Investigating Massive Gravity Using The European Pulsar Timing Array Dataset

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Outline

1. PTAs and Gravitational Waves
2. The Overlap Reduction Function
3. Ghost-Free Massive Gravity
4. ORF in Massive Gravity
5. Mode Suppression
6. Analysis Pipeline
7. Current

PTAs and Gravitational Waves

PTAs and Gravitational Waves

- Pulsar period changes when a gravitational wave (GW) passes through

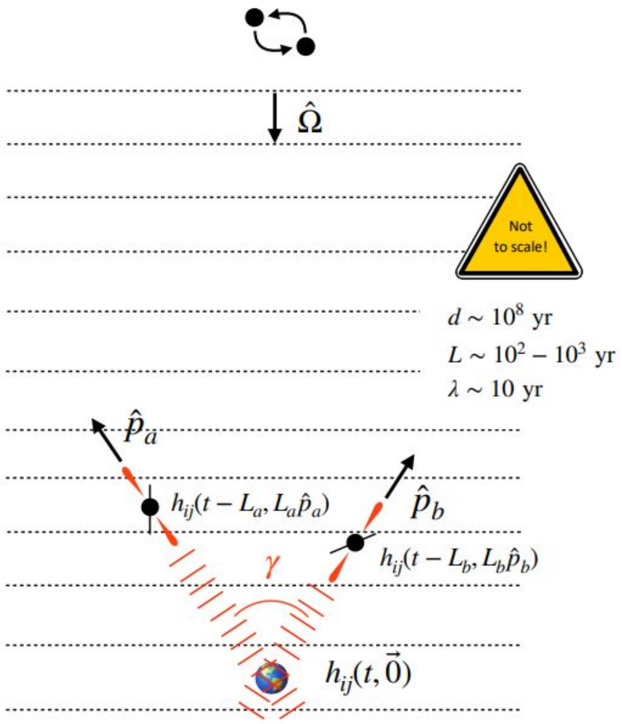

Figure 8 from Romano+24

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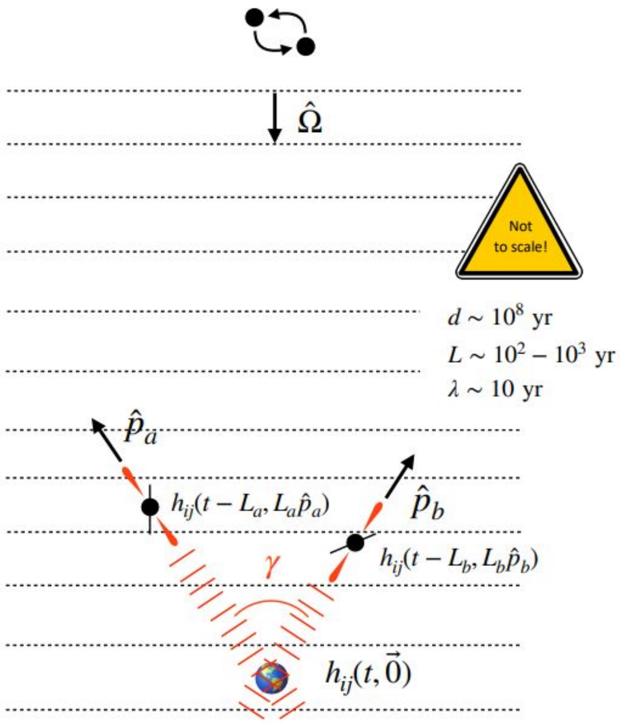

