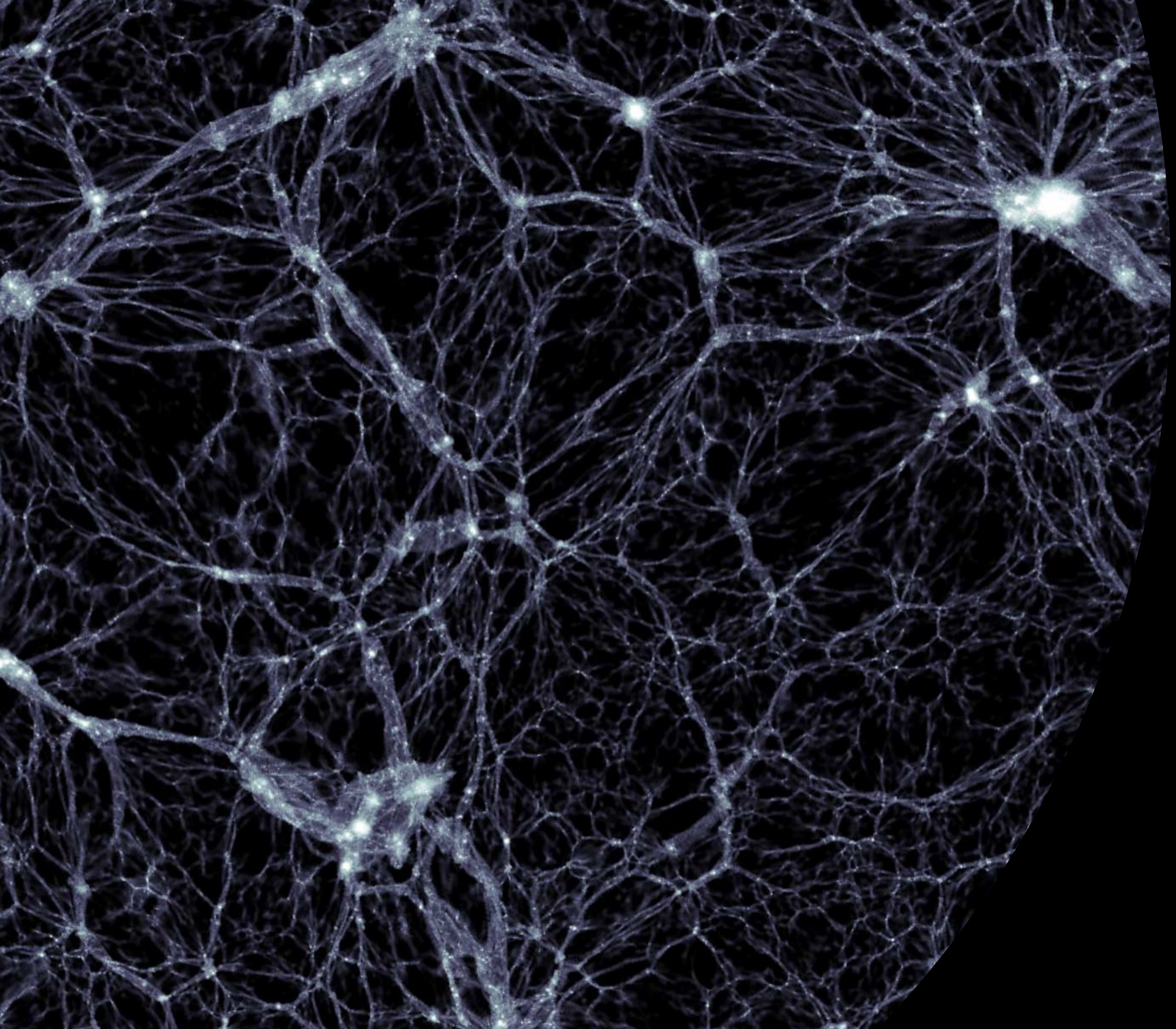

Credit: Markus Haider, Illustris Collaboration.

Number counts of GW in ΛCDM and Scalar-Tensor Theories

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In collaboration with:

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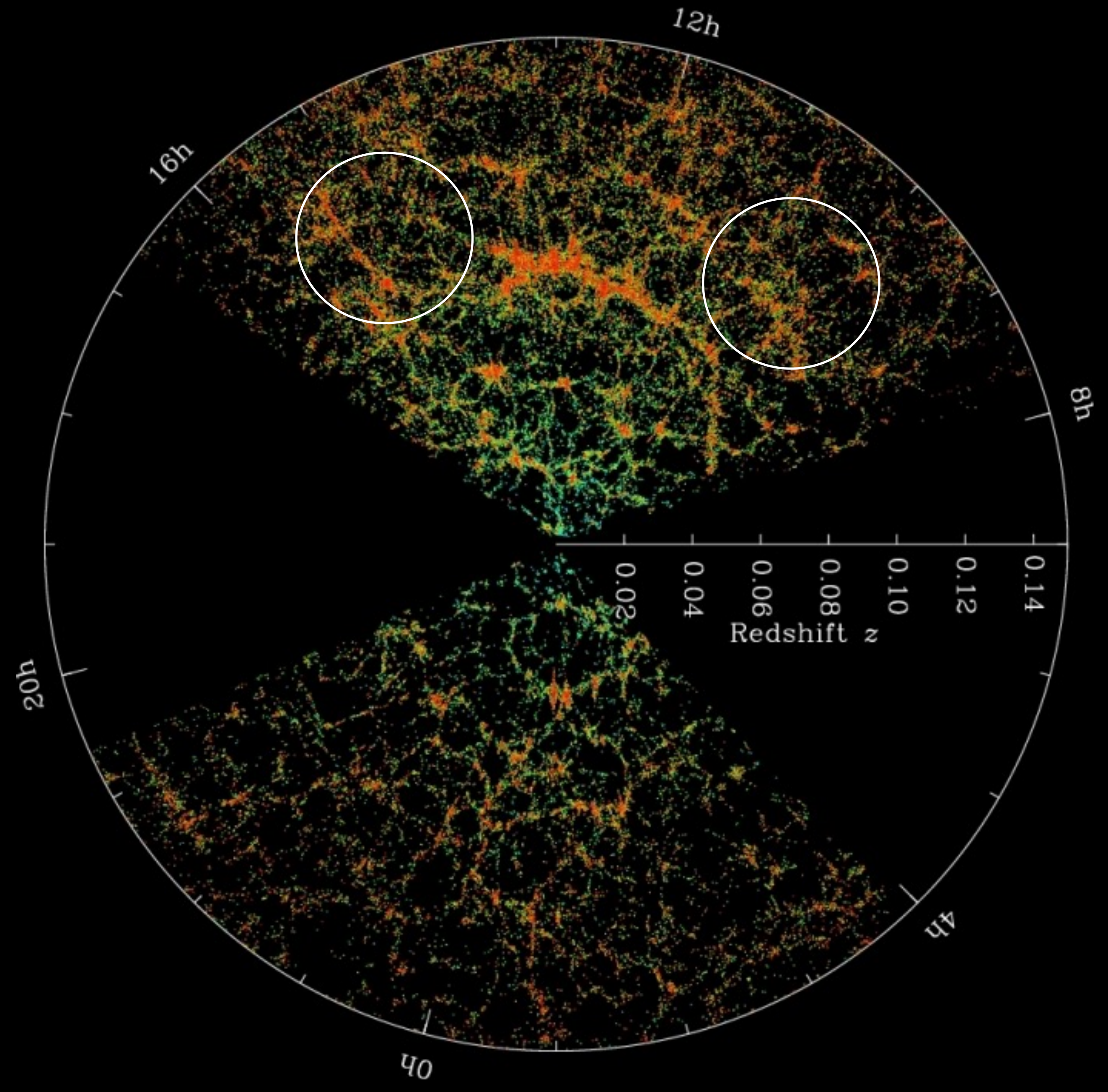
