho} p^{\sigma} \chi_{ab} \quad : 5+5 \text{ spin-2 degrees of freedom})$$

Most general diff-invariant Lagrangian:

$$\mathcal{L}_{\text{diff}} = \mathcal{L}_{EH} + \sum_{\pm} \frac{\alpha_{\pm}}{2} h_{\mu\nu} \chi^{\pm\mu\nu} p^2 + \frac{p^2 + M_{\pm}^2}{4} \chi_{\mu\nu}^{\pm} \chi^{\pm\mu\nu}$$

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Special case arising from modified Plebanski:

$$\alpha_+^2 + \alpha_-^2 = 2, \quad M_+ = M_- = M$$

Additional 5-parameter
shift symmetry for kinematical terms.

Remaining coupling is the Barbero-Immirzi-parameter:
parametrizes parity violating terms

$$\alpha_+ - \alpha_- \sim 1/\gamma$$

Do effect equations of motion!

**Different from length metric gravity
with no higher order derivatives.**

LQG: Barbero-Immirzi parameter is small. Can we measure it?

Renormalization flow for area metric actions

[Borissova, BD, Eichhorn, Schiffer 2025]

- First study of functional renormalization flow for area metric theories; development of general set-up provided
- How do additional area metric degrees of freedom (aka shape mismatching dof) behave under renormalization?
- What happens to their masses? What happens to length - shape-mismatching couplings?
- Flow of parity violating couplings?
- Truncate to four third order terms which couple length and shape-mismatching degrees of freedom

Results:

- Masses for shape-mismatching degrees of freedom can be generated and grow towards IR (good)
- At least one of the couplings remains relevant (might be good, but dangerous)
- Parity symmetry is not emergent (and thus needs to be controlled)

How dangerous are parity violating terms?

Gravitational waves in area metric dynamics

$$\mathcal{L}_{\text{diff}} = \mathcal{L}_{EH} + \sum_{\pm} \frac{\alpha_{\pm}}{2} h_{\mu\nu} \chi^{\pm\mu\nu} p^2 + \frac{p^2 + m^2}{4} \chi_{\mu\nu}^{\pm} \chi^{\pm\mu\nu}$$

[BD 2026]

equations of motion:

$$\square h_{ab} = \frac{1}{2} \sum_{\pm} \alpha_{\pm} (\mathcal{D}^{\mp} \chi^{\pm})_{ab}.$$

$$(\square - m^2) \chi_{ab}^{\pm} = \alpha_{\pm} (\mathcal{D}^{\pm} h)_{ab}.$$

chiral wave operators

$$\mathcal{D}^{\pm} \equiv \partial_0^2 + \nabla^2 \pm 2i \mathcal{C} \partial_0.$$

tensor curl

$$(\mathcal{C} X)_{ab} \equiv \epsilon_a{}^{cd} \partial_c X_{db}$$

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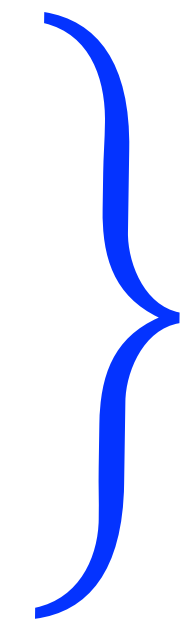
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Imply:

$$\square h_{ab} = 0.$$

If: $\alpha_+^2 + \alpha_-^2 = 2$

Gravitational wave propagates as in (linearized) GR!

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But a gravitational waves drags along a χ field:

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$$(\chi_1^+, \chi_2^+, \chi_1^{\times}, \chi_2^{\times}) = 2 \frac{k^2}{m^2} h^+ \left(\Re \alpha_+, \Im \alpha_+, \Im \alpha_+, -\Re \alpha_+ \right)$$

Note the $1/m^2$ - suppressed by Planck mass squared.

Could there be an observational signature?

Observational signature?

[BD 2026]

Electro-magnetic fields couple naturally to the area metric!