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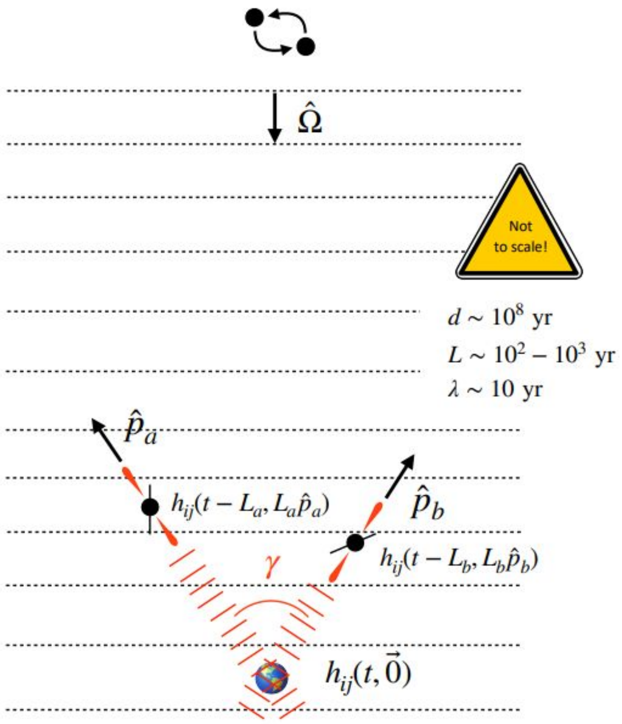
- GW cause a time-dependent redshift in the signal measured, $z(t)$, cross-correlated between pulsars (Sazhin 1978)

- Observable: residual defined by

$$R_a(t) = \int_0^t dt' z_a(t')$$



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The Overlap Reduction Function

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- We take the two-point correlation function of sky-averaged redshifts…

$$\langle \tilde{z}_a(f) \tilde{z}_b^*(f') \rangle \propto \delta(f - f') \Omega_{GW}(f) \Gamma_{ab}(\xi, f)$$

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- For an isotropic, stochastic background the overlap reduction function (ORF) is…

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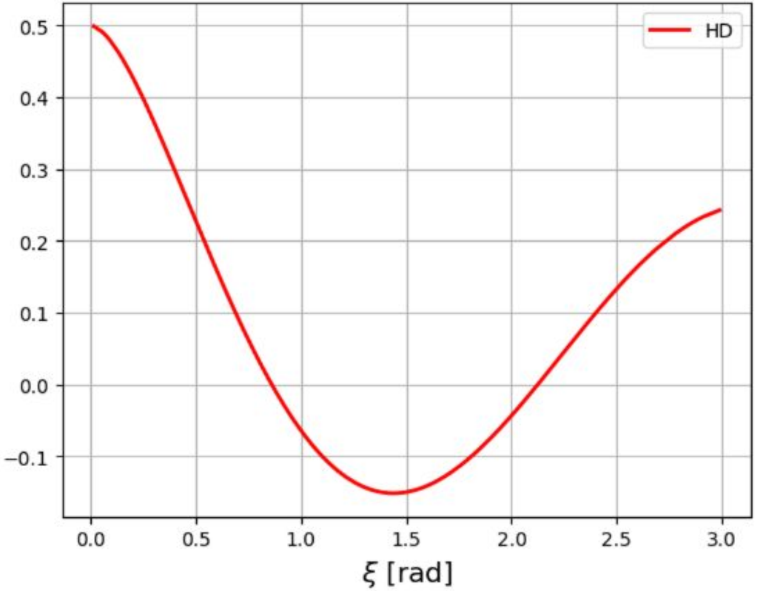

Ghost-Free Massive Gravity

Choi+25

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- Consider stationary, isotropic, stochastic GW background
- Modified dispersion relation…

$$\omega^2 = k_0^2 = |\mathbf{k}|^2 + m^2$$

- Group velocity…

$$A \equiv \frac{k_0}{|\mathbf{k}|} = \sqrt{1 - \left(\frac{m}{2\pi f}\right)^2}$$

Choi+25

ORF in Massive Gravity

Choi+25, Liang+21

ORF in Massive Gravity

- Back to the two-point correlation of sky-integrated redshifts…

$$\langle \tilde{z}_a(f)\tilde{z}_b^*(f')\rangle \propto \delta(f - f')|f|^{-3} \sum_{I\in\{T,V,S\}} \sum_{i\in I} \Omega_i(f)\Gamma_{ab,i}(\xi, |f|)$$