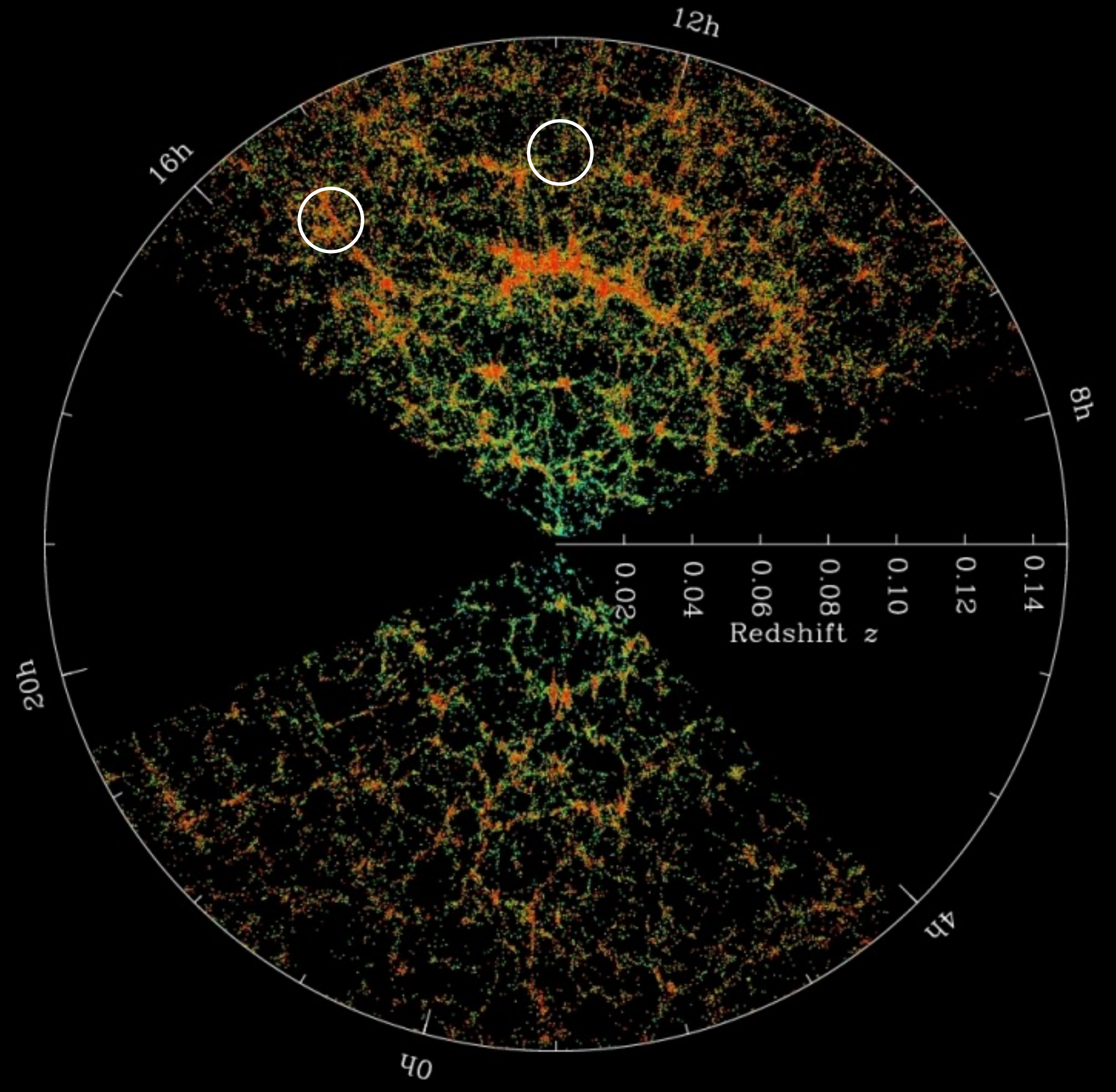
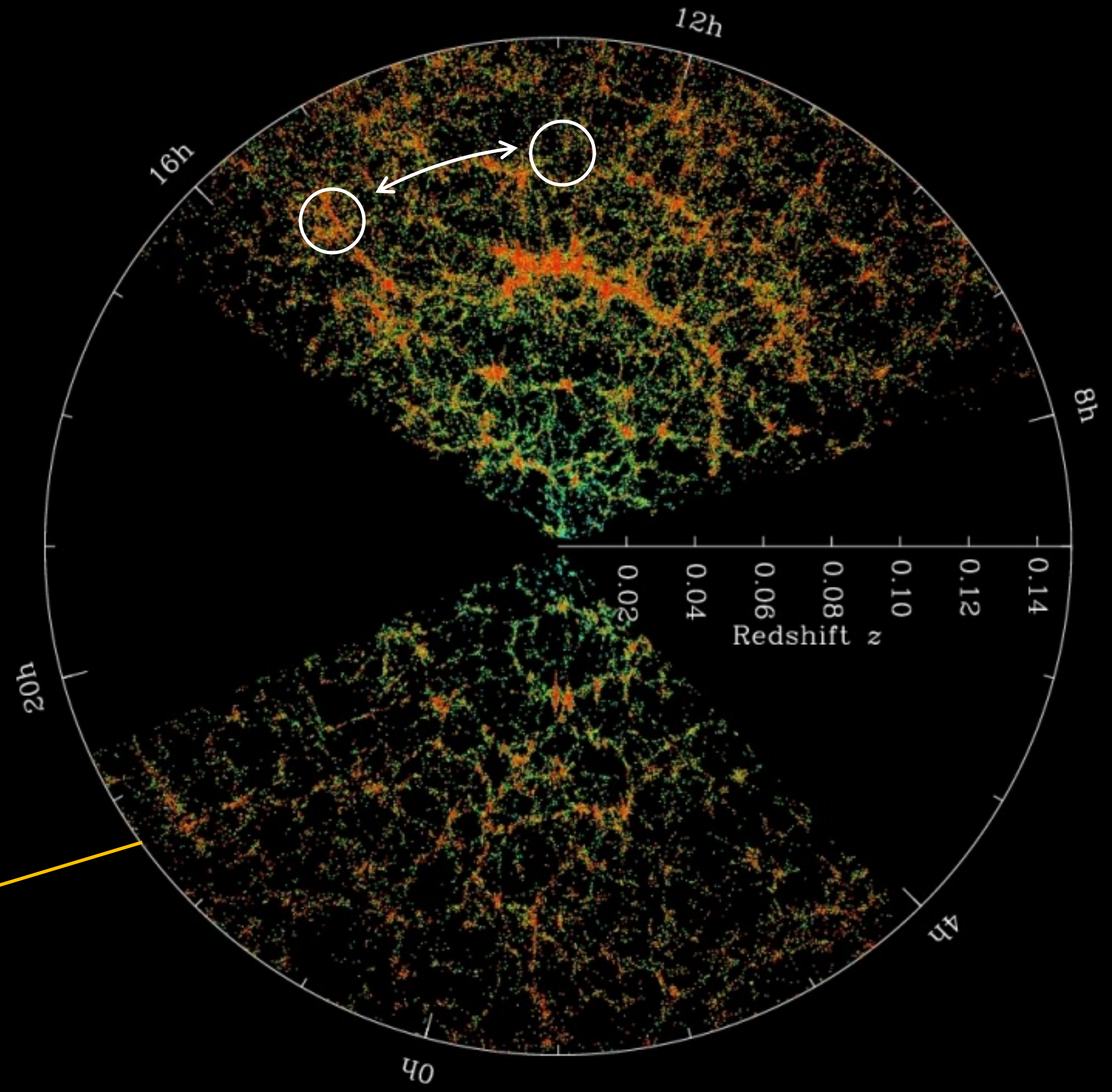
Is the Universe homogeneous and isotropic?



