Title: Weak gravitational lensing: from galaxy surveys to gravitational waves - VIRTUAL

Speakers: Guilherme Brando

Series: Cosmology & Gravitation

Date: January 11, 2024 - 11:00 AM

URL: https://pirsa.org/24010075

Abstract: In this talk, I will discuss two lines of research revolving around the study of weak gravitational lensing in our Universe. First, I will present a pipeline that has been in development to model the matter power spectrum from large to small scales, focusing on stage-IV photometric galaxy surveys. I will discuss the fundamental ingredients of this pipeline, the consistency checks performed to validate it, and how this new tool fares when performing a full Bayesian parameter estimation analysis with an LSST-like survey. In the second part of this talk, I will present a new and exciting methodology to study weakly-lensed gravitational waves in the wave-optics regime.

---

Zoom link https://pitp.zoom.us/j/98447653523?pwd=QjFDdk1LZ25LeDd6Nk5iRCtGbFNYQT09

# Weak gravitational lensing: from galaxy surveys to gravitational waves

Guilherme Brando

Perimeter Institute - 11/01/2024

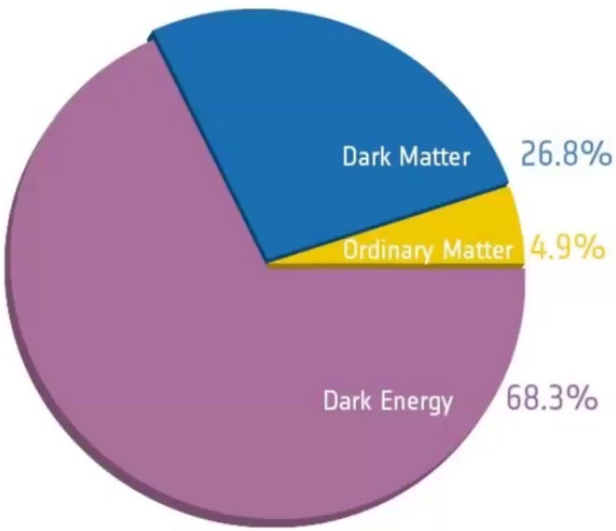
MAX-PLANCK-INSTITUT
FÜR GRAVITATIONSPHYSIK
(Albert-Einstein-Institut)

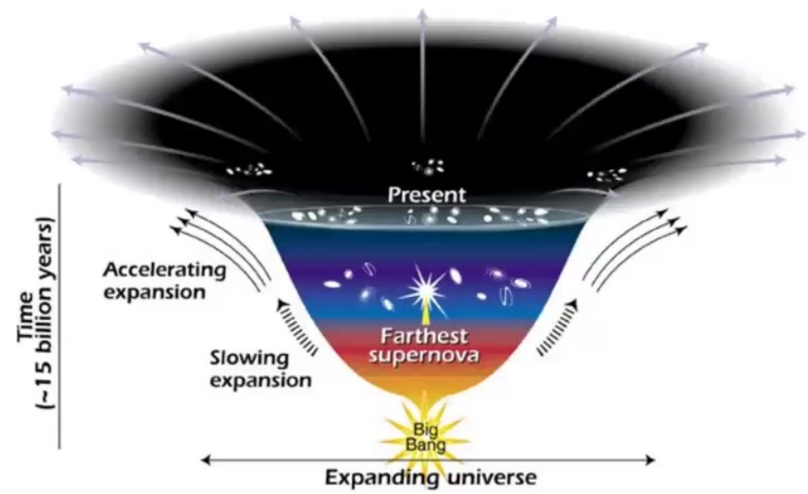
Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

# Motivation

- Standard Model

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

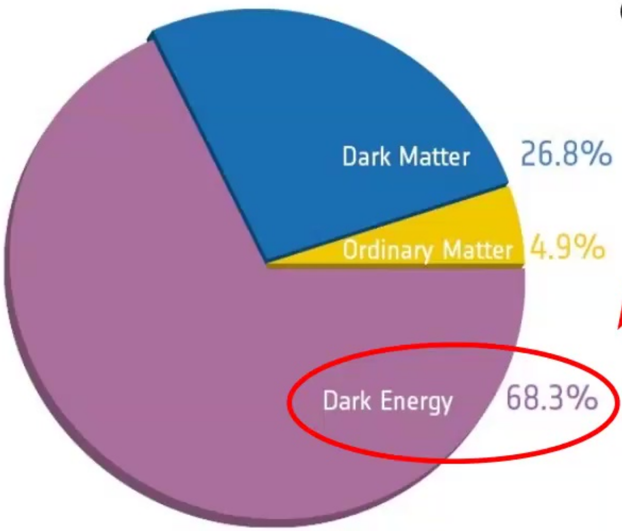


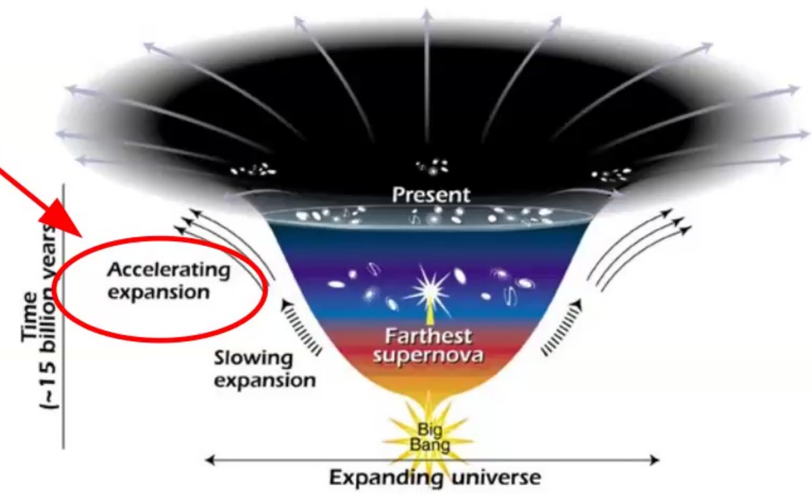



# Motivation

- Standard Model

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



# Motivation

- Why look for beyond-LCDM theories?
  - Cosmological Constant problem → orders of magnitude of discrepancy
  - Cosmological tensions
  - Stress-tests of the concordance model
  - Cosmological tests of gravity

# Modelling Small Scales

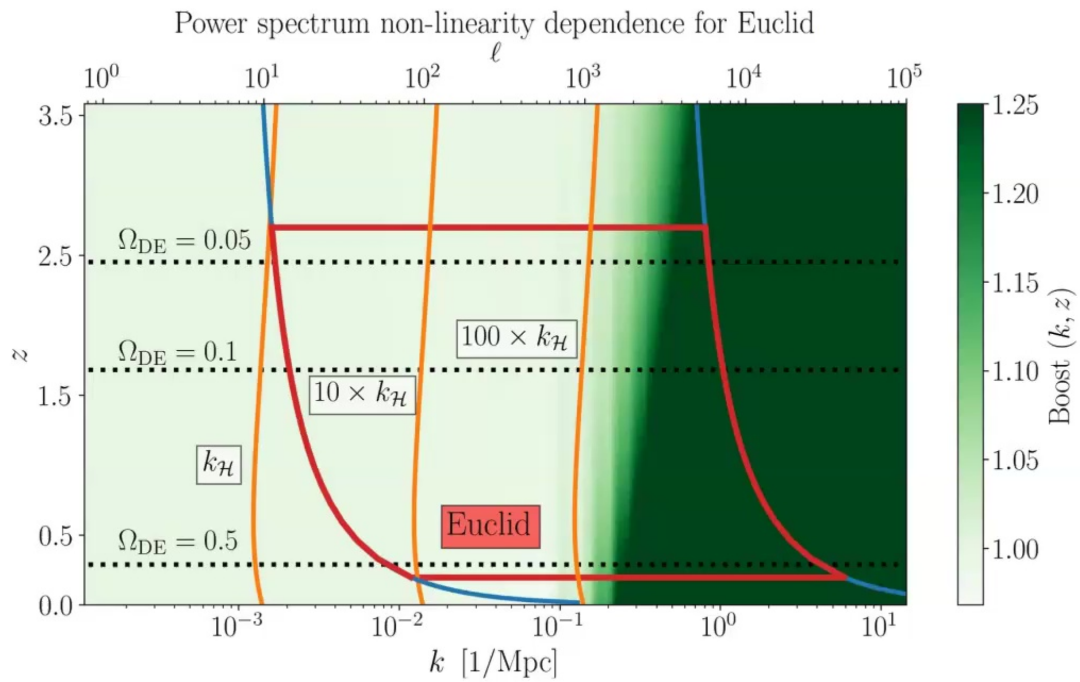
- Large scale structure cosmology → modelling of beyond-LCDM theories in the non-linear regime (small scales)

  - Current fast and accurate tools

    Einstein-Boltzmann solvers

    ↓

    Only valid in linear scales!!