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- Mode decomposition…

$$\langle \tilde{z}_a(f)\tilde{z}_b^*(f')\rangle \propto \left(\frac{\Omega_T}{\beta_T}\Gamma_{ab,T}+\frac{\Omega_V}{\beta_V}\Gamma_{ab,V}+\frac{\Omega_S}{\beta_S}\Gamma_{ab,S}\right)$$

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- An effective ORF…

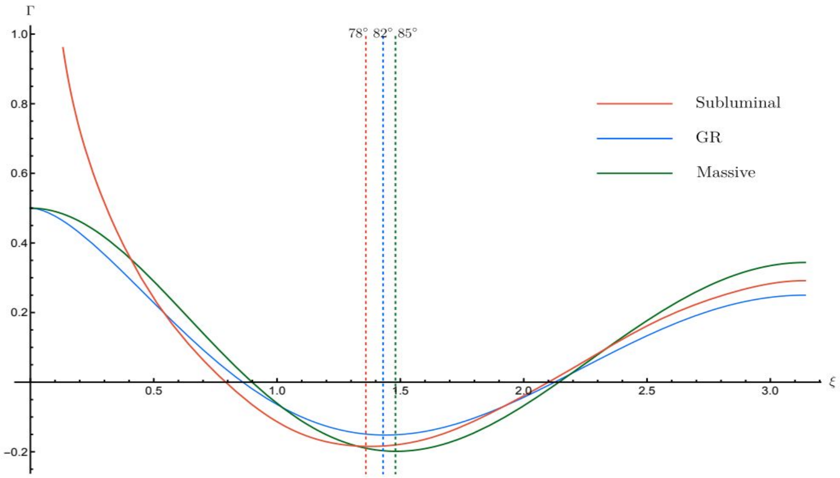
$$\Gamma_{ab}^{\text{eff}} = \beta\left(\Gamma_{ab,T} + \Gamma_{ab,V}\frac{\Omega_V}{\Omega_T} + \Gamma_{ab,S}\frac{\Omega_S}{\Omega_T}\right)$$

Choi+25, Liang+21

ORFs: Graphical Representation

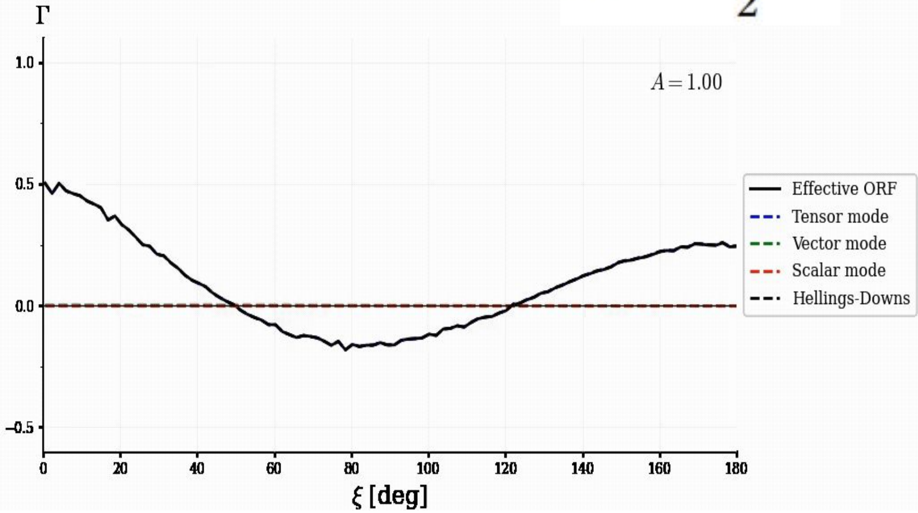
MG: $\Gamma_{ab}^{\text{eff}} = \beta\left(\Gamma_{ab,T} + \Gamma_{ab,V}\frac{\Omega_V}{\Omega_T} + \Gamma_{ab,S}\frac{\Omega_S}{\Omega_T}\right)$ GR: $\Gamma_{ab}(\xi) = \frac{3}{2}x\ln x - \frac{1}{2}x + \frac{1}{2},$

$$x = \frac{1-\cos\xi}{2}$$



Massive Gravity and GR Comparison

Figure 1 from Liang+23



Variation in $A = \frac{|\mathbf{k}|}{k_0} = \sqrt{1 - \left(\frac{m}{2\pi f}\right)^2}$