Is the Universe homogeneous and isotropic?



Is the Universe homogeneous and isotropic?

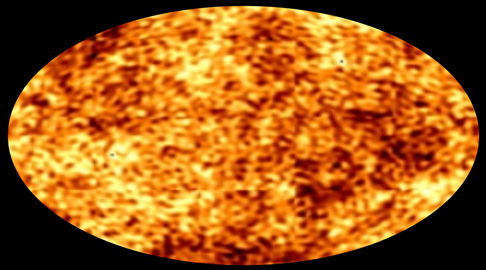


Data

$$\hat{\Delta}(z,\hat{n}) \equiv \frac{N(z,\hat{n}) - \bar{N}(z)}{\bar{N}(z)}$$

Is the Universe homogeneous and isotropic?

Primordial perturbations

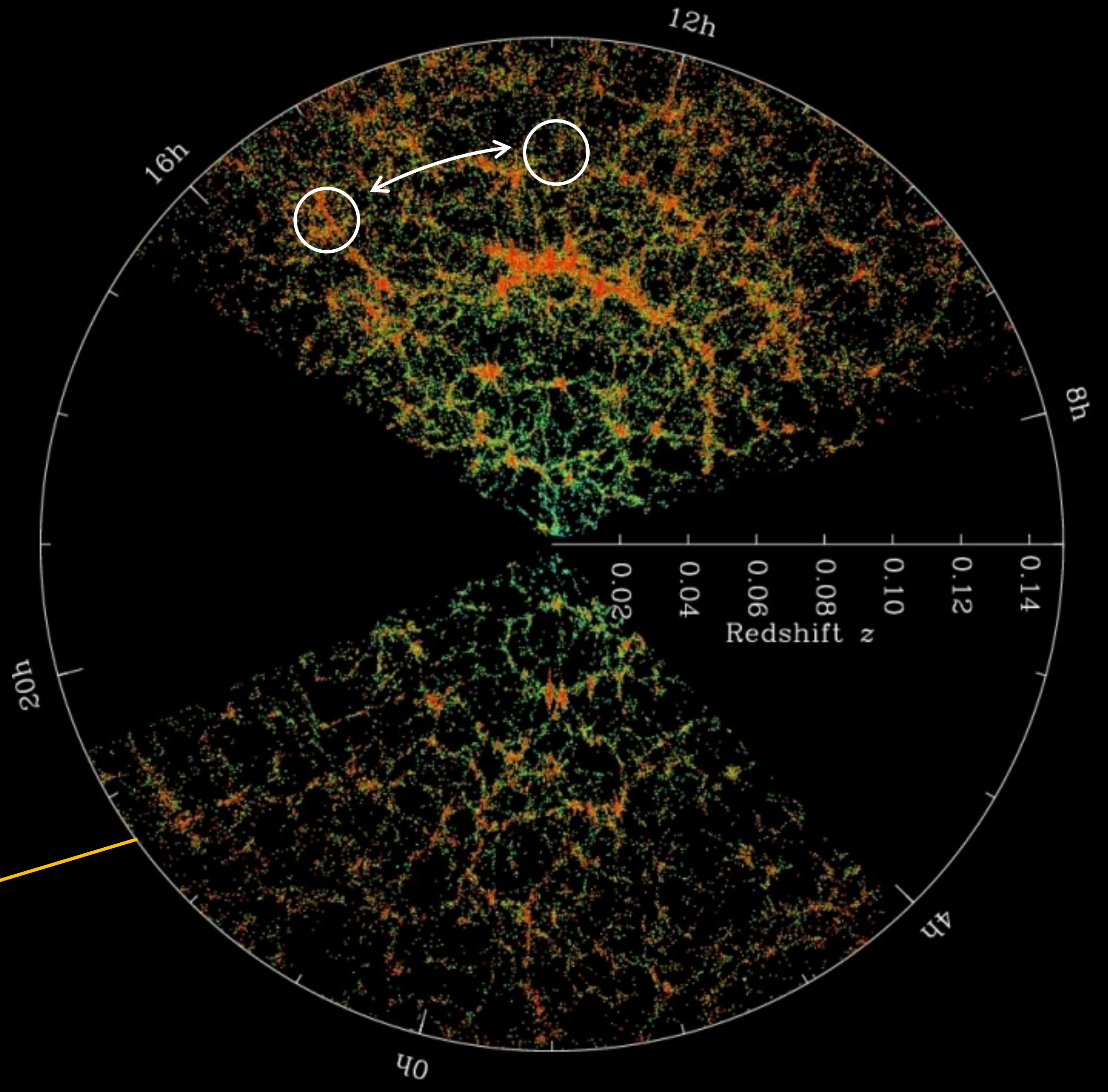


Cosmological model →

Theory ?

Data

$$\hat{\Delta}(D,\hat{n}) \equiv \frac{N(D,\hat{n}) - \bar{N}(D)}{\bar{N}(D)}$$

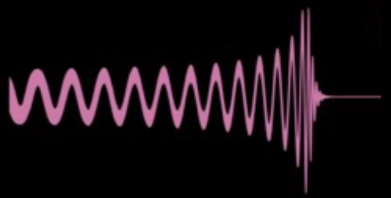


Mpetha, Congedo and Taylor (2022)

- GW propagate in an expanding FRW Universe following

$$\ddot{h}_{+,\times} + 2\mathcal{H}\dot{h}_{+,\times} + k^2 h_{+,\times} = 0$$

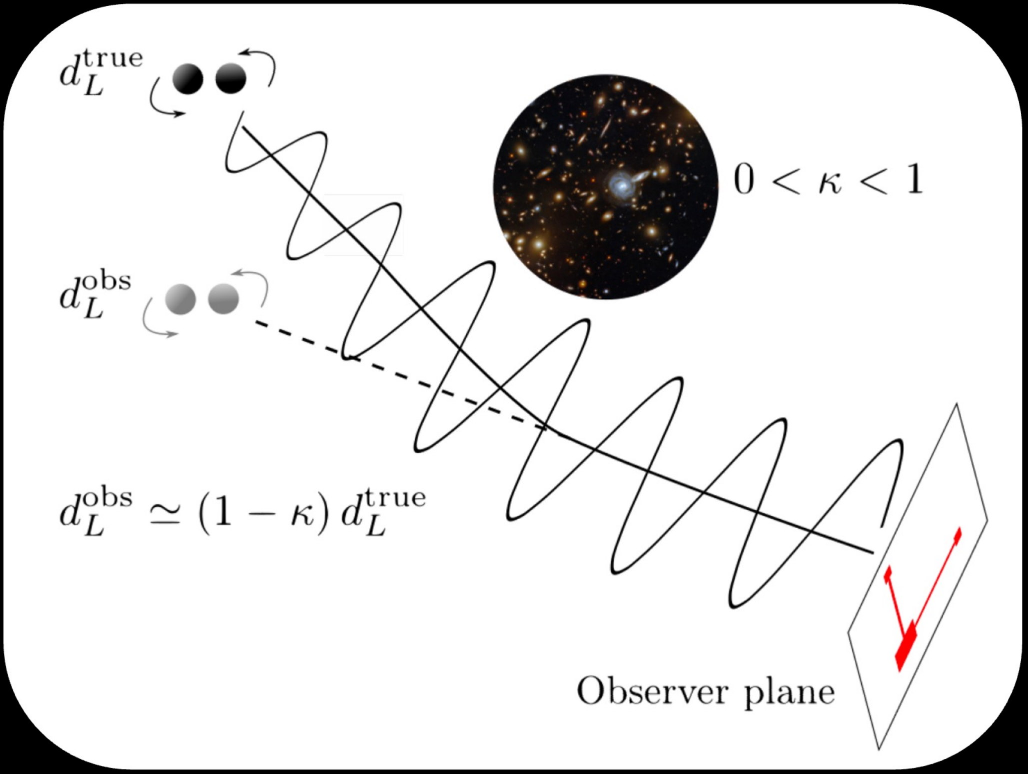
- From the strain, we can measure the luminosity distance of the binary



$$D(z,\bar{n}) = \bar{D}(\bar{z}) + \Delta D(z,\bar{n})$$

Background

Perturbations: Bertacca et al. (2019)



