

Studying Inhomogeneous Universes and Modified Gravity with Standard Sirens



Marios Kalomenopoulos,

31/3/2021,

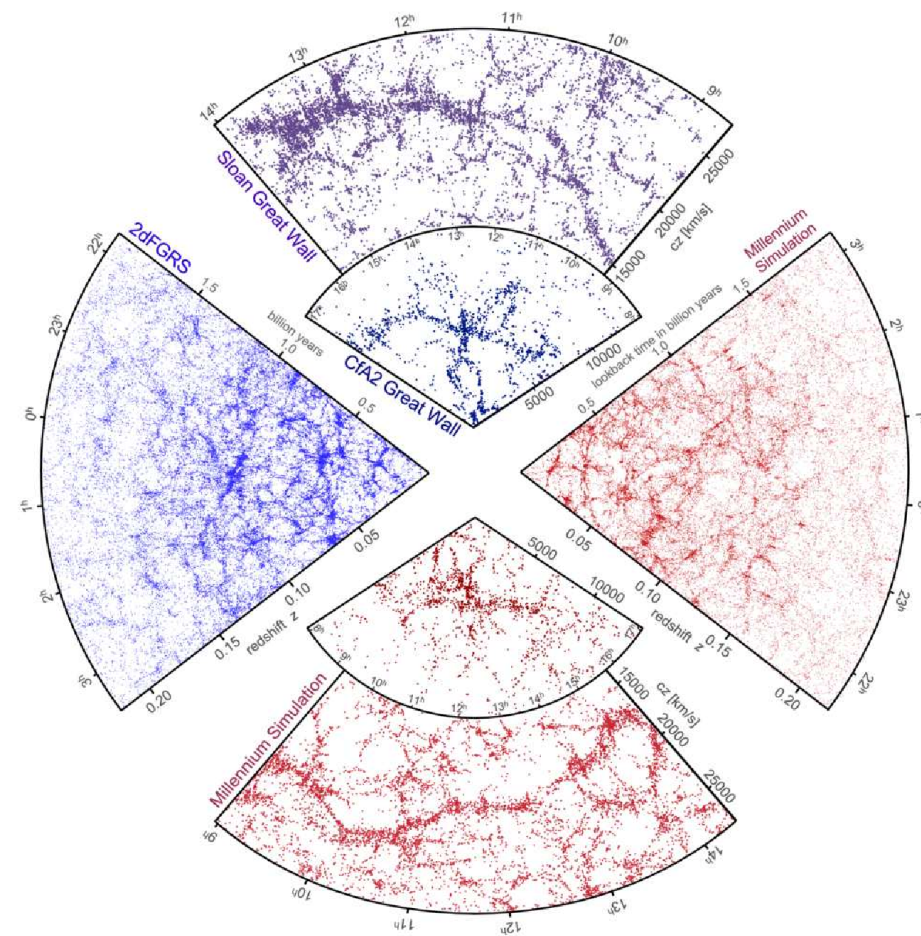
Paris (*"Gravitational waves: a new messenger to explore the universe"*)

Based on work with S. Khochfar, J. Gair & S. Arai -
arXiv:2007.15020 (MNRAS accepted)

Motivation

- One of the basic assumptions in Cosmology: Universe is homogeneous, **on large scales**.
 - Fluctuations on smaller scales can introduce deviations from FRW and systematics in observations.
 - To study these, we exploit a DM cosmological simulation that can resolve the non-linear clustering.

- Questions:
 - What can GWs Standard Sirens say about inhomogeneities in the Universe?
 - Can matter inhomogeneities mimic effects we expect from modified gravity theories?



Model & Parameters

A. Modified Gravity

$$h''_{ij} + [2 + \nu(\tau)]\mathcal{H}h'_{ij} + [c_T(\tau)^2 k^2 + a(\tau)^2 \mu^2]h_{ij} = a(\tau)^2 \Gamma \gamma_{ij}$$



