

# Investigating the degeneracy between modified gravity and neutrino mass with redshift-space distortions<sup>†</sup>

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with Kazuya Koyama, Hans Winther, Ben Bose, and Gong-Bo Zhao

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COSMO-19  
RWTH Aachen  
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<sup>†</sup>Based on 1902.10692

# Modified gravity

- Problems exist with  $\Lambda$  as explanation for cosmic acceleration<sup>1</sup>
- Modifications to GR could be responsible instead
- Modified gravity (MG) introduces a new scalar field that accelerates expansion
- Scalar field couples to matter via metric, producing fifth force

$$\mathcal{L}_{\text{ST}} = R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \mathcal{L}_m(\psi_m^{(i)}, \tilde{g}_{\mu\nu})$$

- Fifth force adds to gravity, **enhancing** structure formation
- Signatures of enhanced structure formation = target of galaxy clustering surveys
- But there's a complication...

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- Neutrinos shown to have mass
  - Massive neutrinos don't cluster below free-streaming scale
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  - Heavier  $m_\nu$  = more suppression
  - Neutrino masses not well constrained → amount of suppression unknown

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- Same amount of structure growth  $\neq$  same **growth rate**
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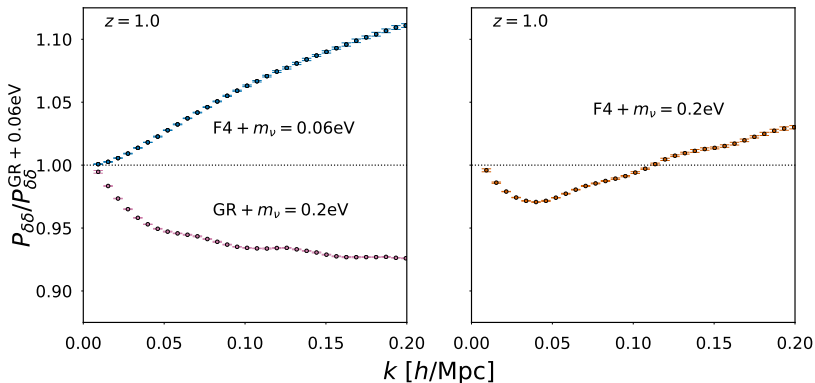
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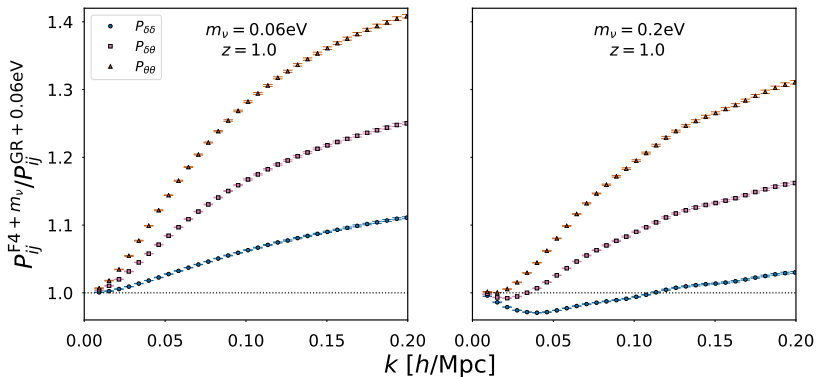
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- **Complication: Velocities not directly measurable for galaxies**
- Redshift contributions = cosmic expansion + peculiar velocity
- Best way to extract peculiar velocities is through **redshift-space distortions (RSD)**
- Galaxy redshifts used as a proxy for distance
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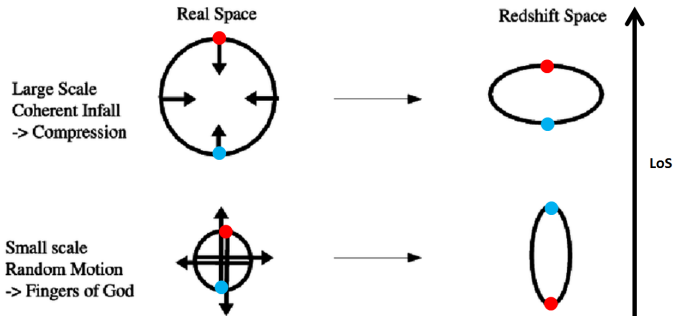
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# Modelling RSD