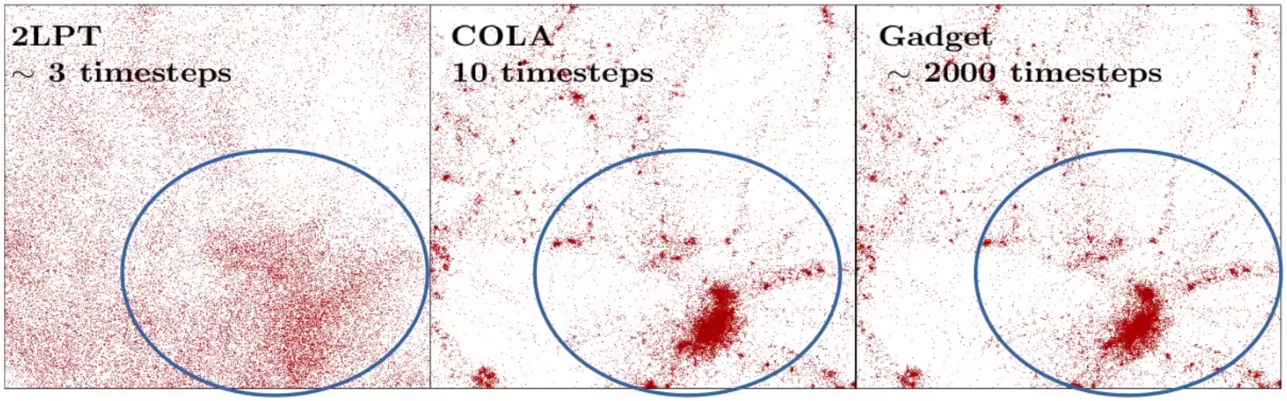


# Modelling Small Scales

- Large scale structure cosmology → modelling of beyond-LCDM theories in the non-linear regime (small scales)
  - Difficulties of modelling non-linear scales in these models:
    - Most predictive way is non-perturbatively → N-body simulations
    - Time-consuming and computationally expensive → even worse for beyond-LCDM
    - Tradeoff between: **predictive power x cost**
    - One viable alternative: COmoving Lagrangian Approximation method (COLA)

# Modelling Small Scales

- One viable alternative: COmoving Lagrangian Approximation method
  - Combines 2LPT to describe large scales with a Particle-Mesh algorithm to solve for small scales
    - ✔ Fast realizations of the density field → two orders of magnitude faster than full N-body




S. Tassev et al - 1301.0322

# Modelling Small Scales

- One viable alternative: COmoving Lagrangian Approximation method
  - Combines 2LPT to describe large scales with a Particle-Mesh algorithm to solve for small scales
    - ✔ Computationally less costly → reduced wall clock

| SimType | Box size ($h^{-3}$Mpc$^3$) | $N_{\rm par}$ | $z_{\rm init}$ | $a_{\rm init}$ | $a_{\rm final}$ | $da$ | $N_{\rm step}$ | CPUs | Wall-clock time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| GADGET-2 | $800^3$ | $1024^3$ | 49 | 1/50 | 1 | – | 3676 | 252 | 149.7 |
| COLA | $800^3$ | $1024^3$ | 29 | 1/30 | 1 | 1/30 | 30 | 256 | 0.39 |
| COLA | $800^3$ | $1024^3$ | 49 | 1/50 | 1 | 1/50 | 50 | 256 | 0.75 |
| COLA | $800^3$ | $1024^3$ | 59 | 1/60 | 1 | 1/60 | 60 | 256 | 0.76 |
| COLA | $800^3$ | $1024^3$ | 119 | 1/120 | 1 | 1/120 | 120 | 256 | 1.51 |

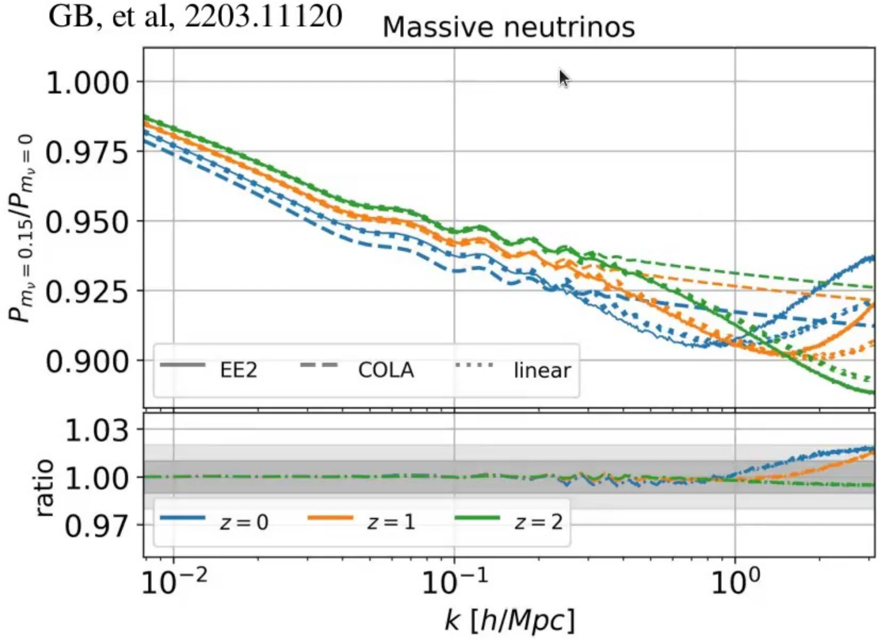
J. Ding et al - 2311.00981

# Modelling Small Scales

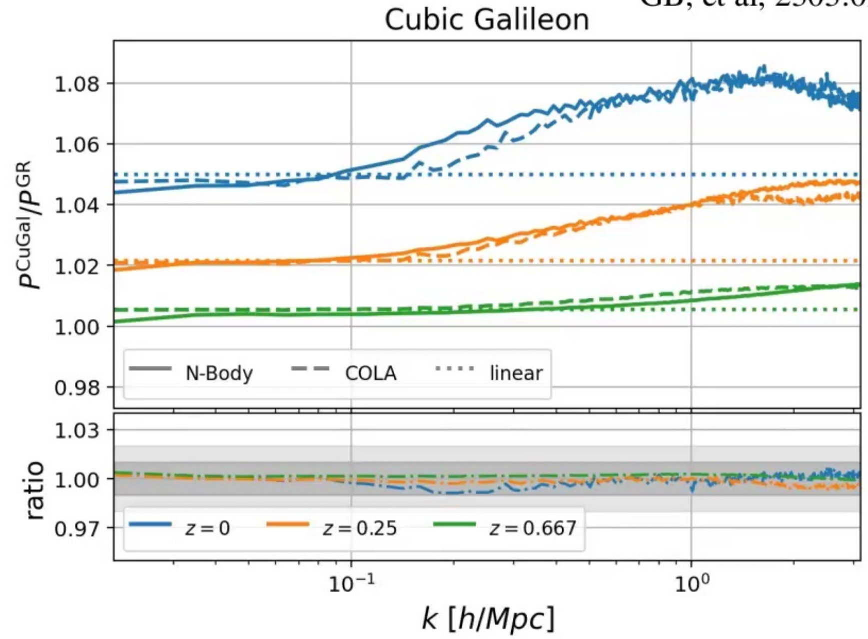
- One viable alternative: COmoving Lagrangian Approximation method