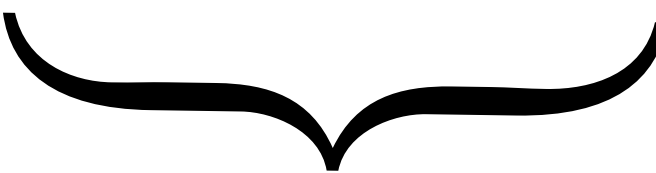
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Eigen-indices k_γ/ω_γ

$$n_\pm = 1 + \frac{1}{2} h_{\hat{k}_\gamma \hat{k}_\gamma} \pm |\chi_{--}^+|$$


Lead to birefringence

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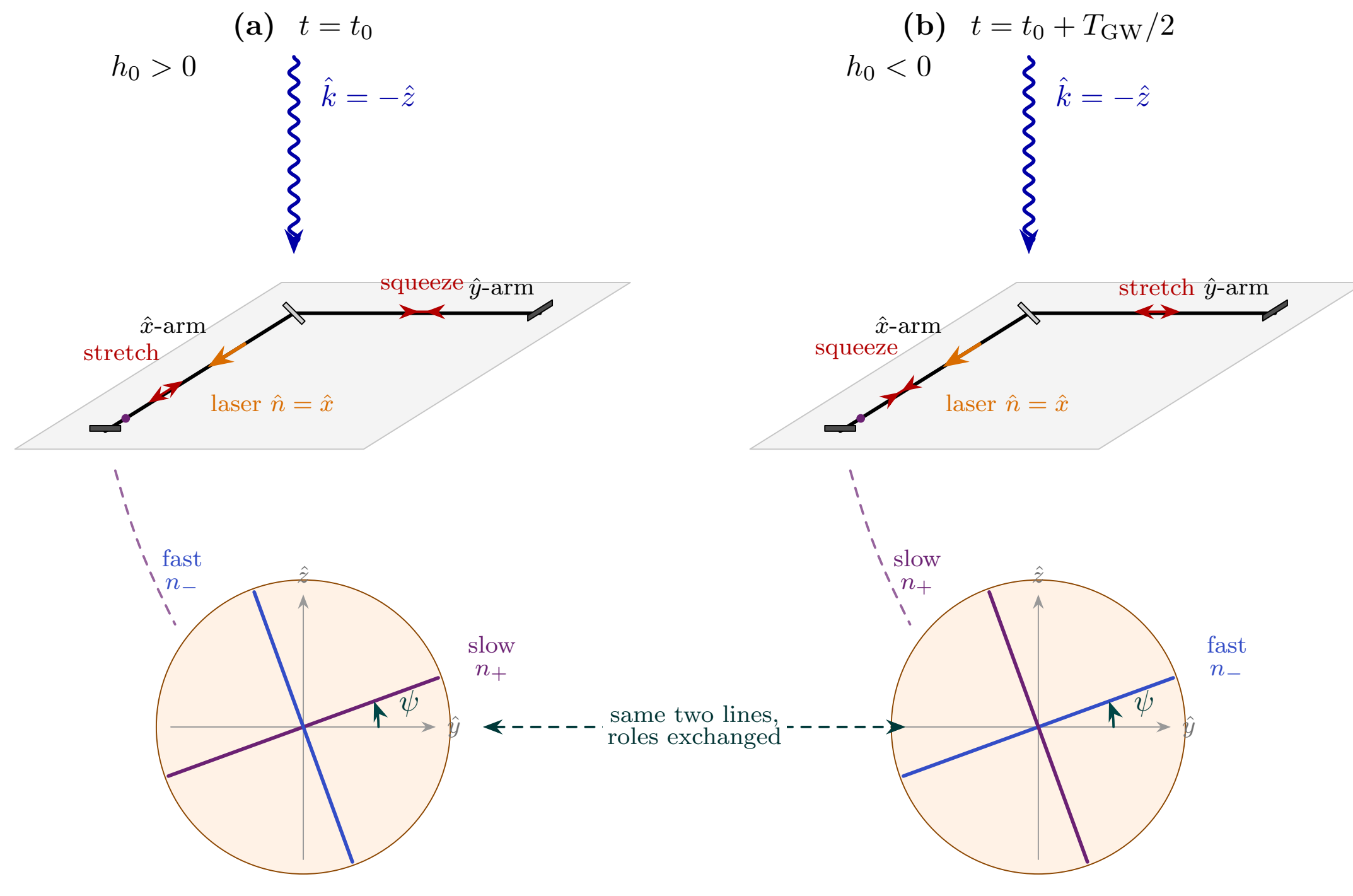
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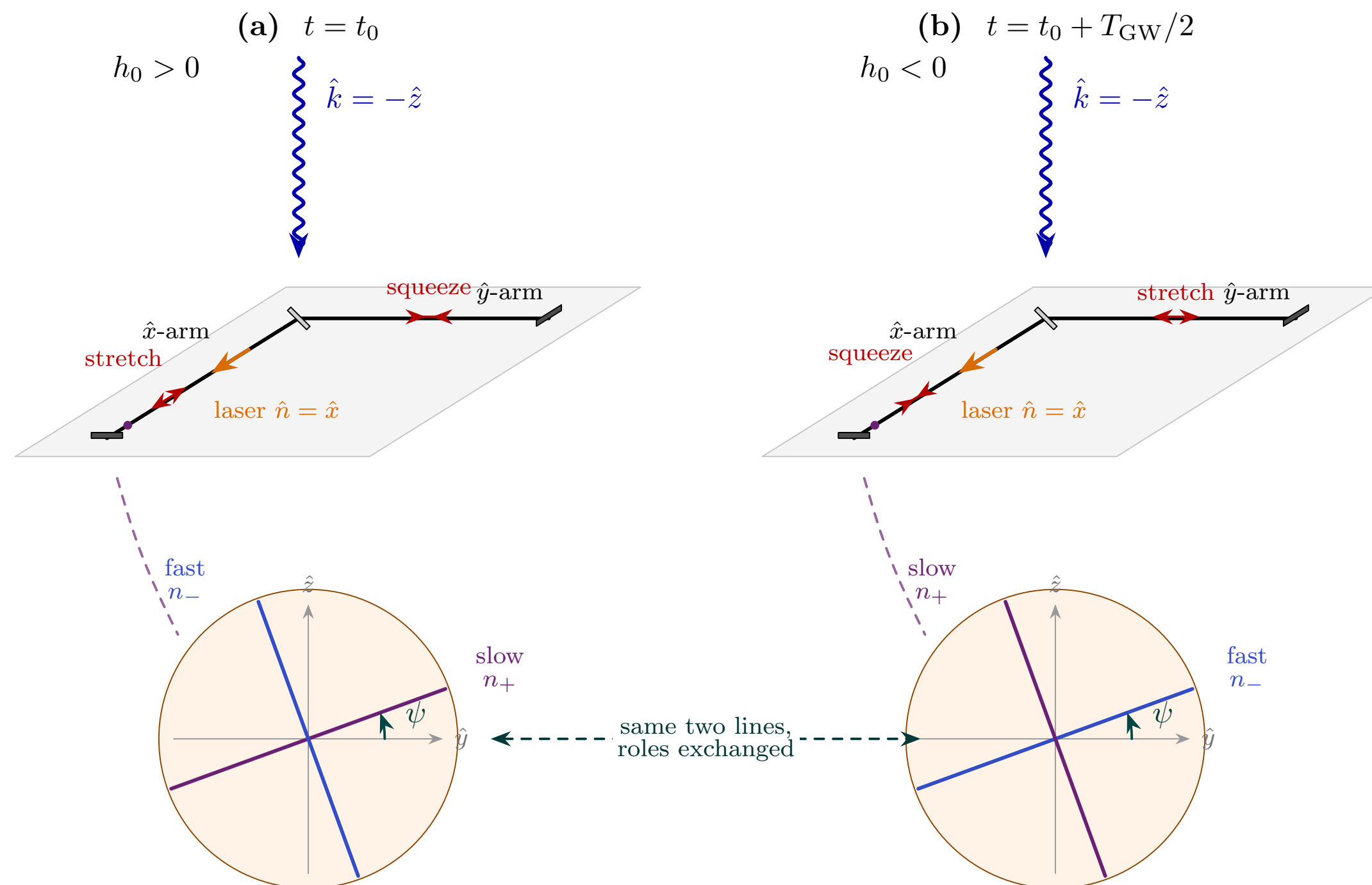
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$$\Delta\phi_{\text{pol}}/\Delta\phi_{\text{strain}} = 2\sqrt{\cosh 2\xi} (\omega_{\text{gw}}/m)^2 \sim 10^{-81}$$

for 100 Hz waves
 $m = \text{Planck mass}$

Very unlikely to lead to any observational constraints on Barbero-Immirzi parameter (if masses are Planck).

Massive χ waves would produce detectable birefringence signal if very light (need adjust arm length).
 Similar to axion dark matter searches.



Summary

- A number of approaches suggest a quantum extension of the configuration space: area instead of length metrics.
- Area metric gravity includes parity violating terms, parametrized by the illusive Barbero-Immirzi parameter.
- The modified Plebanski deformation of general relativity is surprisingly mild: no extra poles/ ghosts as generically happens in modified gravity.
- Gravitational waves propagate as in (linearized) GR, but drag area metric wave along.
- Leads to electro-magnetic birefringence, but amplitude is extremely weak if we assume additional area degrees of freedom are Planck mass suppressed.
- Outlook: cosmological backgrounds, non-linear action, black hole solutions.
- Results could (drastically) change for parity violating area metric background.



Thank you!