Vector and Scalar Mode Suppression

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- Expect vector and scalar modes to be suppressed in the massless (GR) limit $$\Gamma_{ab}^{\text{eff}} = \beta\left(\Gamma_{ab,T} + \Gamma_{ab,V}\frac{\Omega_V}{\Omega_T} + \Gamma_{ab,S}\frac{\Omega_S}{\Omega_T}\right)$$

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Free parameters in our model (we test for several values)

Analysis Pipeline

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TOAs, white noise, red noise, DM, chromatic

Dataset (EPTA DR2)

- TOAs: time of signal arrival (compared relative to modelled arrival), yields residual
- Both cross-correlated (red) and un-correlated (white) noise sources

Analysis Pipeline

TOAs, white noise, red noise, DM, chromatic

GR (Hellings-Downs) or MG

Dataset (EPTA DR2)

Enterprise package

- Calculate covariance of common SGWB process from the ORF and power spectrum
- Combine with other covariances (white, red, DM, chromatic) in Enterprise

Analysis Pipeline

TOAs, white noise, red noise, DM, chromatic → GR (Hellings-Downs) or MG → A_{GW}, γ_{GW}, Bayes factor

Dataset (EPTA DR2)

Enterprise package

Bayesian analysis

- A_{GW} and γ_{GW} are parameters in the power spectrum, and a good indicator of physicality of model
- Bayes factor indicates model preference (GR or MG)

Analysis Pipeline

TOAs, white noise, red noise, DM, chromatic

GR (Hellings-Downs) or MG

A_{GW}, γ_{GW}, Bayes factor

Dataset (EPTA DR2)

Enterprise package

Bayesian analysis

Repeat for several values of m and n_s, calculating the Bayes factor each and ensuring model convergence via a Gelman-Rubin diagnostic

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- GR model alone replicates posteriors of past EPTA papers that show a preference for a SGWB (Antoniadis+ 23)

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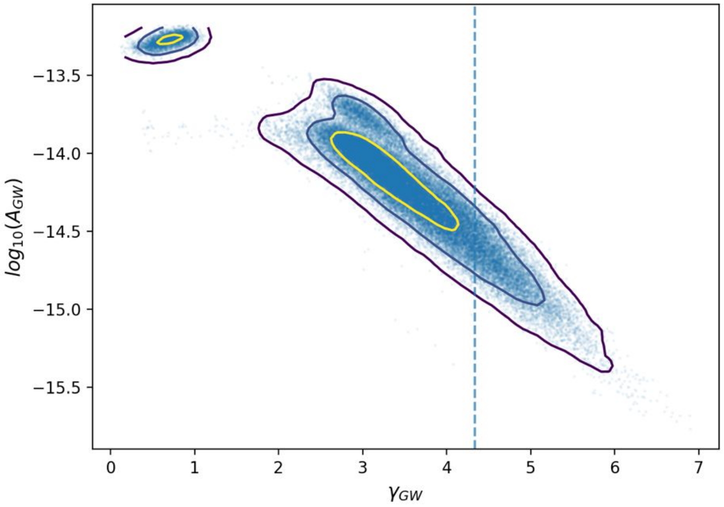