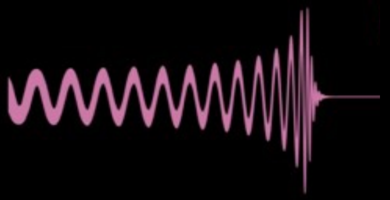
$$\hat{\Delta}(D,\hat{n}) \equiv \frac{N(D,\hat{n}) - \bar{N}(D)}{\bar{N}(D)} = \text{density fluctuations} + \text{relativistic effects}$$

Mpetha, Congedo and Taylor (2022)

- GW propagate in an expanding FRW Universe following

$$\ddot{h}_{+,\times} + 2\mathcal{H}\left[1 + \alpha_M(\eta)/2\right]\dot{h}_{+,\times} + k^2 h_{+,\times} = 0$$

- From the strain, we can measure the luminosity distance of the binary

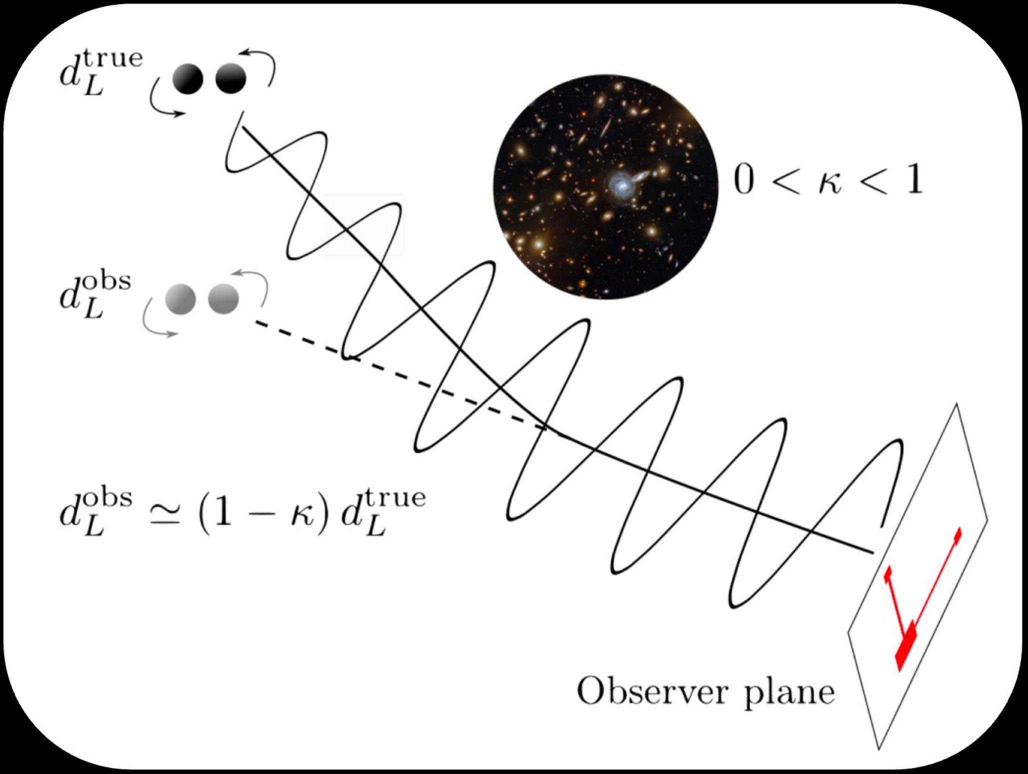


$\rightarrow$ $D(z, \bar{n}) = \bar{D}(\bar{z}) + \Delta D(z, \bar{n})$

Background $(\alpha_M(\eta), \varphi)$

Perturbations $(\alpha_M(\eta), \varphi)$: Garoffolo et al. (2020)

MG models: ST Horndeski with $c_T = 1$



$$\hat{\Delta}(D, \hat{n}) \equiv \frac{N(D, \hat{n}) - \bar{N}(D)}{\bar{N}(D)} = \text{density fluctuations} + \text{relativistic effects}$$

GW number counts in Scalar-Tensor theories of Gravity

$$\hat{\Delta}(D,\vec{n}) = \delta_{\rm N}^{\rm gw} + \Lambda_{\rm D}(\chi,\alpha_M)\,\boldsymbol{v}\cdot\boldsymbol{n} + \Lambda_{\rm LSD}(\chi,\alpha_M)\,\partial_\chi(\boldsymbol{v}\cdot\boldsymbol{n})$$

Doppler

Luminosity Space Distortions

Peculiar velocity effects

GW number counts in Scalar-Tensor theories of Gravity

$$\hat{\Delta}(D,\vec{n}) = \delta_{\rm N}^{\rm gw} + \underbrace{\Lambda_{\rm D}(\chi,\alpha_M)\,\boldsymbol{v}\cdot\boldsymbol{n}}_{\text{Doppler}} + \underbrace{\Lambda_{\rm LSD}(\chi,\alpha_M)\,\partial_\chi(\boldsymbol{v}\cdot\boldsymbol{n})}_{\text{Luminosity Space Distortions}}$$

$$+ \underbrace{\int_0^\chi d\chi'\,\Lambda_{\rm L}(\chi,\chi',\alpha_M)\,\nabla_\Omega^2(\Phi+\Psi)}_{\text{Lensing}} + \underbrace{\Lambda_{\rm TD}(\chi,\alpha_M)\int_0^\chi d\chi'(\Phi+\Psi)}_{\text{Time delay}} + \underbrace{\Lambda_{\rm ISW}(\chi,\alpha_M)\int_0^{\bar{\chi}} d\chi'(\dot{\Phi}+\dot{\Psi})}_{\text{Integrated Sachs-Wölfe}}$$