  ✔ Examples of extensions to LCDM in COLA

GB, et al, 2203.11120



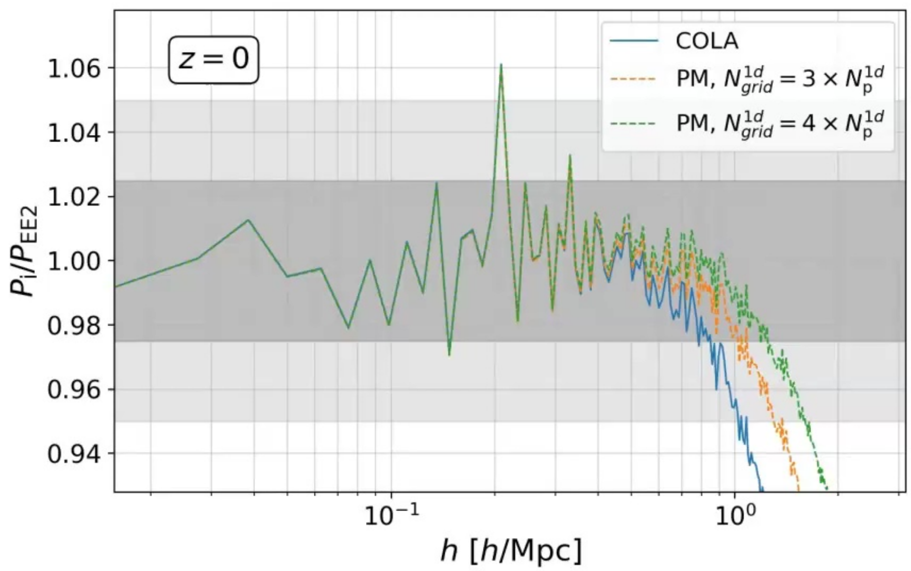

GB, et al, 2303.09549

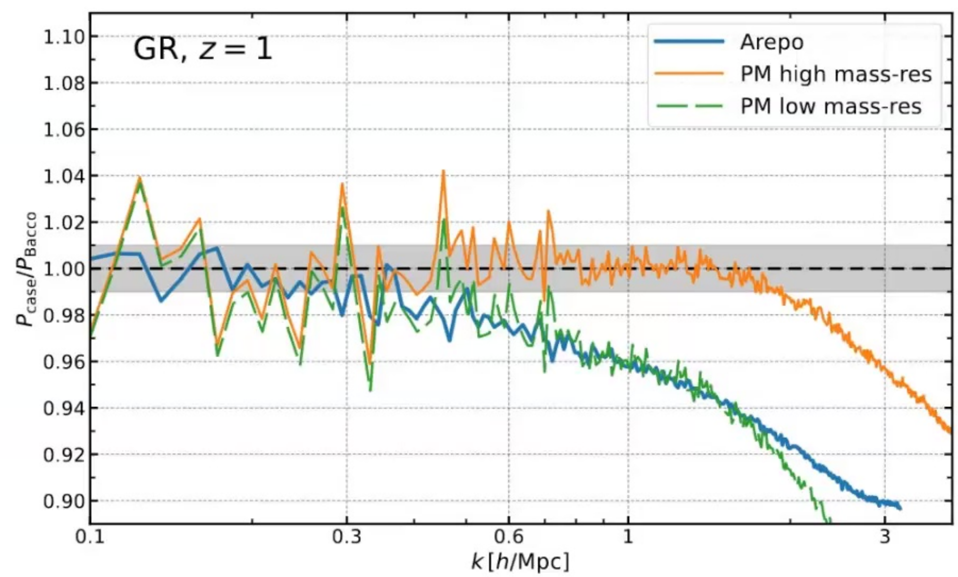


# Modelling Small Scales

- One viable alternative: COmoving Lagrangian Approximation method

  ✔ Validated and benchmarked



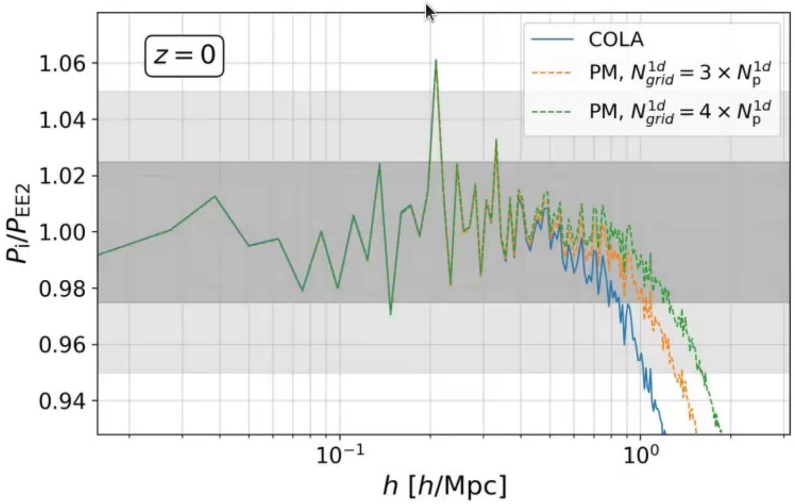

B. Fiorini et al - 2310.05786

# Modelling Small Scales

- Emulation methods for the matter power spectrum → emulation of the boost

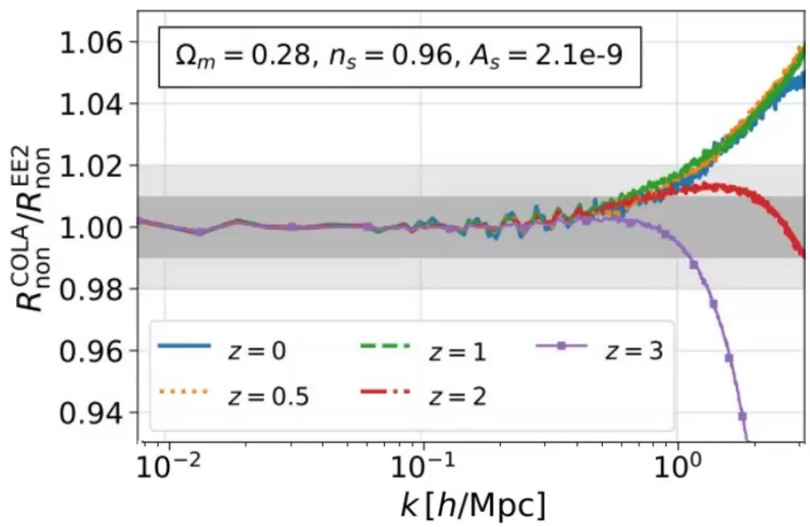
$$B = \frac{P_{\rm non}}{P_{\rm lin}} \qquad B^{\rm case} = B^{\rm ref}\frac{R^{\rm case}_{\rm non}}{R^{\rm case}_{\rm lin}} \qquad R_{\rm lin/non} = \frac{P^{\rm case}_{\rm lin/non}}{P^{\rm ref}_{\rm lin/non}}$$

EuclidEmulator2




COLA

GB et al - 2203.11120



# Modelling Small Scales

- Large scale strcture cosmology → modelling of beyond-LCDM theories in the non-linear regime (small scales)

  - I have shown examples of COLA for certain fixed cosmologies and theories.

  - To go further we need:

    - Construct a COLA-based emulator → wCDM (validation!)
    - Perform a full parameter estimation for a stage-IV survey

| | Default-precision | High-precision |
|---|---|---|
| $N_{\mathrm{particles}}$ | $1024^3$ | $1024^3$ |
| L [Mpc/h] | 1024 | 512 |
| $N_{\mathrm{mesh}}$ | $2048^3$ | $3072^3$ |
| $z_{\mathrm{initial}}$ | 19 | 19 |
| $\ell_{\mathrm{force}}$ [Mpc/h] | 0.5 | 0.17 |

| Parameter | Min. | Max. | Ref. |
|---|---|---|---|
| $\Omega_{\mathrm{m}}$ | 0.24 | 0.40 | 0.319 |
| $\Omega_{\mathrm{b}}$ | 0.04 | 0.06 | 0.049 |
| $n_s$ | 0.92 | 1.00 | 0.96 |
| $A_s \times 10^{-9}$ | 1.7 | 2.5 | 2.1 |
| $h$ | 0.61 | 0.73 | 0.67 |
| $w$ | $-1.3$ | $-0.7$ | $-1.0$ |

# LSSTY1 – like survey

- Cosmic shear:
  - Shear angular power spectrum:

$$C_{\kappa\kappa}^{ij}(\ell) = \int \frac{d\chi}{\chi^2} q_\kappa^i(\chi) q_\kappa^j(\chi) P_{\rm NL}\left(k = \frac{\ell + 1/2}{\chi}, z(\chi)\right)$$