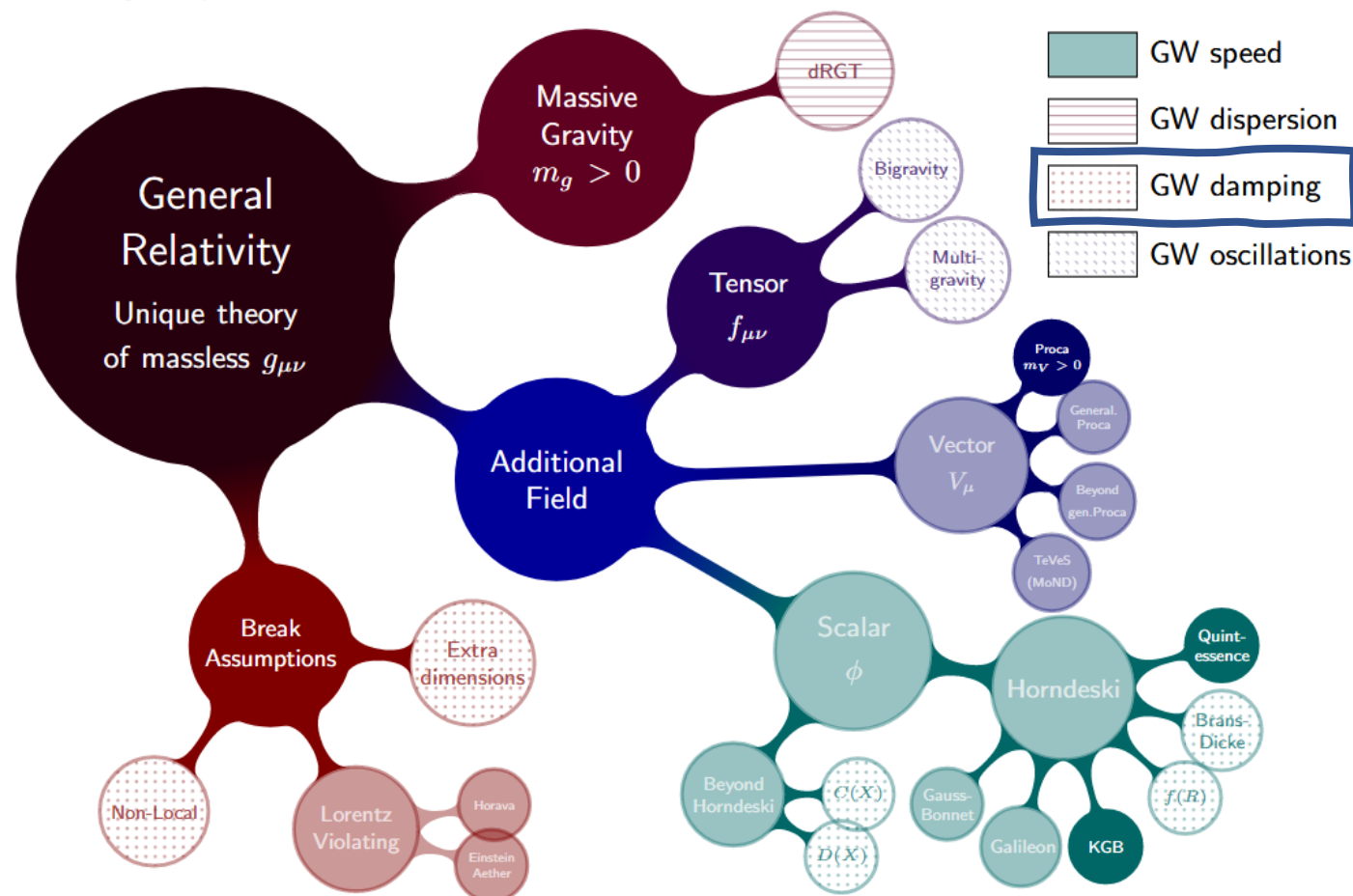
$$d_L^{\text{gw}}(z) = d_L^{\text{E/M}}(z) \exp \left\{ \int_0^z \frac{\nu(z')}{2} \frac{dz'}{1+z'} \right\}$$



Constant ν (“friction term”)

$$d_L^{\text{gw}}(z) = d_L^{\text{E/M}}(z) (1+z)^{\nu/2}$$

Modified gravity roadmap



Model & Parameters

B. Inhomogeneous “effective” models

DR
$$\frac{d^2 D}{dz^2} + \left(\frac{d \ln H}{dz} + \frac{2}{1+z} \right) \frac{dD}{dz} = -\frac{3}{2} \Omega_m \frac{H_0^2}{H^2} (1+z) \alpha(z, \delta) D$$

mDR
$$\frac{d^2 D}{dz^2} + \left(\frac{(1+z)H_0^2}{2H^2} [3\alpha(z, \delta)\Omega_m(1+z) + 2\Omega_k] + \frac{2}{1+z} \right) \frac{dD}{dz} = -\frac{3}{2} \Omega_m \frac{H_0^2}{H^2} (1+z) \alpha(z, \delta) D,$$

with $H(z)^2 = H_0^2 [\alpha(z, \delta)\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2]$

Schneider et al. 1992; Clarkson et al. 2012

- Dyer-Roeder (DR) assumes Λ CDM background evolution. - Modified Dyer-Roeder (mDR) tries to model effects on local dynamics.