Peculiar velocity effects

Integrated relativistic effects during propagation

GW number counts in Scalar-Tensor theories of Gravity

$$\hat{\Delta}(D,\vec{n}) = \delta_{\rm N}^{\rm gw} + \Lambda_{\rm D}(\chi,\alpha_M)\,\boldsymbol{v}\cdot\boldsymbol{n} + \Lambda_{\rm LSD}(\chi,\alpha_M)\,\partial_\chi(\boldsymbol{v}\cdot\boldsymbol{n})$$

Doppler — Luminosity Space Distortions

$$+\int_0^{\chi} d\chi'\,\Lambda_{\rm L}(\chi,\chi',\alpha_M)\,\nabla^2_\Omega(\Phi+\Psi) + \Lambda_{\rm TD}(\chi,\alpha_M)\int_0^{\chi} d\chi'(\Phi+\Psi) + \Lambda_{\rm ISW}(\chi,\alpha_M)\int_0^{\bar{\chi}} d\chi'(\dot{\Phi}+\dot{\Psi})$$

Lensing — Time delay — Integrated Sachs-Wölfe

$$+\Lambda_\Phi(\chi,\alpha_M)\Phi + \Lambda_{\partial_\chi\Phi}(\chi,\alpha_M)\,\partial_\chi\Phi + \Lambda_{\dot{\Phi}}(\chi,\alpha_M)\dot{\Phi} + \Lambda_\Psi(\chi,\alpha_M)\Psi$$

Local potentials

- Peculiar velocity effects (blue)
- Integrated relativistic effects during propagation (green)
- Local potentials at the wave emission (yellow)

GW number counts in Scalar-Tensor theories of Gravity

$$\hat{\Delta}(D,\vec{n}) = \delta_{\rm N}^{\rm gw} + \Lambda_{\rm D}(\chi,\alpha_M)\,\boldsymbol{v}\cdot\boldsymbol{n} + \Lambda_{\rm LSD}(\chi,\alpha_M)\,\partial_\chi(\boldsymbol{v}\cdot\boldsymbol{n})$$

Doppler — Luminosity Space Distortions

$$+ \int_0^{\chi} d\chi'\,\Lambda_{\rm L}(\chi,\chi',\alpha_M)\,\nabla^2_\Omega(\Phi+\Psi) + \Lambda_{\rm TD}(\chi,\alpha_M)\int_0^{\chi} d\chi'(\Phi+\Psi) + \Lambda_{\rm ISW}(\chi,\alpha_M)\int_0^{\bar{\chi}} d\chi'(\dot{\Phi}+\dot{\Psi})$$

Lensing — Time delay — Integrated Sachs-Wölfe

$$+ \Lambda_{\Phi}(\chi,\alpha_M)\Phi + \Lambda_{\partial_\chi\Phi}(\chi,\alpha_M)\,\partial_\chi\Phi + \Lambda_{\dot{\Phi}}(\chi,\alpha_M)\dot{\Phi} + \Lambda_{\Psi}(\chi,\alpha_M)\Psi$$