  - 5 tomographic bins with source and lens galaxies drawn from:

$$n(z) \propto z^2 \exp[-(z/z_0)^\alpha]$$
$$(z_0, \alpha) = (0.191, 0.870)$$

  - Different masks (scale cuts) per bin

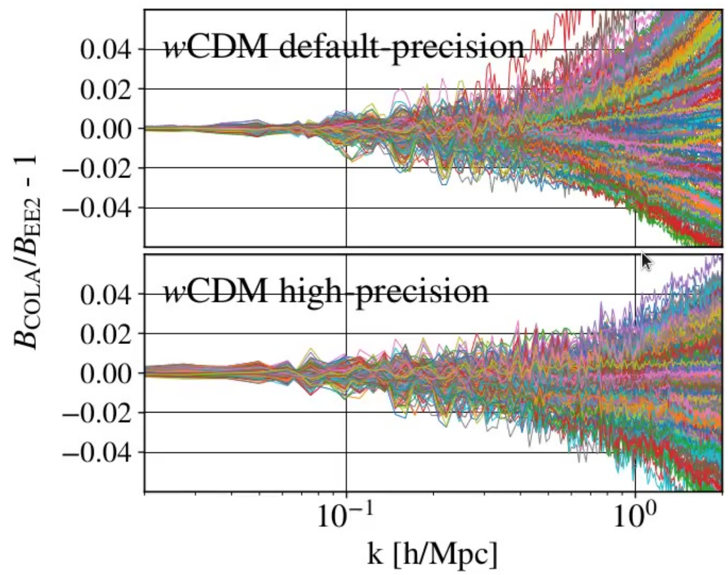
| Parameter | Fiducial | Prior |
|---|---|---|
| **Survey specifications** | | |
| Area | 12300 $\deg^2$ | – |
| Shape noise per component | 0.26 | – |
| $n_{\rm eff}^{\rm sources}$ | 11.2 $\rm arcmin^{-2}$ | – |
| $n_{\rm eff}^{\rm lens}$ | 18 $\rm arcmin^{-2}$ | – |
| **Photometric redshift offsets** | | |
| $\Delta z_{\rm source}^i$ | 0 | $\mathcal{N}$[0, 0.02] |
| **Intrinsic alignment (NLA)** | | |
| $A^1$ | 0.7 | $\mathcal{U}$[-5, 5] |
| $\eta^1$ | -1.7 | $\mathcal{U}$[-5, 5] |
| **Shear calibration** | | |
| $m^i$ | 0 | $\mathcal{N}$[0, 0.005] |
| **Baryon PCA amplitude** | | |
| $Q^1$ | 3 | $\mathcal{U}$[0, 4] |
| $Q^2$ | 0 | $\mathcal{U}$[-2.5, 2.5] |

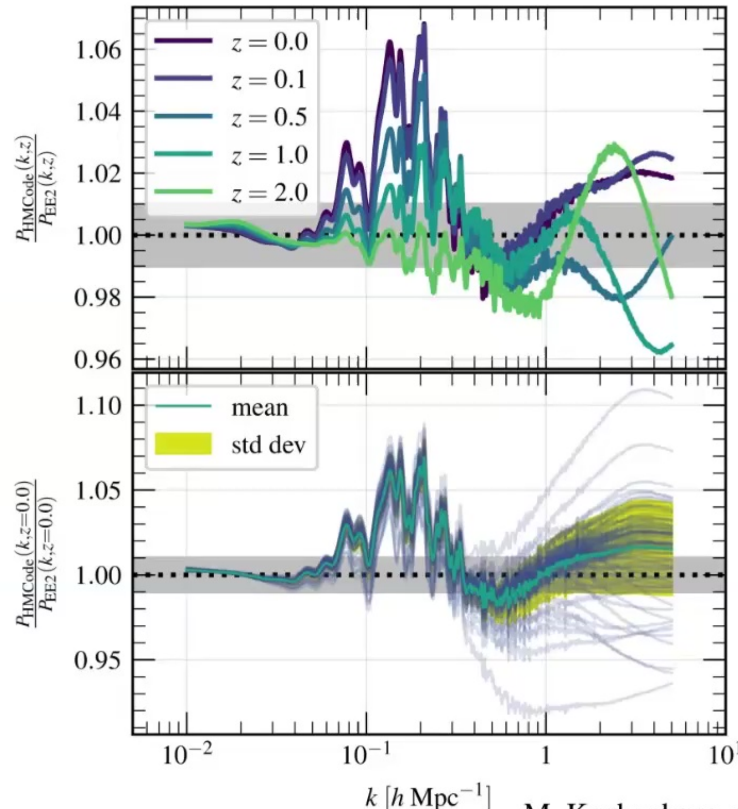
| | bin 0 | bin 1 | bin 2 | bin 3 | bin 4 |
|---|---|---|---|---|---|
| M2 | 5.7 | 4.3 | 3.7 | 3.4 | 0.5 |
| M3 | 2.9 | 2.1 | 1.9 | 1.7 | 0.2 |
| M4 | 1.4 | 1.1 | 0.9 | 0.8 | 0.1 |

Maximum scale $k_{\rm max}[h/Mpc]$

# Emulator

- Comparison between COLA and HMCode:



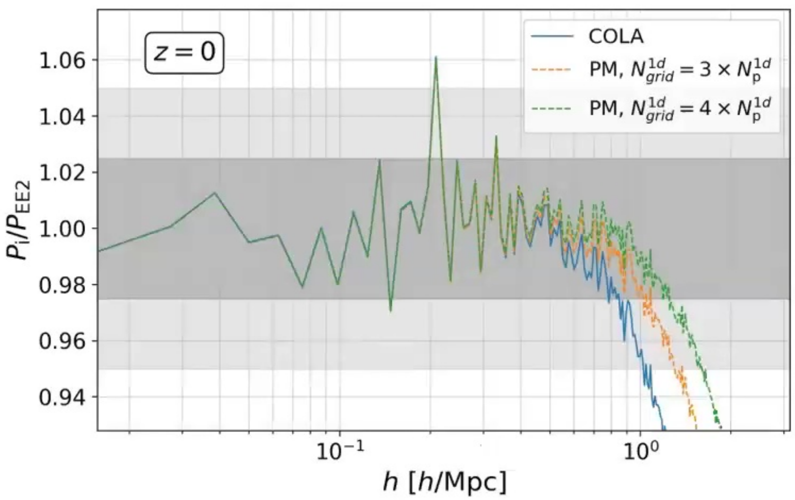

M. Knabenhans, et al - 2010.11288

# Modelling Small Scales

- Emulation methods for the matter power spectrum → emulation of the boost

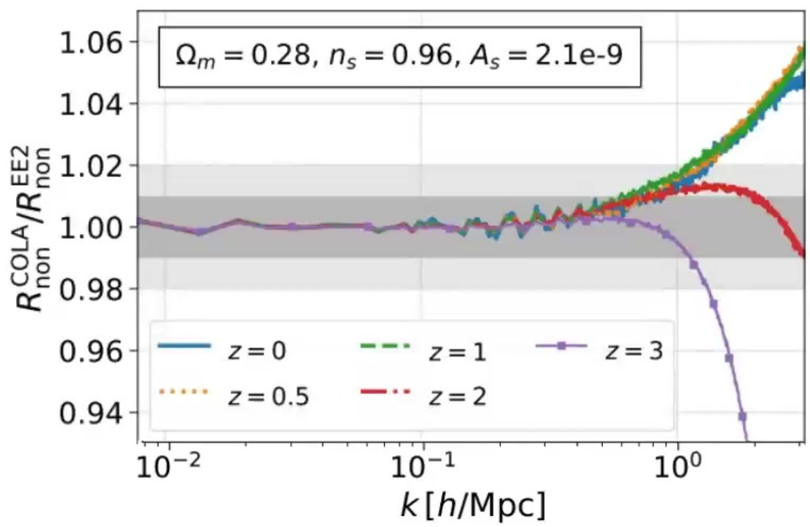
$$B = \frac{P_{\rm non}}{P_{\rm lin}} \qquad B^{\rm case} = B^{\rm ref}\frac{R^{\rm case}_{\rm non}}{R^{\rm case}_{\rm lin}} \qquad R_{\rm lin/non} = \frac{P^{\rm case}_{\rm lin/non}}{P^{\rm ref}_{\rm lin/non}}$$