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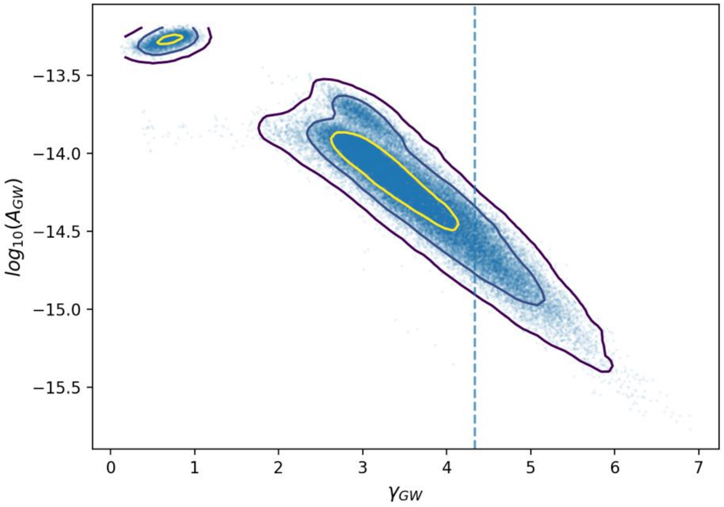

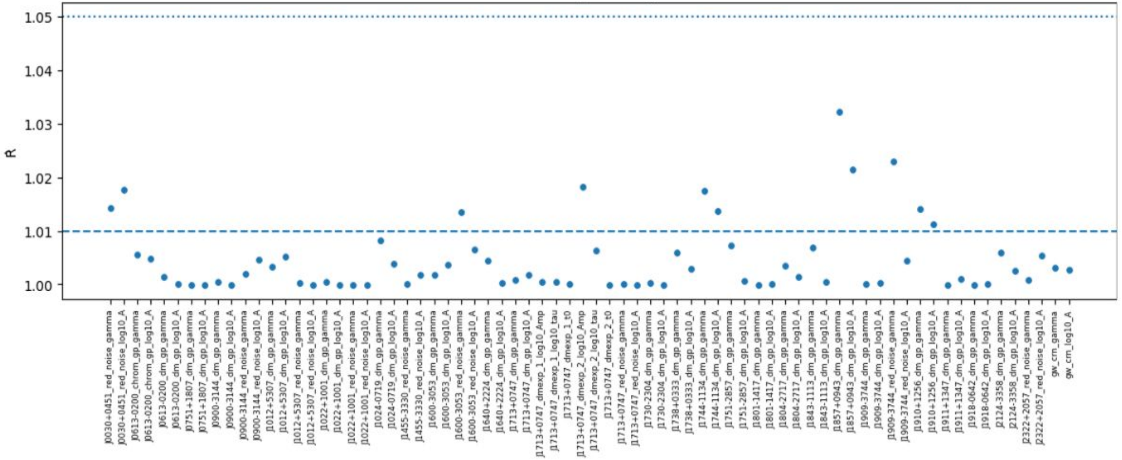

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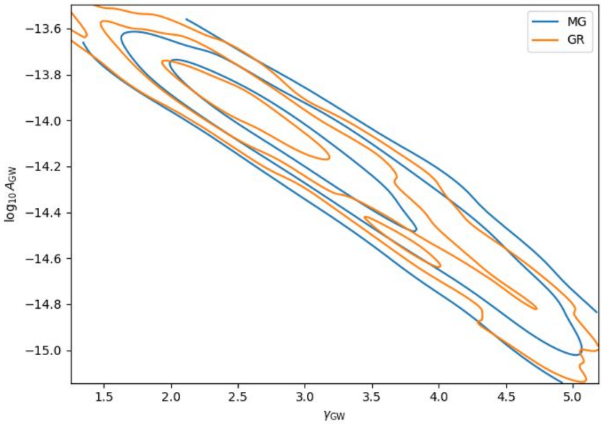