- RSD effects propagate through to statistics like power spectra
- Need to **model RSD theoretically** to extract peculiar velocity information
- Plan: model RSD with MG &  $m_\nu$ , extract growth rate, use to break degeneracy
- TNS model<sup>1</sup>:

$$P^z(k, \mu, z) = D_{\text{FoG}}(k, \mu, z; \sigma_\nu) [P_{\delta\delta}(k, z) - 2\mu^2 P_{\delta\theta}(k, z) + \mu^4 P_{\theta\theta}(k, z) + A(k, \mu, z) + B(k, \mu, z)]$$

free parameter 

- $P_{\delta\delta/\delta\theta/\theta\theta}$  and  $A$  &  $B$  computed with perturbation theory using code MG-Copter<sup>2</sup>
- $D_{\text{FoG}}$  is phenomenological, e.g.:

$$D_{\text{FoG}}(k, \mu, z; \sigma_\nu) = \exp(-k^2 \mu^2 \sigma_\nu^2)$$


- Fit free parameter  $\sigma_\nu$  to simulations from MG-PICOLA<sup>3,4</sup>
- Result: TNS model matches  $P^z$  from dark matter simulations

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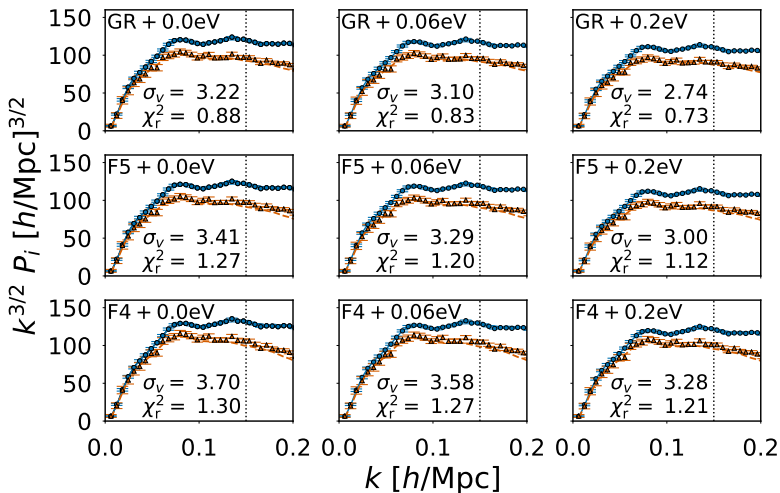
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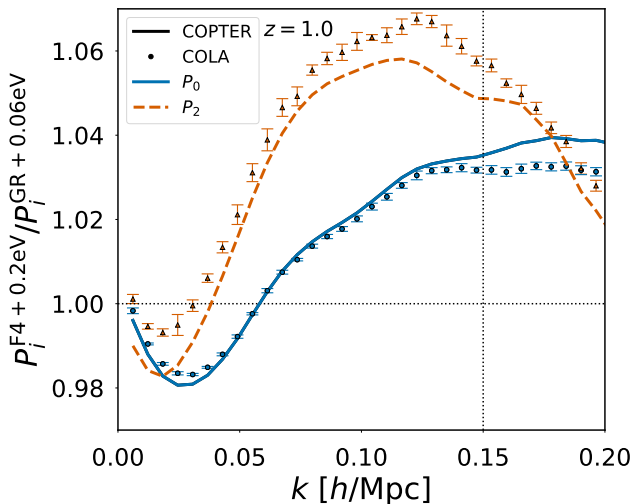
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# Model vs Simulation