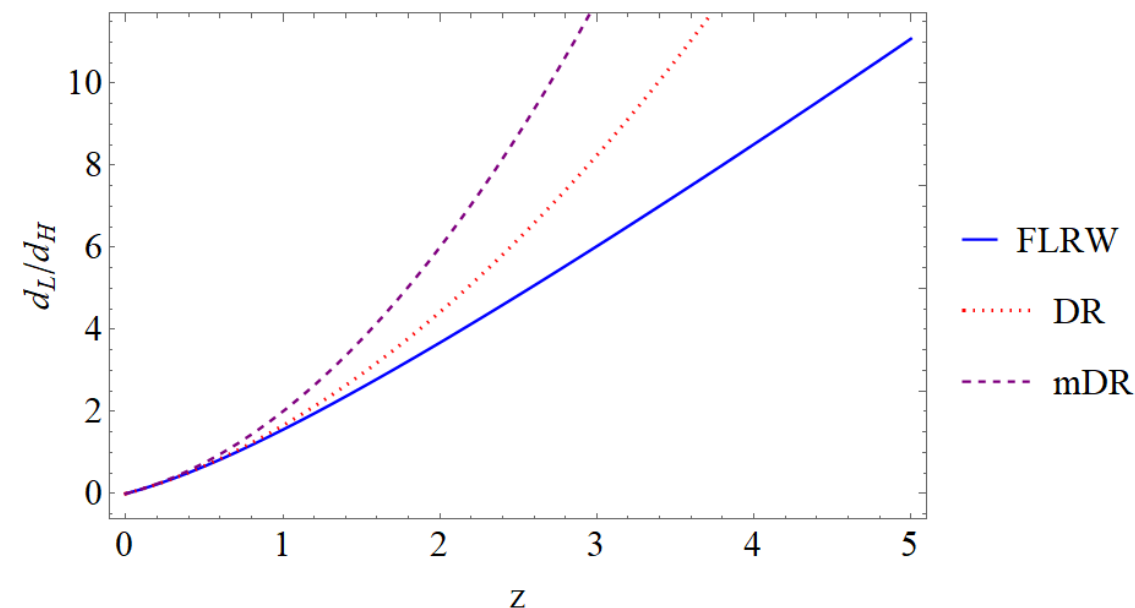
- Parameter α (clustering of matter): $\alpha = 1$ standard RW & $\alpha = 0$ extreme “empty beam” case (Figure).

Linder 1988; Bolejko 2011

- Parameterisations of α :

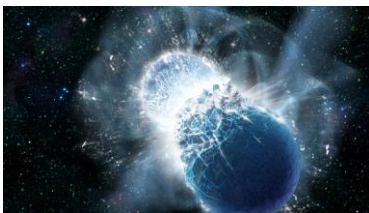
1) $\alpha = a_0 + a_1 z$ or

2) $\alpha = 1 + f(z)\bar{\delta}_{1D}$, where $\delta = \delta\rho/\rho$, the density contrast and $f(z) = (1+z)^{-5/4}$.



The Setup

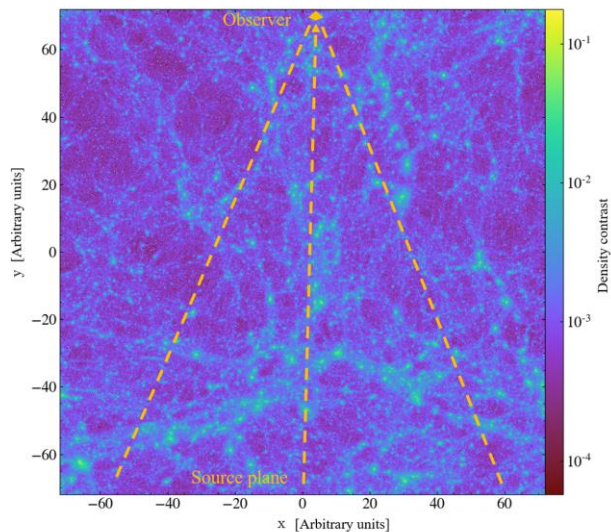
Step 1: Seed GWs sources.



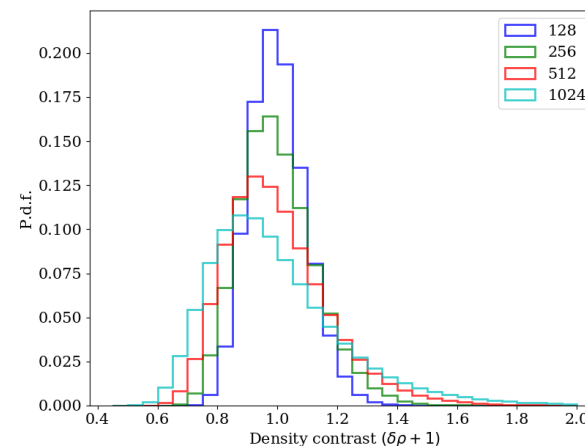
[Credit: NASA/Swift/Dana Berry]

- 350 GWs sources
- From $z = 0$ to $z = 5$
- Masses/rates based on a population synthesis model
- ET (& CE).