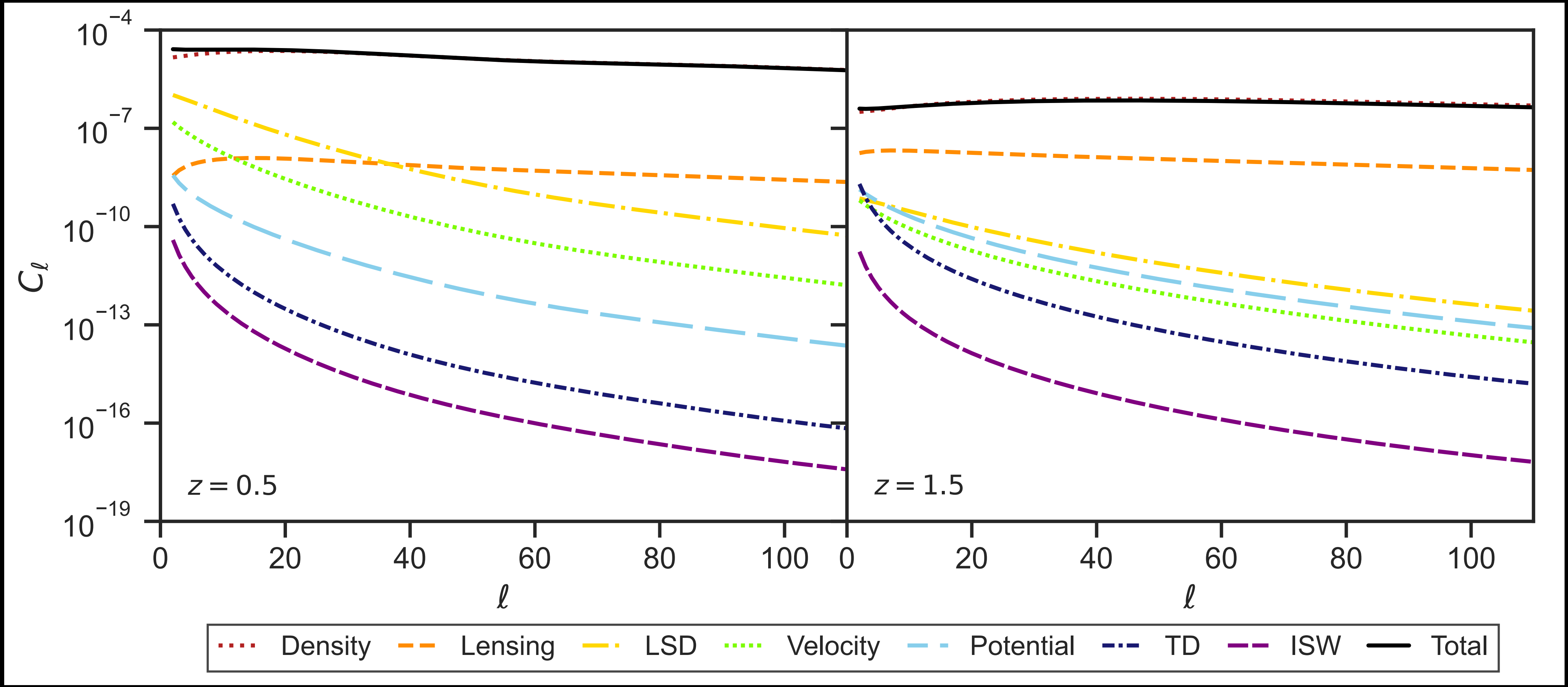
Local potentials

$$+ \Lambda_{\dot{\delta\varphi}}(\chi,\alpha_M)\left(\frac{\dot{\delta\varphi}}{\varphi}\right) + \Lambda_{\delta\varphi}(\chi,\alpha_M)\frac{\delta\varphi}{\varphi}$$

Scalar field

- Peculiar velocity effects
- Integrated relativistic effects during propagation
- Local potentials at the wave emission
- Interaction of the GW with the DE scalar field