# Model vs Simulation: distinguishability captured



## Summary and Future Work

- Amount of structure growth: GR + light neutrinos  $\approx$  MG + heavy neutrinos
- Growth *rate* can distinguish between GR + light neutrinos & MG + heavy neutrinos
- Extract growth rate from galaxy clustering by modelling RSD
- Current progress: RSD model tested against dark matter simulations<sup>†</sup> ✓
- To do: Test extraction of growth rate from dark matter simulations
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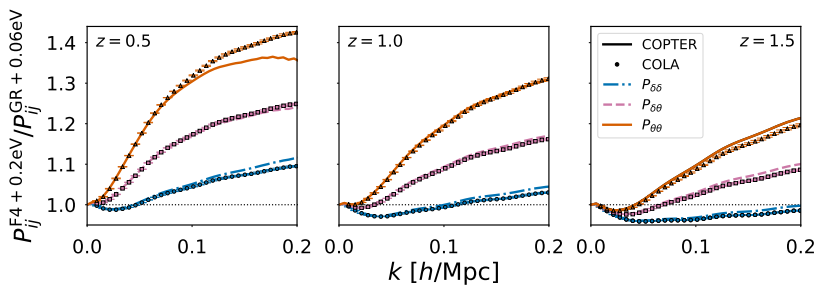
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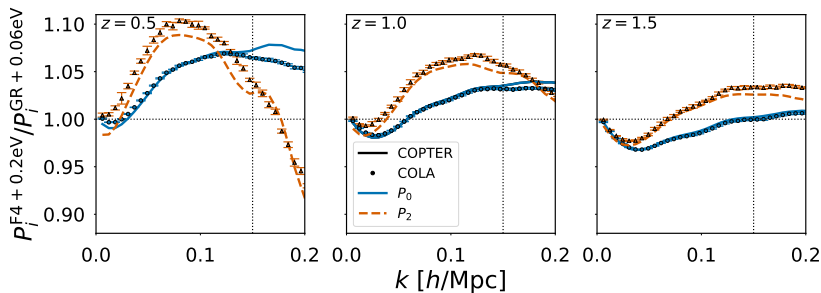
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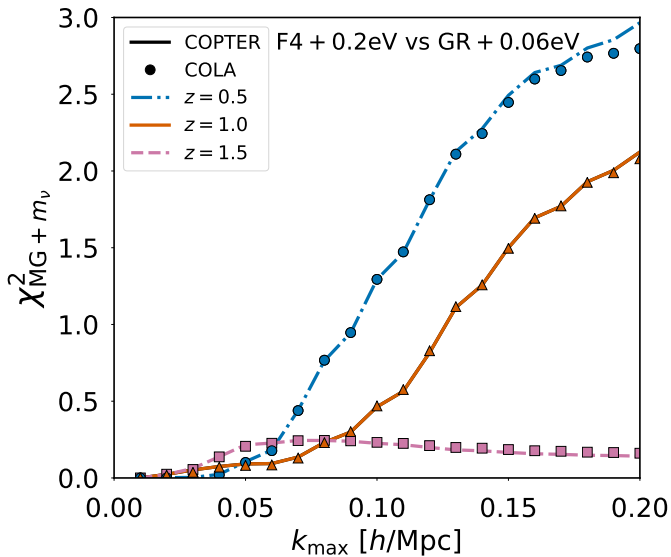
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## Bonus: modelling RSD

- TNS model is still applicable for MG+ $m_\nu$
- But components need to be recomputed
- Ben Bose significantly modified Copter<sup>1</sup> to include MG with MG-Copter<sup>2</sup>

$$P_{\delta\theta}^{13}(k) = \frac{k^3}{(2\pi)^2} F_1(k) P_{L,0}(k) \int_0^\infty r^2 P_{L,0}(kr) G_3(k, r, x) dr \\ + \frac{k^3}{(2\pi)^2} G_1(k) P_{L,0}(k) \int_0^\infty r^2 P_{L,0}(kr) F_3(k, r, x) dr$$

- By rewriting SPT equations in MG-Copter we can include  $m_\nu$  exclusively through  $P_L(k)$  and  $f(k)$  taken from MGCAMB<sup>3,4</sup>, similar to Saito+ (2009)

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