Step 2: Follow their propagation through a realistic matter distribution.



Step 3: Calculate the mean density contrast along the rays.



Step 4: Answer our initial questions.

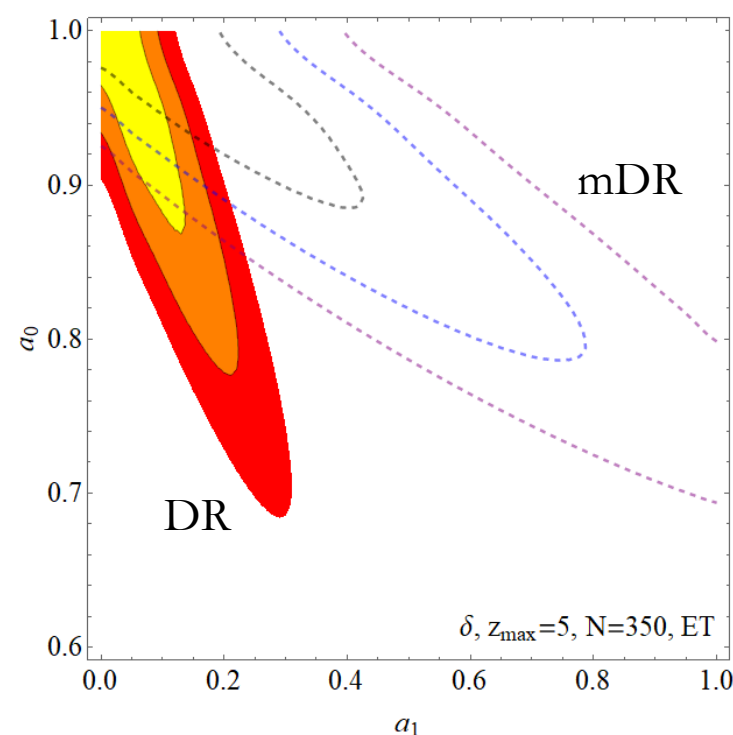
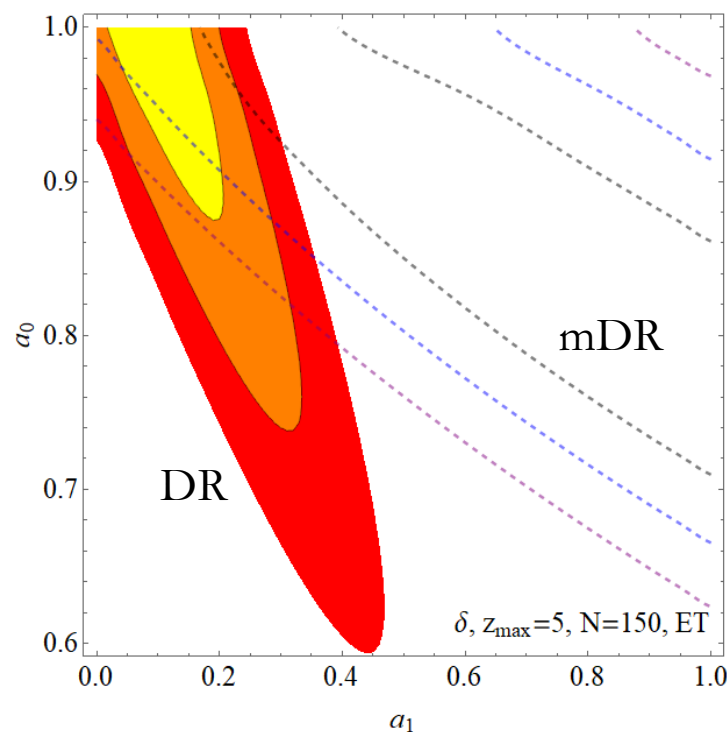
- 1) Investigate how future, ground-based detectors can constrain the inhomogeneities in our Universe.
- 2) Investigate the level of the degeneracy between GW signals expected in modified gravity theories and cosmological models based on standard gravity but including matter density inhomogeneities.