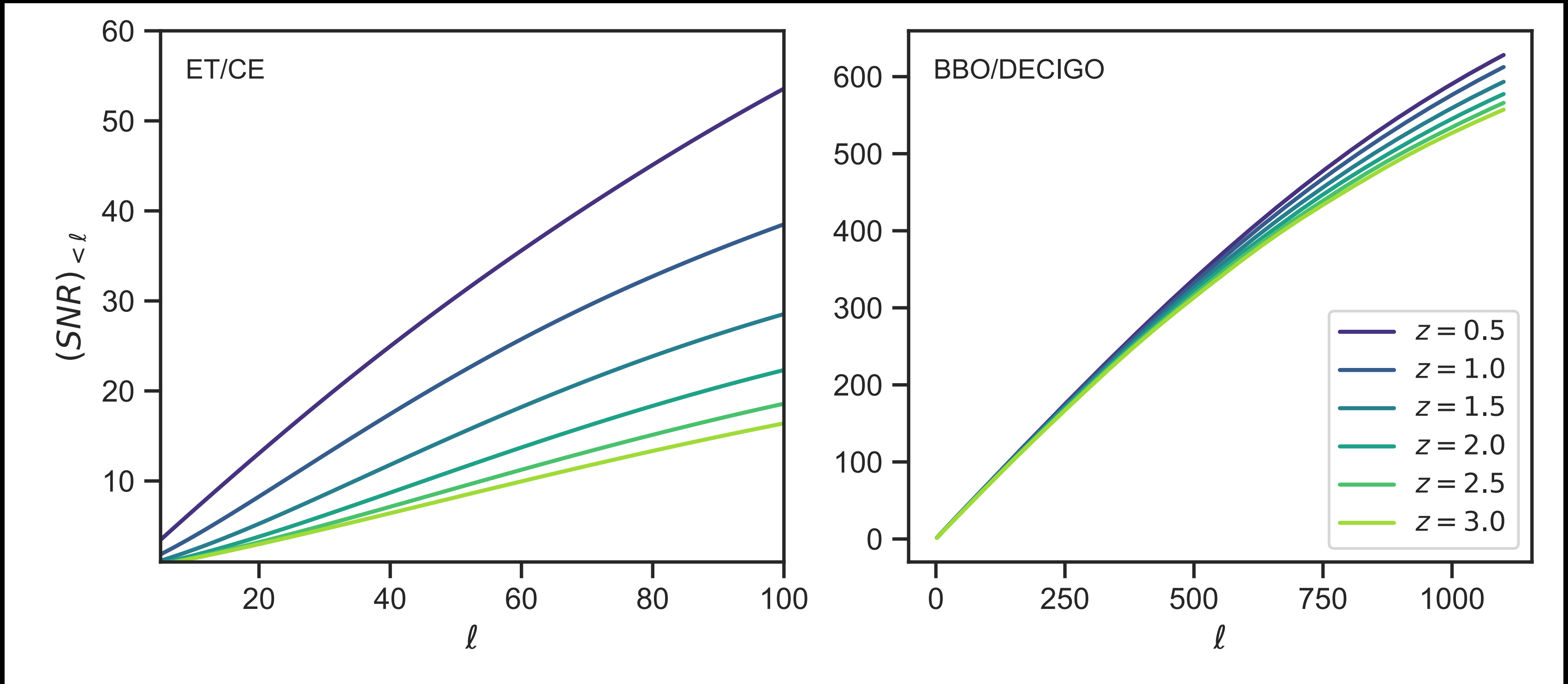
Number counts signal in standard GR



Observability

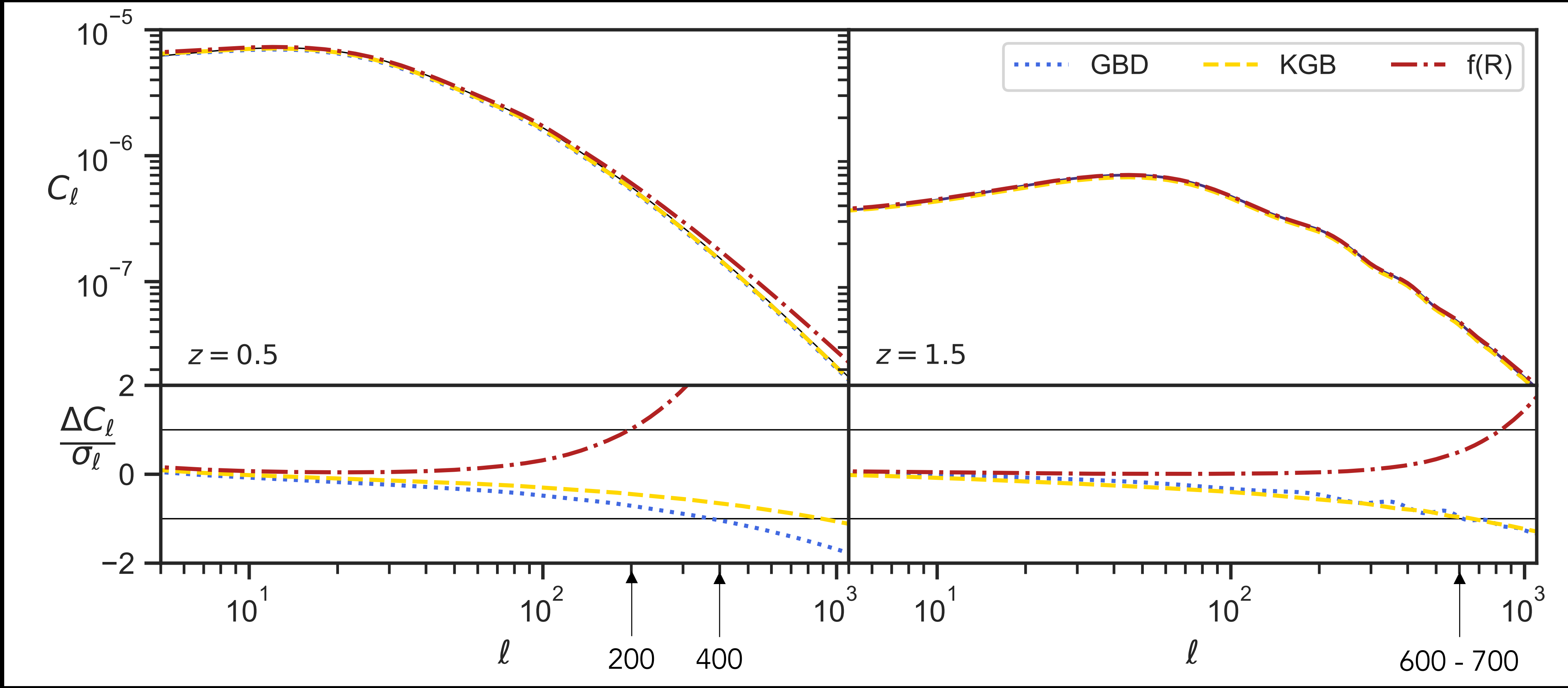
We define a cumulative signal to noise

$$\left(\frac{S}{N}\right)^2_{<\ell} = \sum_\ell \frac{2\ell+1}{2}\left[\frac{C_\ell}{\sigma_D^2/N_{\rm gw} + C_\ell}\right]^2$$



The signal is observable in both detectors!

Number counts in Scalar-Tensor theories



GW number counts is potentially observable by next generation detectors

Key Takeaways

The GW signal can be cross-correlated with LSS to give even more information.

Deviations from ΛCDM can only be measured effectively probing the smallest scales.

Crucial improvement needed is accuracy on the measure of D_L and on sky-locations

Thank you!

And thanks to ***Mattia Pantiri*** and ***Alessandra Silvestri***

GW number counts in Scalar-Tensor theories of Gravity

$$\hat{\Delta}(D,\boldsymbol{n}) = \delta_{\rm gw} + \left[1 + \frac{\gamma}{\mathcal{H}}(\dot{\zeta} - \zeta\mathcal{H}) - \zeta(\beta+1)\right]\boldsymbol{v}\cdot\boldsymbol{n} - \left[\frac{\gamma}{\mathcal{H}}\zeta\right]\partial_{\bar{\chi}}(\boldsymbol{v}\cdot\boldsymbol{n}) -$$

$$\int_0^{\bar{\chi}} d\chi' \left[\left(\frac{\beta-1}{2}\right)\frac{\bar{\chi}-\chi'}{\bar{\chi}\chi'} + \frac{\gamma}{2\mathcal{H}\bar{\chi}^2}\right]\nabla^2_{\Omega}(\Phi+\Psi) + \left[\frac{1-\beta}{\bar{\chi}} + \frac{\gamma}{\mathcal{H}\bar{\chi}^2}\right]\int_0^{\bar{\chi}} d\chi'(\Phi+\Psi) +$$

$$+ \left[\zeta(\beta+1) - \frac{\gamma}{\mathcal{H}}\dot{\zeta}\right]\int_0^{\bar{\chi}} d\chi'(\dot{\Phi}+\dot{\Psi}) + \left[\beta - 1 - \frac{\gamma}{\bar{\chi}\mathcal{H}}\right]\Phi + \frac{\gamma}{\mathcal{H}}\partial_{\bar{\chi}}\Phi +$$

$$+ \left[\frac{\gamma}{\mathcal{H}}(\zeta-1)\right]\dot{\Phi} + \left[1 - \frac{\gamma}{\mathcal{H}}\left(\frac{1}{\bar{\chi}} + \dot{\zeta}\right) + \zeta(\beta+1)\right]\Psi +$$

$$+ \gamma\frac{\alpha_M}{2}\left(\frac{\dot{\delta\varphi}}{\varphi}\right) + \gamma\left[\frac{\dot{\alpha_M}}{2} + \frac{\alpha_M}{2}\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}} - \beta - 1\right)\right]\frac{\delta\varphi}{\varphi}$$