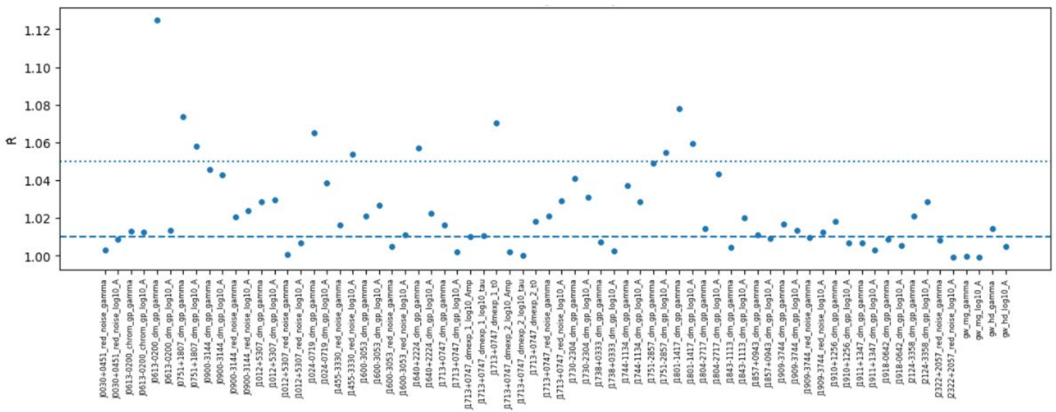

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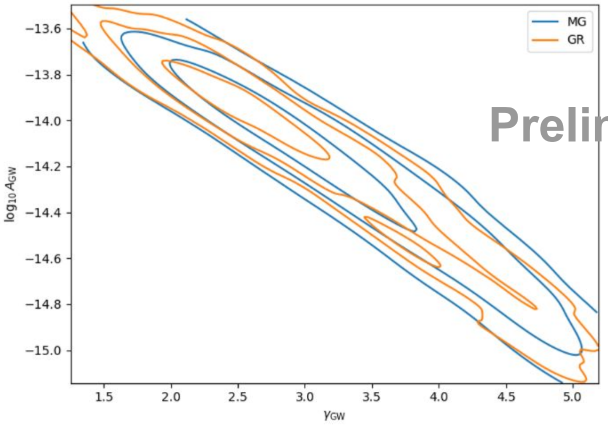
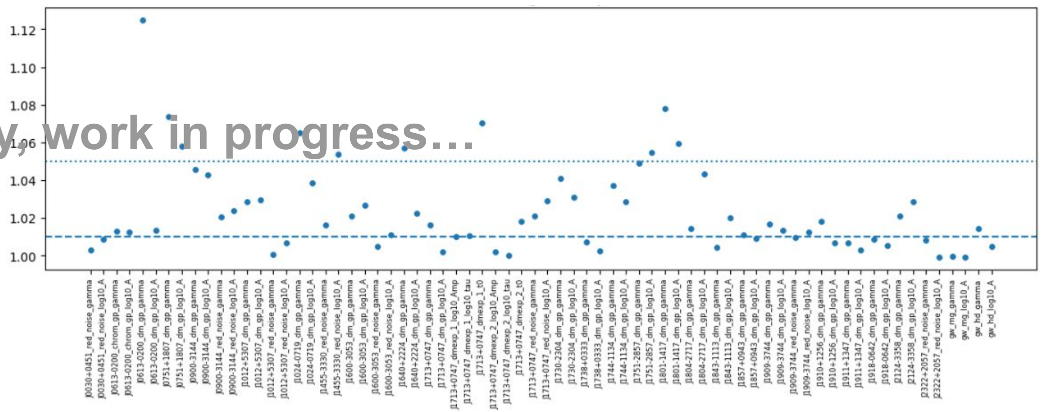


Preliminary, work in progress…



Conclusion and Next Steps

- PTA datasets offer an exciting way to probe alternate theories of gravity (like MG)
- ORFs of angular correlation are a useful tool to analyze these datasets; MG case has additional free parameters of mass and suppression coefficients
- Numerical methods can be unstable and computationally intensive; ongoing work is being done to converge MCMC and probe parameter space

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- We acknowledge support from the following grants: Shota Rustaveli NSF of Georgia FR-24-901; the NSF Astronomy and Astrophysics Research Grants (AAG) AST2307698 and AST2408411; NASA Astrophysics Theory Program (ATP) 80NSSC22K0825
- M.B. thanks Tina Kahniashvili, Chris Choi, Alberto Roper Pol, and Hippolyte Quelquejay-Leclere for their invaluable discussions and support
- M.B. appreciates and acknowledges the benefactors of the Carnegie Mellon University HURAY Fellowship for their financial support

- Thank you all for your attention!