Homogeneity Probe

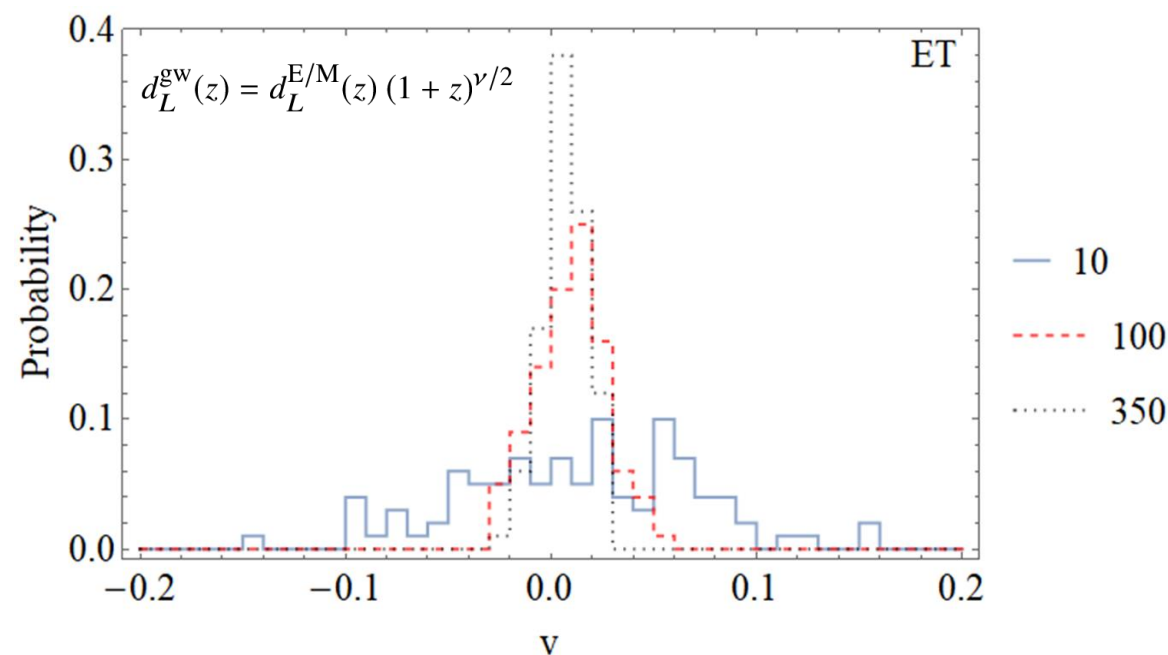
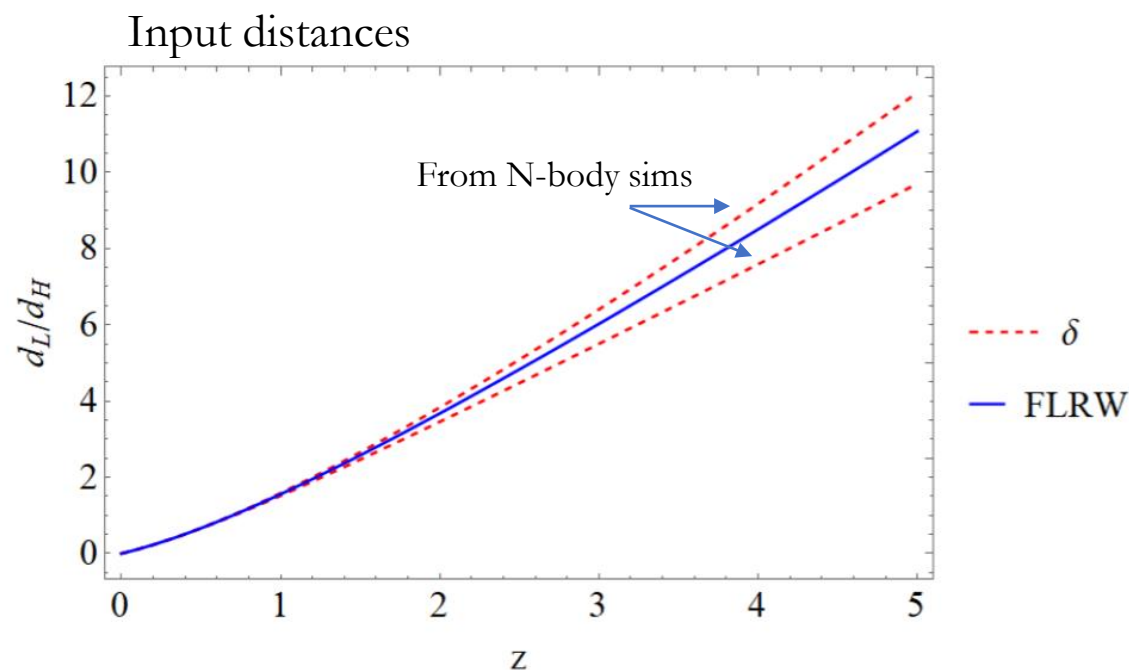
- Practically unconstrained from E/M observations + different systematics.
Busti et al. (2012a); Dhawan et al. (2018), ...

- **Right:** Constraints on the inhomogeneity parameters (a_0, a_1) based on a realistic density distribution from numerical simulations from future GW detectors (results are similar for CE).

- Both cases **consistent** with an FLRW background, where $(a_0, a_1) = (1, 0)$ and the parameters are **significantly constrained** ($\sim 20\%$ in 2σ).



Degeneracy with Modified Gravity



- Probability distribution for the ν parameter based on different number of observations

Currently, weakly constrained: $-75.3 \leq \nu \leq 78.4$

Nishizawa & Arai 2019

- The presence of inhomogeneities can mimic a deviation from GR, leading to higher uncertainties when constraining ν .

- For **350** GWs observations with EM counterparts the accuracy on ν is increased to the order of **1%**.

Summary

- ET & CE crucial for cosmological studies, putting **strong constraints** on the **inhomogeneity parameters**.
- **They can break the degeneracy** between modified gravity effects and matter anisotropies.
- An accuracy of **1% on the friction parameter** can be achieved with **350 observations**.

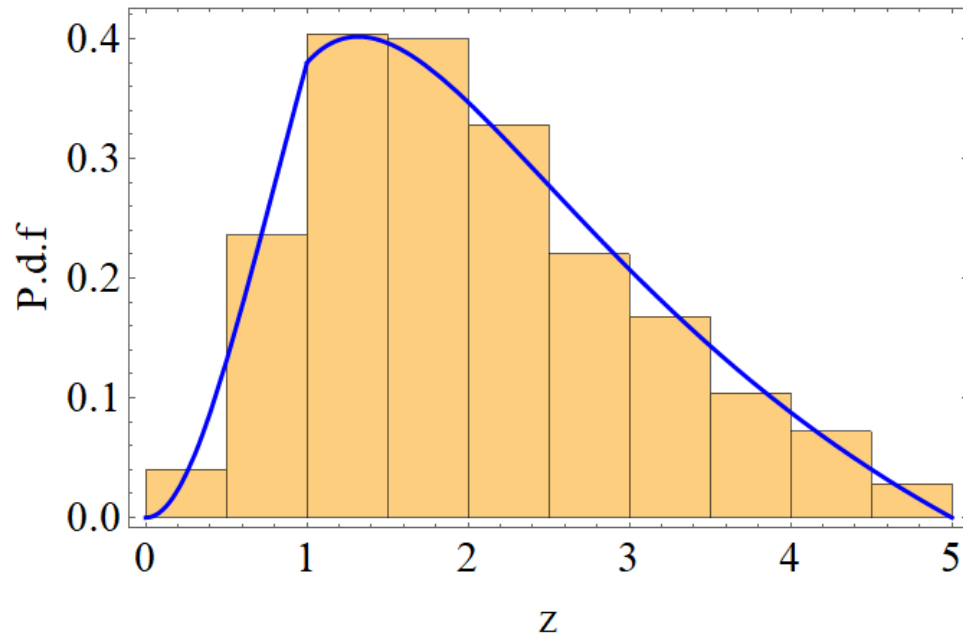
Thank you!

For more details: arXiv:2007.15020
& mariok@roe.ac.uk

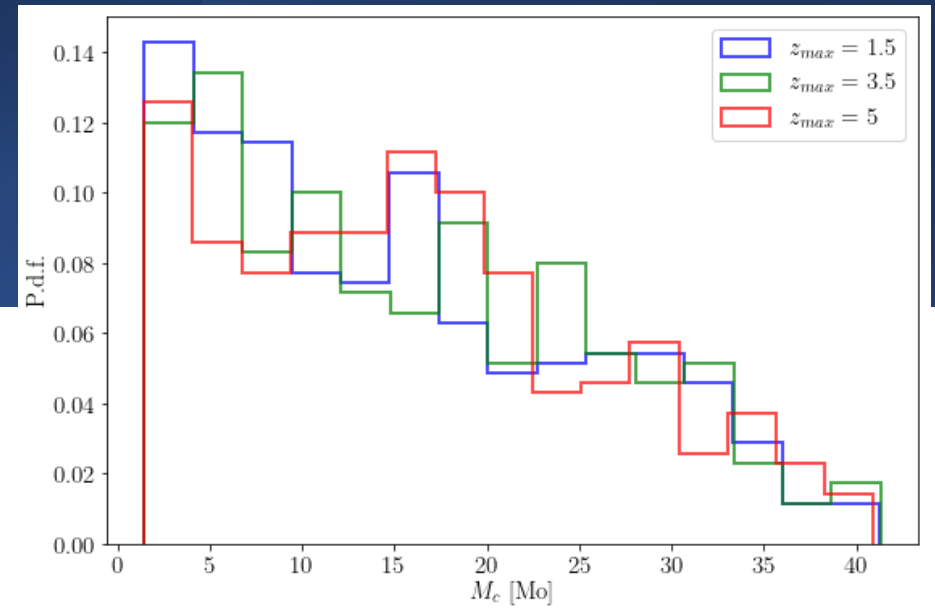


Bonus Slides

Sources



$$P(z) \sim \frac{4\pi D_c^2(z) R(z)}{H(z)(1+z)}, \quad R(z) = \begin{cases} 1+2z, & z \leq 1 \\ \frac{3}{4}(5-z), & 1 < z < 5 \\ 0, & z \geq 5 \end{cases}$$