Backup: Overlap Reduction Function in Massive Gravity

- Theoretical form of redshift for ghost-free MG…

$$z_a(f,\hat{\mathbf{\Omega}}) = \sum_{I\in\{T,V,S\}} \sum_{i\in I} \left(e^{-i2\pi f L_a (1+\frac{|\mathbf{k}|}{k_0}\hat{\mathbf{\Omega}}\cdot\hat{\mathbf{p}}_a)} - 1 \right) h^i(f,\frac{|\mathbf{k}|}{k_0}\hat{\mathbf{\Omega}}) F_a^i(\hat{\mathbf{\Omega}})$$

- Consider the two-point correlation of sky-integrated redshifts…

$$\langle \tilde{z}_a(f)\tilde{z}_b^*(f')\rangle \propto \delta(f-f')|f|^{-3} \sum_{I\in\{T,V,S\}} \sum_{i\in I} \Omega_i(f)\Gamma_{ab,i}(\xi,|f|)$$

- The form of the ORF…

$$\Gamma_{ab,i}(|f|) = \beta_I \int_{\text{sky}} d^2\hat{\mathbf{\Omega}} \left(e^{-i2\pi f L_b (1+\frac{|\mathbf{k}|}{k_0}\hat{\mathbf{\Omega}}\cdot\hat{\mathbf{p}}_b)} - 1 \right) \left(e^{i2\pi f L_a (1+\frac{|\mathbf{k}|}{k_0}\hat{\mathbf{\Omega}}\cdot\hat{\mathbf{p}}_a)} - 1 \right) F_a^i(\hat{\mathbf{\Omega}}) F_b^i(\hat{\mathbf{\Omega}})$$

- Back to the two-point correlation…

$$\langle \tilde{z}_a(f)\tilde{z}_b^*(f')\rangle \propto \left(\frac{\Omega_T}{\beta_T}\Gamma_{ab,T} + \frac{\Omega_V}{\beta_V}\Gamma_{ab,V} + \frac{\Omega_S}{\beta_S}\Gamma_{ab,S} \right)$$

Choi+25, Liang+21

Backup: dRGT Gravity and Ghost Mode of Nonlinear MG

- Boulware-Deser Ghost: 6th degree of freedom in nonlinear MG
- Extra mode is formed for which the Hamiltonian has the wrong sign, yielding a “ghost instability”
- Symmetric polynomials of dRGT action removes this 6th degree of freedom

Backup: vDVZ Discontinuity and the Vainshtein Mechanism

- Concern of Massive Gravity: Fierz-Pauli (linearized) MG fails to reproduce GR due to an extra helicity-0 contribution

- Vainshtein Mechanism: non-linear contributions become important for distances to sources lower than some *Vainstein radius*, which screens the helicity-0 mode

- That mode is strongly suppressed, restoring GR near sources

Backup: Vector/Tensor Modes of ORF Scaling with Graviton Mass

- Vector Mode of ORF…

$$\Gamma_V = \frac{\beta_V}{4}\frac{1}{1-A^2}\mathrm{Re}\left[\int_0^{\pi} d\theta \int_0^{2\pi} d\phi \, \sin\theta \, \left(e^{i2\pi f L_a x_a} - 1\right)\left(e^{-i2\pi f L_b x_b} - 1\right)\frac{\chi(\theta,\phi,\xi;A)}{x_a x_b}\right]$$

- Limit of $A \to 1$ (massless limit) keeps integral bounded and leads to…

$$\Gamma_V \propto \left(\frac{m}{\omega}\right)^{-2}$$

- By a similar calculation of the scalar mode of the ORF…

$$\Gamma_S \propto \left(\frac{m}{\omega}\right)^{-4}$$

Credit to Chris Choi for working out the tedious argument