- 1) Mass secondary \leq Mass primary
- 2) Mass primary \rightarrow BHs, NS
- 3) Type of sources \rightarrow BBHs, BNSs, BH-NS (with frequencies 0.6, 0.25, 0.15)
- 4) $M_{NS} = [1, 2]$ Mo
- 5) $M_{BH} = [3, 50]$ Mo
- 6) M_{BH} (in BH-NS) = $[3, 10]$ Mo

Errors Handling

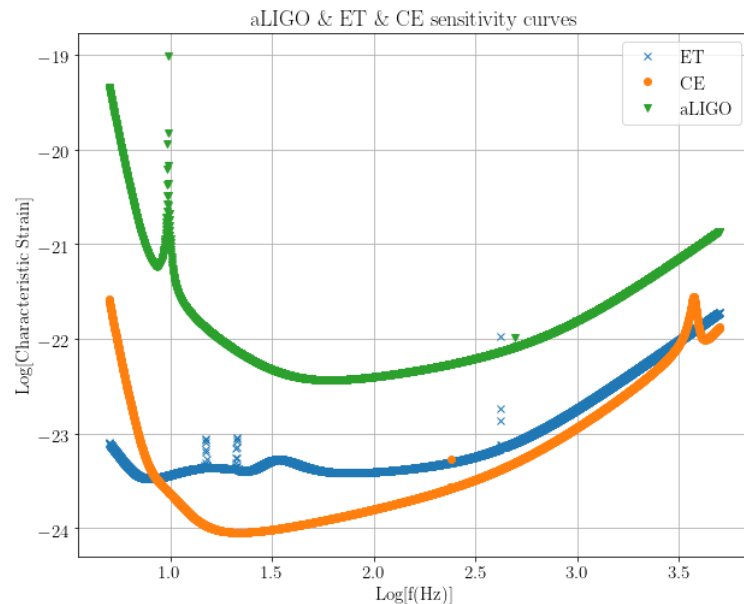
Model the distance errors

$$\sigma_{d_L} = \sqrt{\left(\frac{2d_L}{\rho}\right)^2 + (0.05z d_L)^2}$$

Instrument
 ρ : S/N

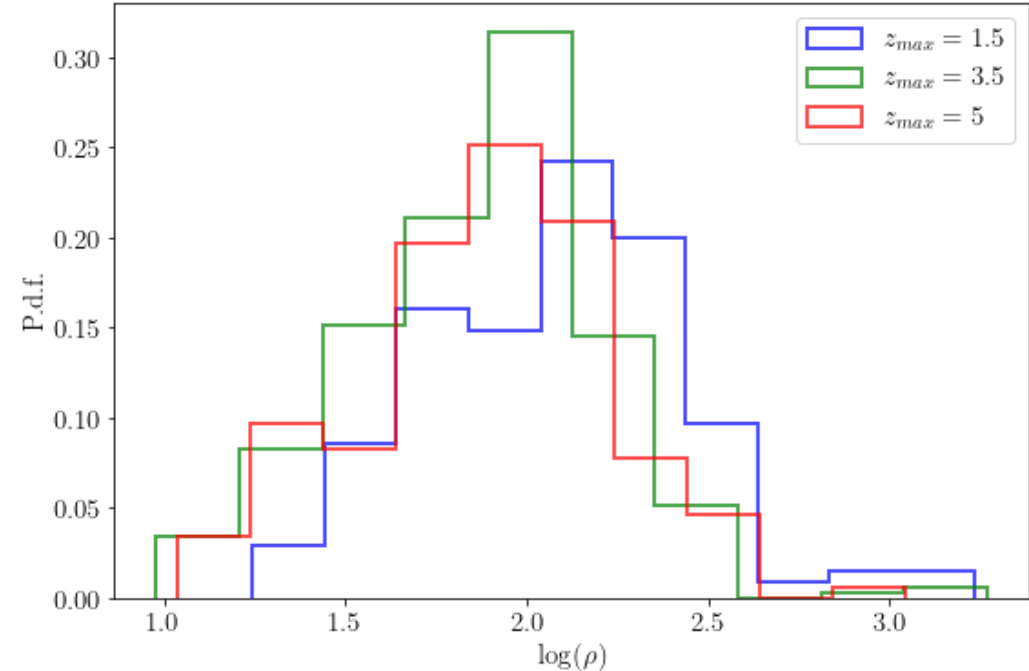
Lensing

Jönsson et al. 2010;
 Sathyaprakash et al. 2010;
 Zhao et al. 2011;
 Marra et al. 2013;
 Fleury et al. 2015

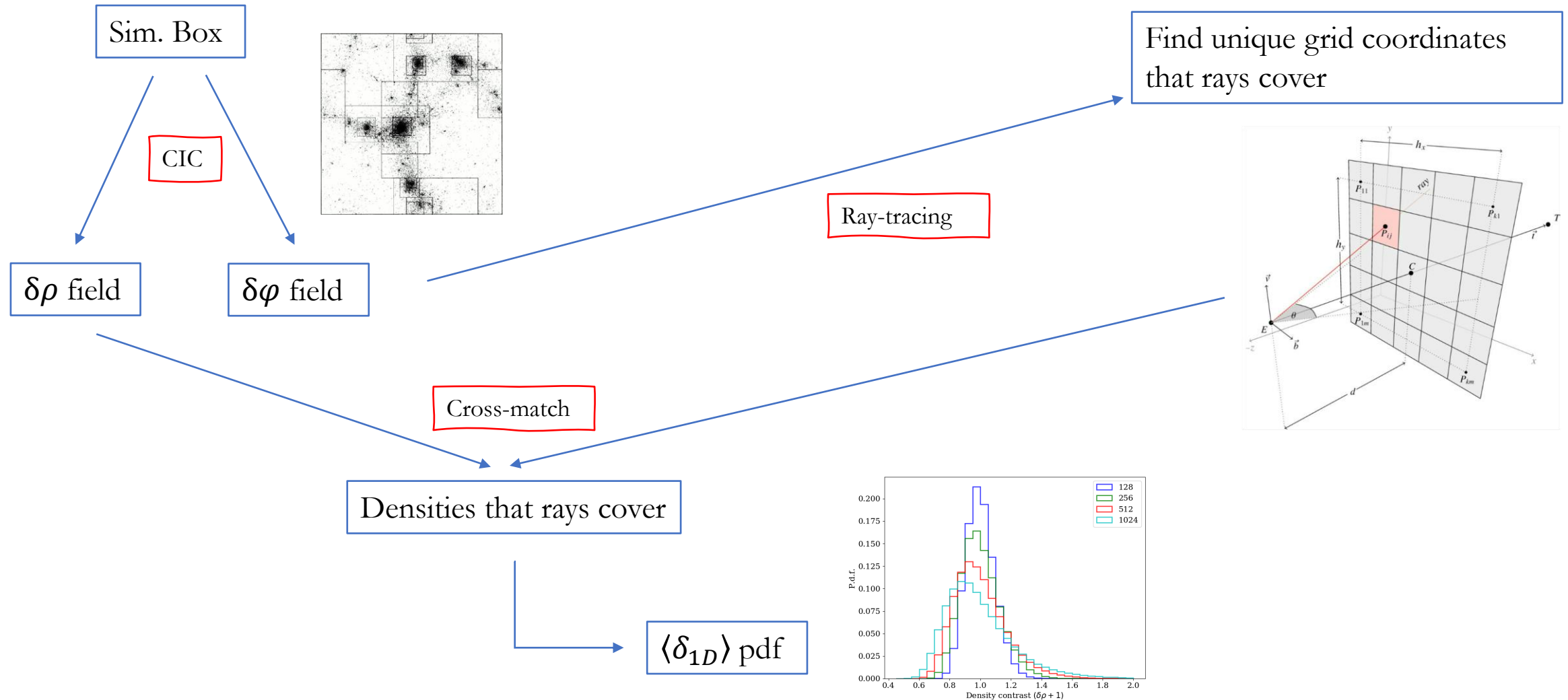


$$\chi^2 = \sum \frac{[d_{FRW}(z) - d_{GW}(z, a_i, \Omega_i)]^2}{\sigma(z)^2}$$

For ET:



How to Ray-trace?



Degeneracy with Cosmological Parameters?

A full analysis, would constrain simultaneously the cosmological parameters.

Based on (Busti et al. 2012b; Fleury et al. 2013; Dhawan et al. 2018) the degeneracy is not strong enough to significantly change the inferred cosmological parameters, when fitting observational data for the Hubble diagram.

So we choose to ignore this in our work.

Right: Constraints on (α, Ω_Λ) using a DR inhomogeneous model with constant α , for a flat universe. We find a weak effect on Ω_Λ . The red vertical line is the input value used in our simulations and the contours show (68%, 95.4%, 99.7%) confidence intervals respectively.