EuclidEmulator2




COLA

GB et al - 2203.11120

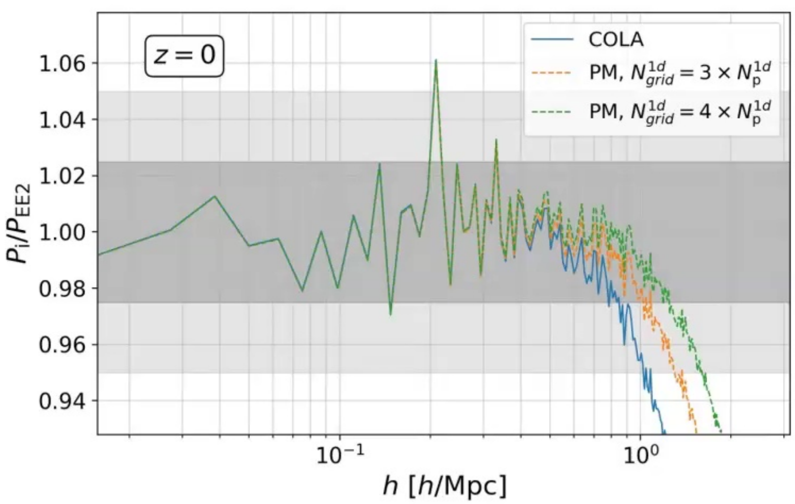


# Modelling Small Scales

- Emulation methods for the matter power spectrum → emulation of the boost

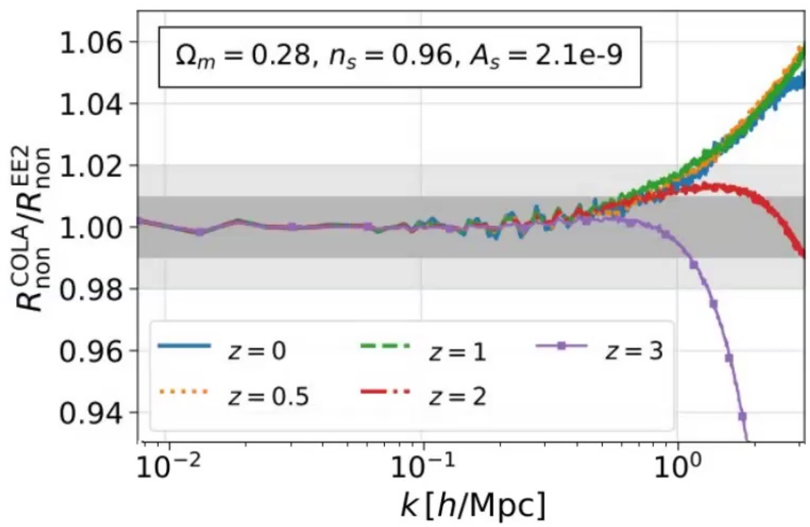
$$B = \frac{P_{\rm non}}{P_{\rm lin}} \qquad B^{\rm case} = B^{\rm ref}\frac{R^{\rm case}_{\rm non}}{R^{\rm case}_{\rm lin}} \qquad R_{\rm lin/non} = \frac{P^{\rm case}_{\rm lin/non}}{P^{\rm ref}_{\rm lin/non}}$$

EuclidEmulator2



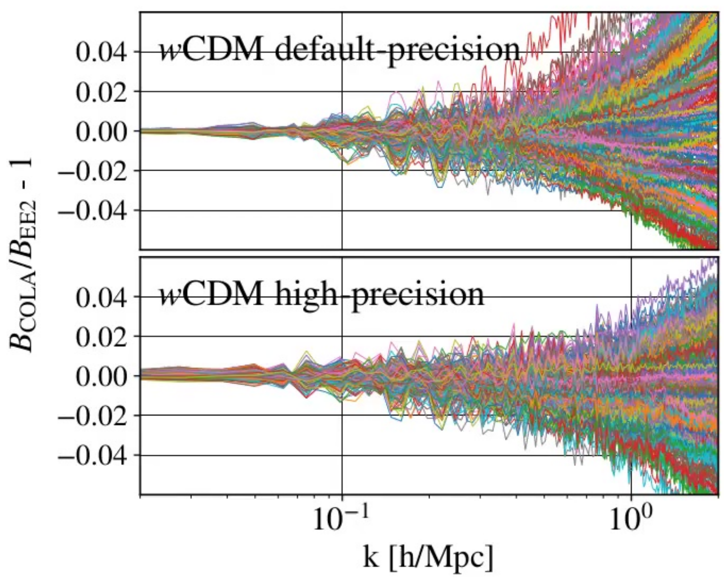

COLA

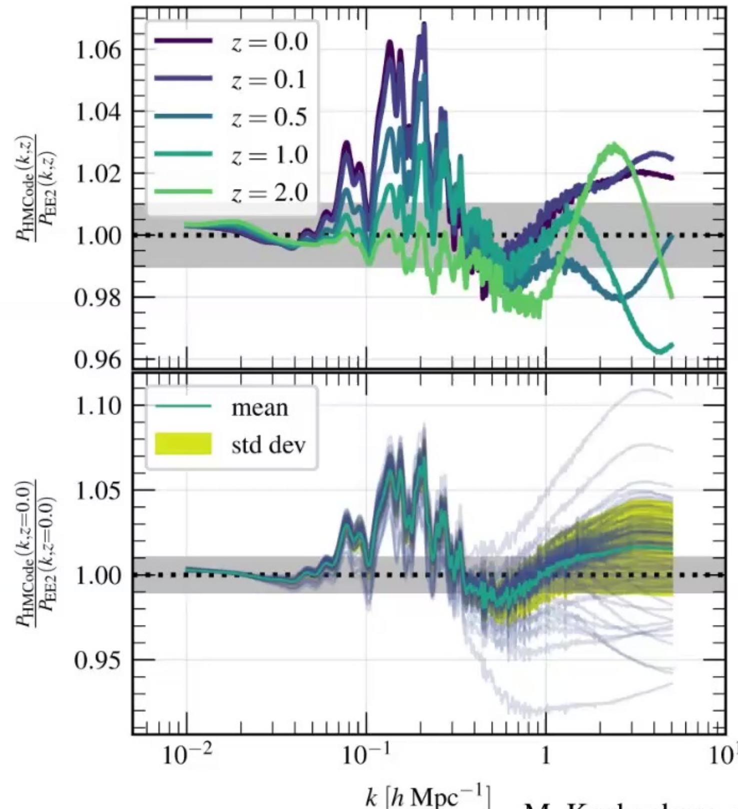
GB et al - 2203.11120



# Emulator

- Comparison between COLA and HMCode:

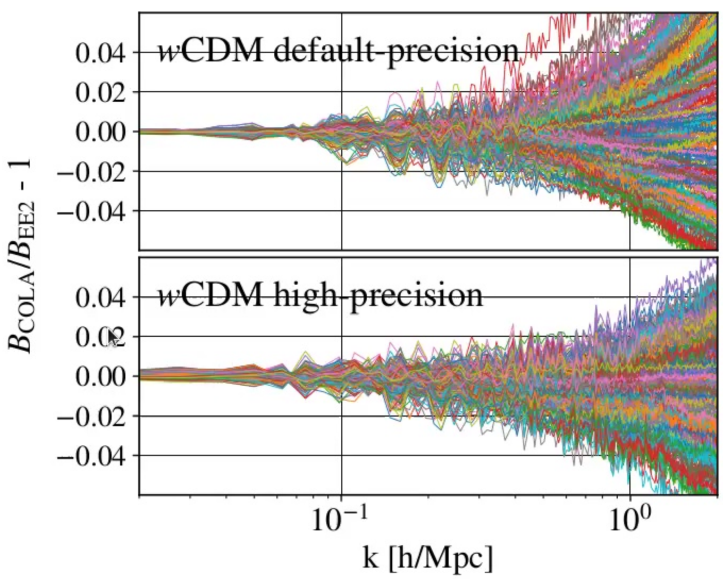



M. Knabenhans, et al - 2010.11288

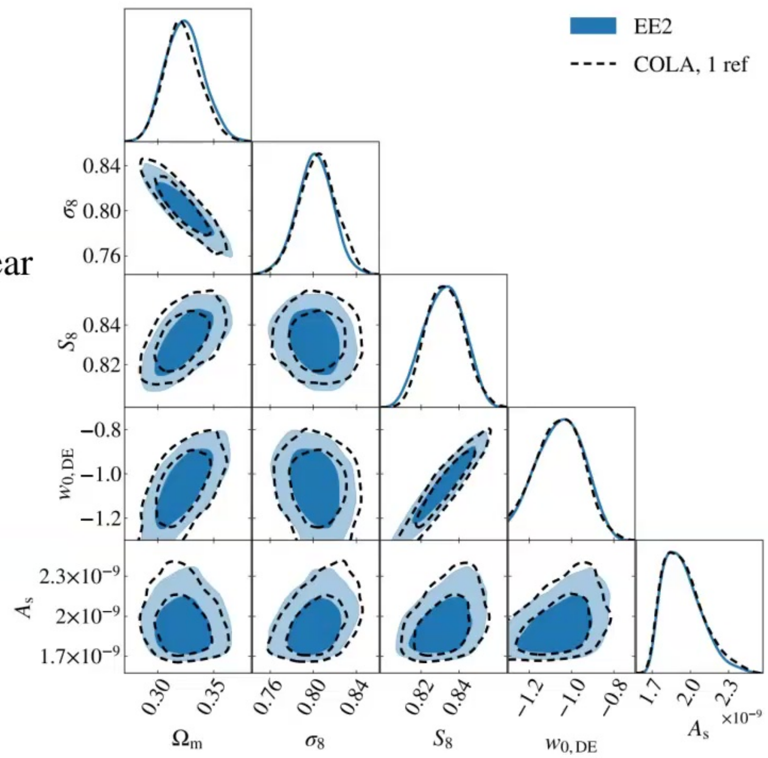
# Results

- Results:



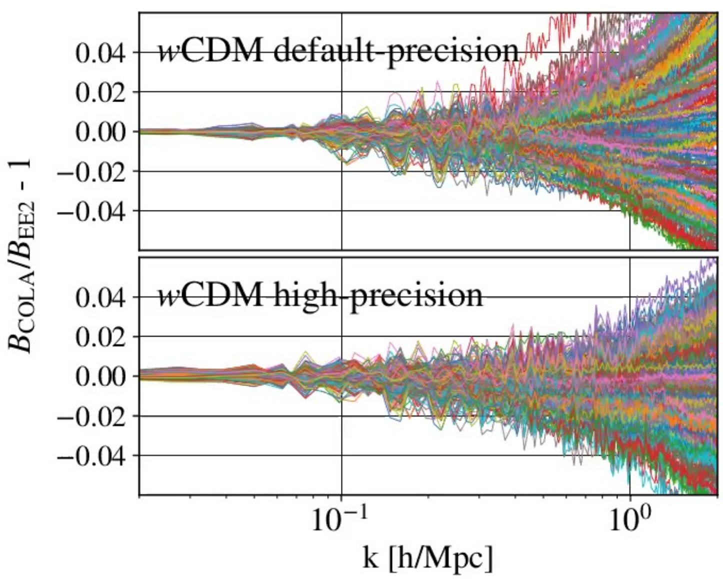

LSST-Y1 Cosmic Shear forecast

Fiducial data vector: EE2 ref + M2 mask

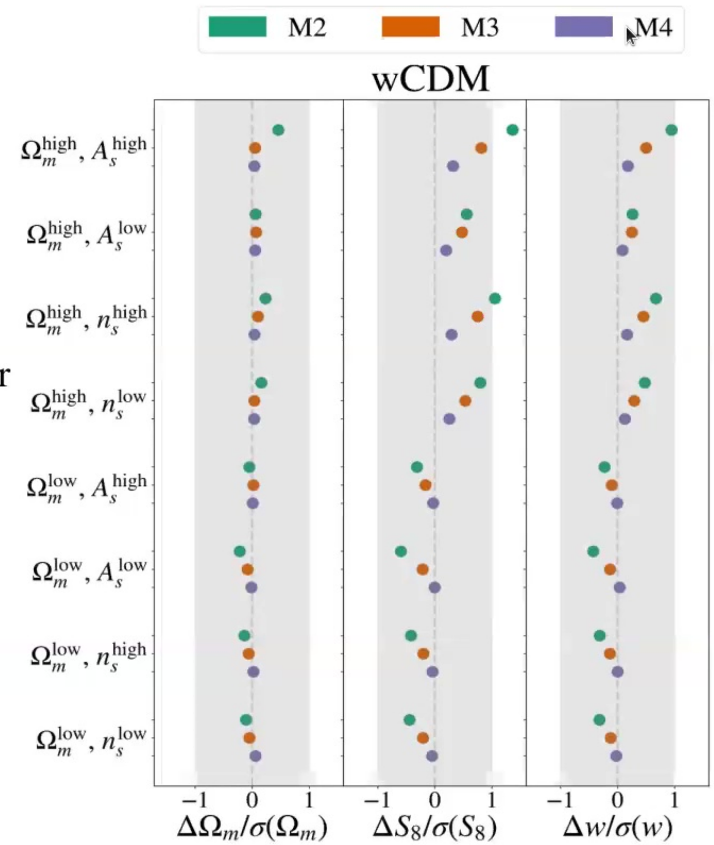


# Results

- Results:

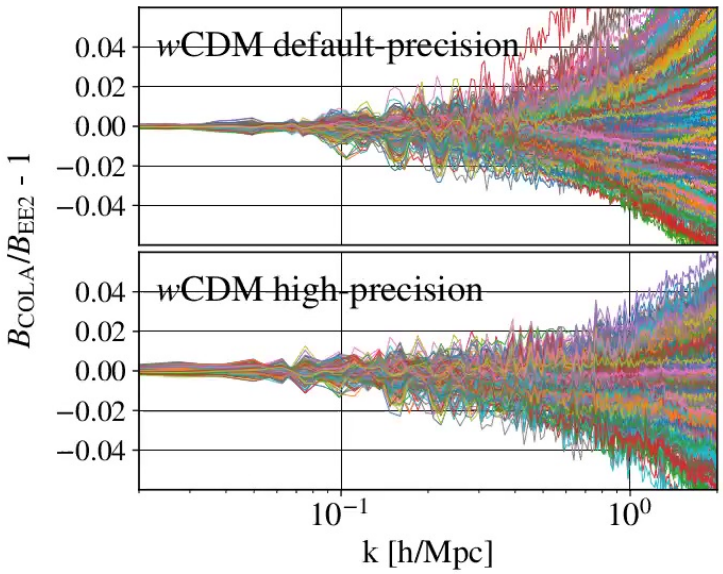



LSST-Y1 Cosmic Shear forecast

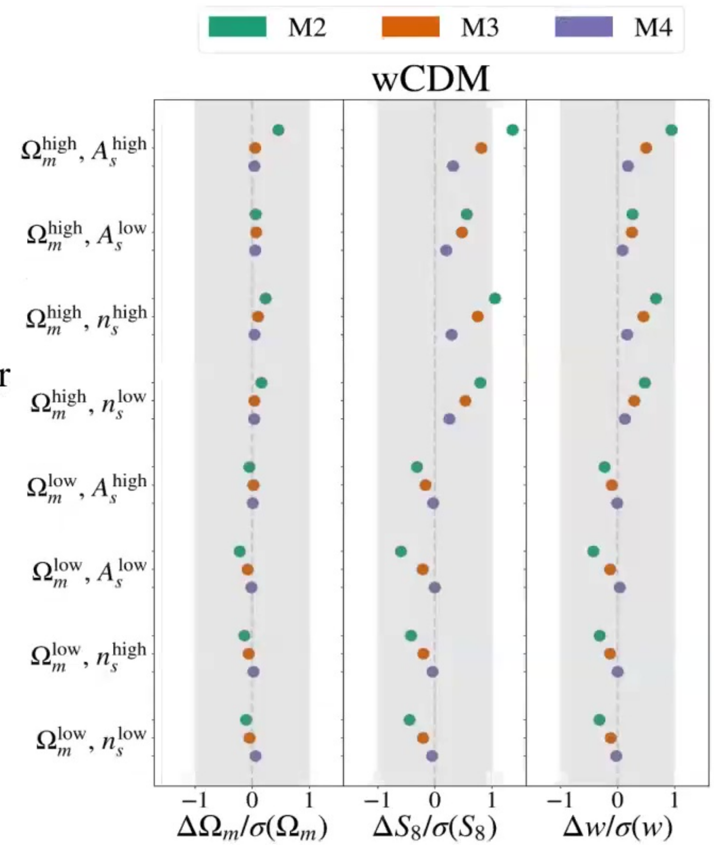


# Results

- Results:




LSST-Y1 Cosmic Shear forecast

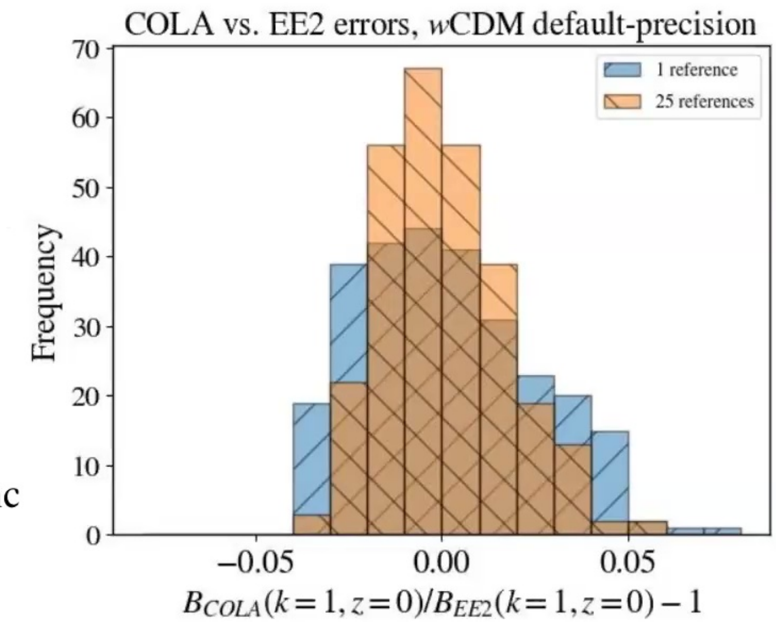


# Results

- Results:
  - Emulated boost has considerable scatter at high k
  - A possible solution is to increase the number of reference boosts:

$$B^{\rm case} = B^{\rm ref}\frac{R^{\rm case}_{\rm non}}{R^{\rm case}_{\rm lin}} \qquad B^{\rm case}(k,z) = \sum_{i=1}^{N_{\rm refs}} w_i B_i^{\rm case}(k,z)$$

  - Increases the calibration process, reduces the distanc between points to be emulated



# Weak gravitational lensing: from galaxy surveys to gravitational waves

Guilherme Brando

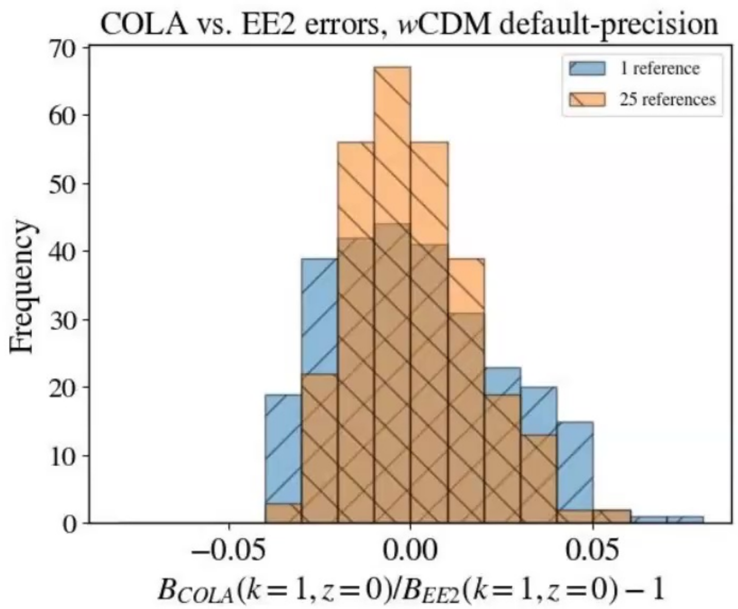
Perimeter Institute - 11/01/2024

MAX-PLANCK-INSTITUT
FÜR GRAVITATIONSPHYSIK
(Albert-Einstein-Institut)

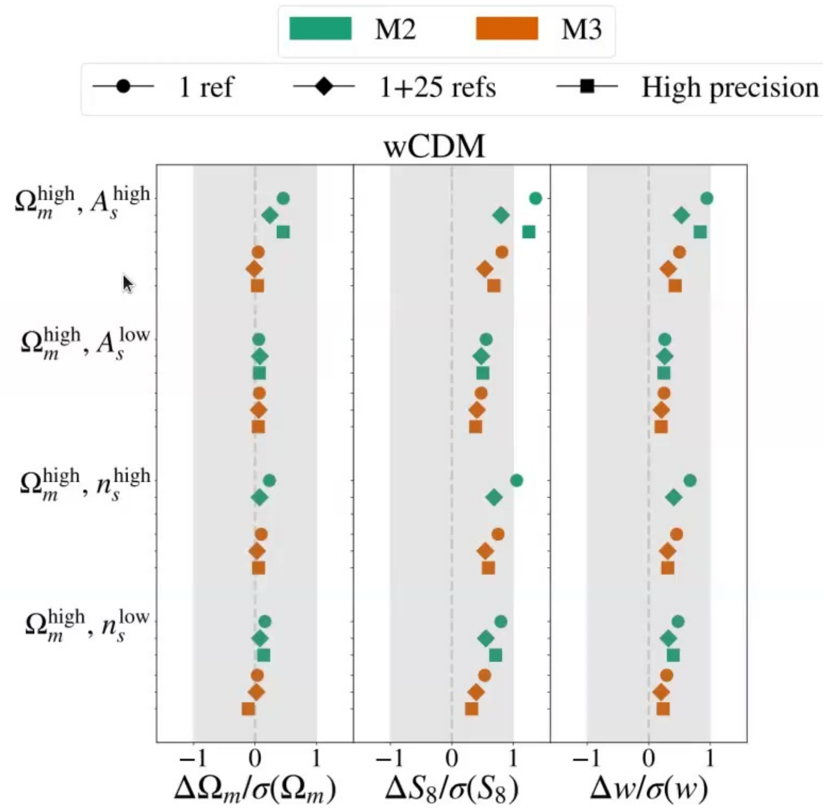
Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

# Results

- Results:

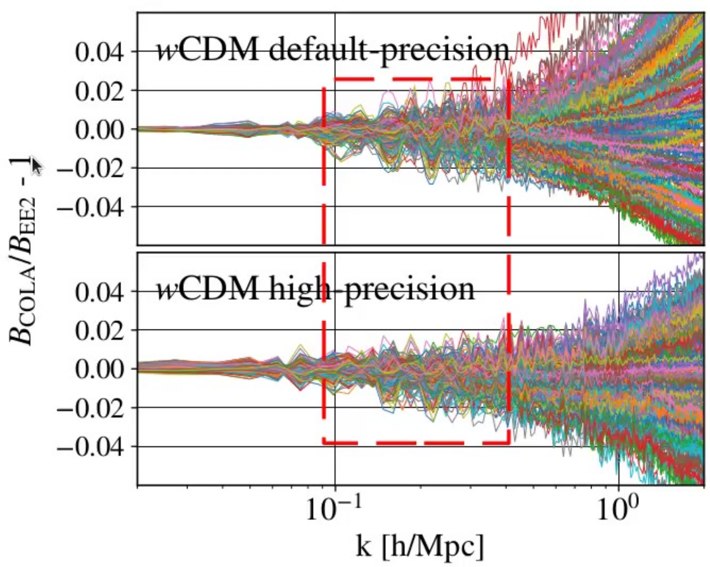


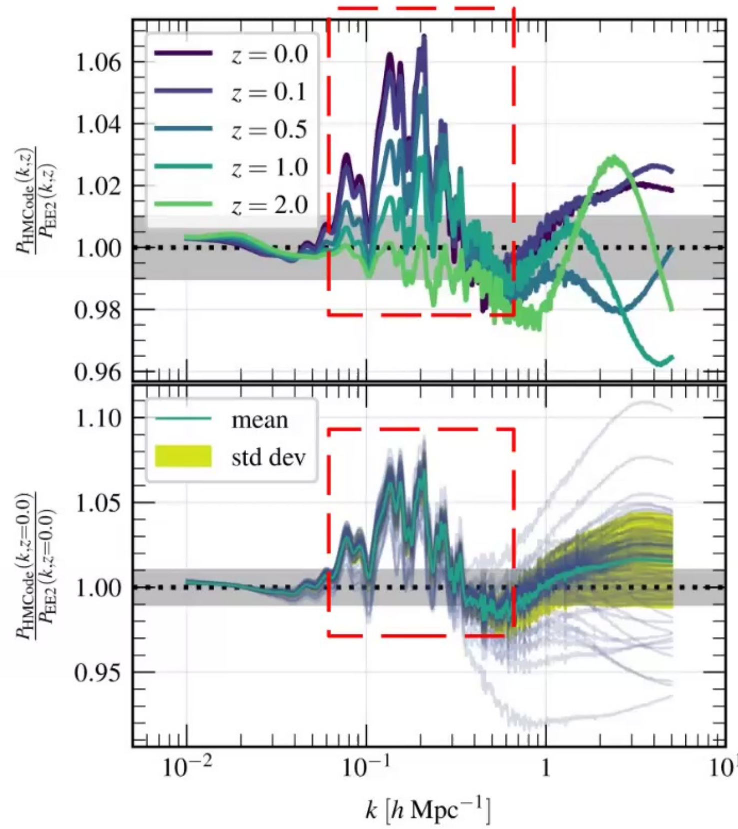

LSST-Y1 Cosmic Shear forecast



# Future

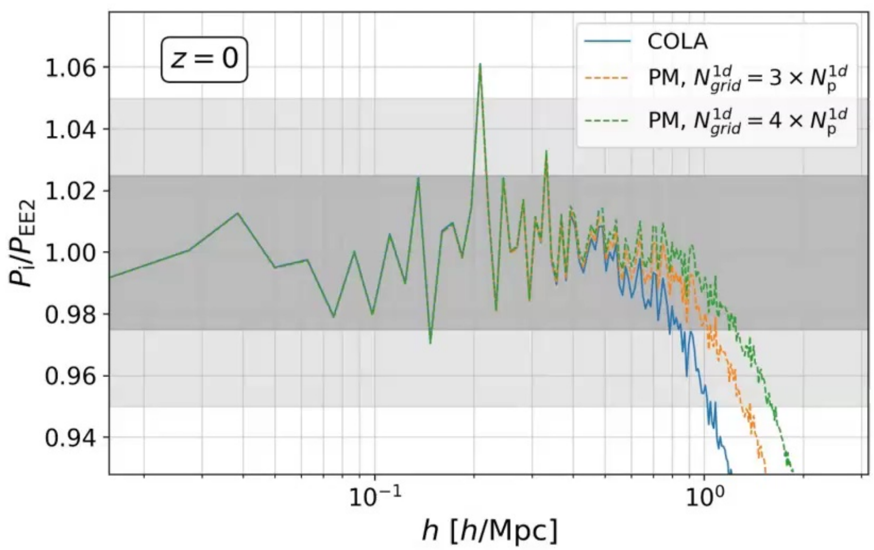
- Where do we need to improve?
  - Reduce BAO-scale scatter:

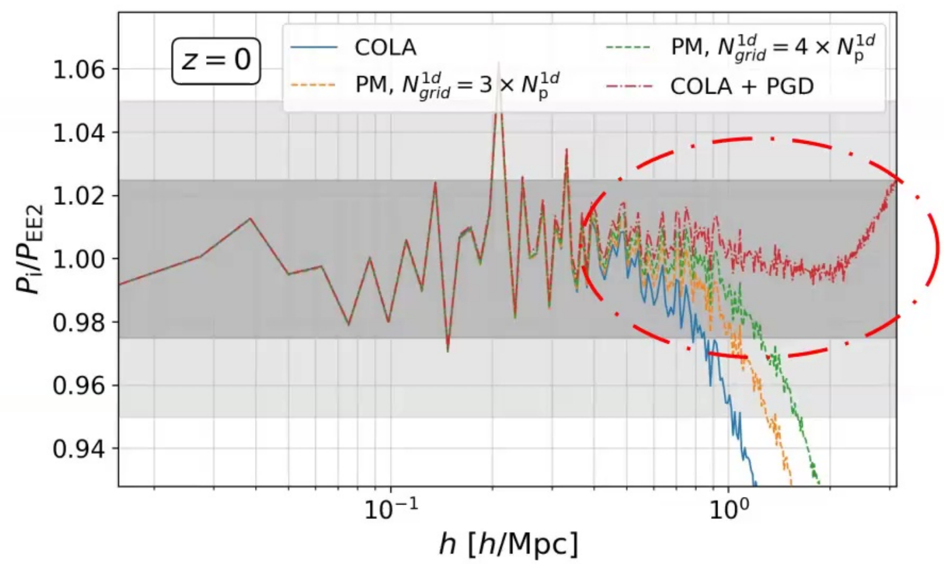


# Future

- Where do we need to improve?
  - Tame high-k behaviour
    - Potential Gradient Descent (PGD): Biwei Dai, Yu Feng and Uros Seljak – 1804.00671

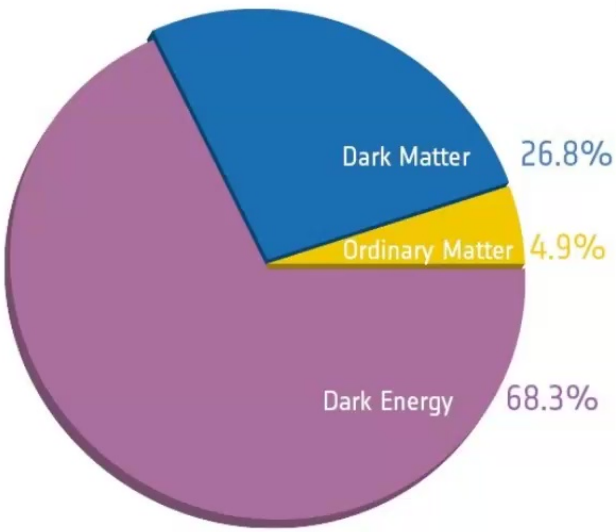


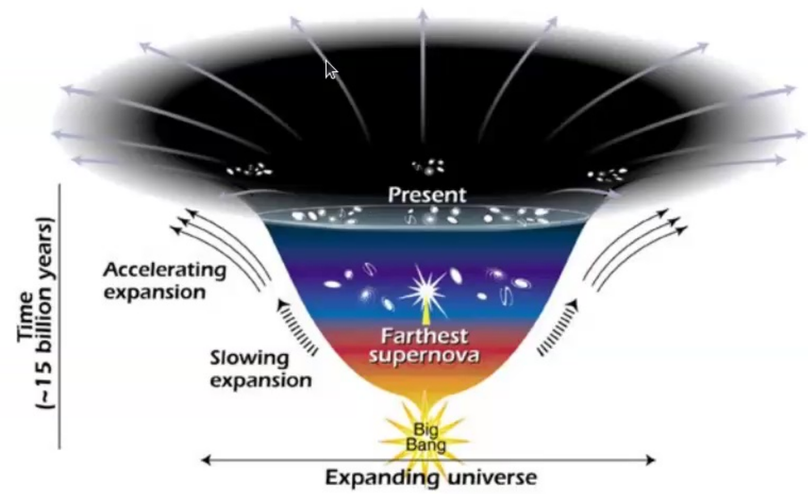



# Motivation

- Standard Model

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



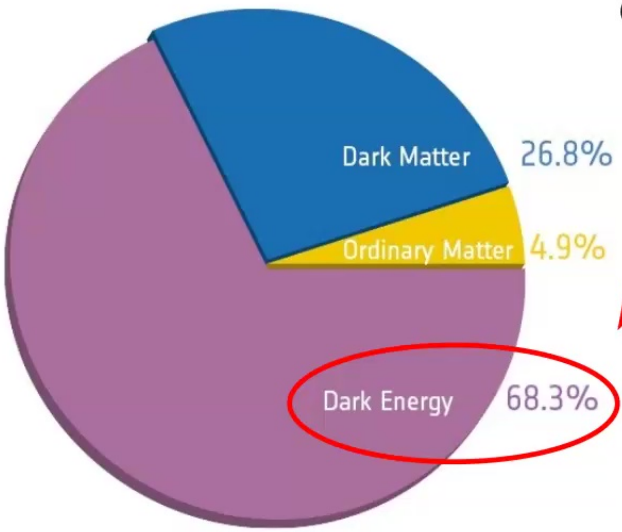



# Conclusions

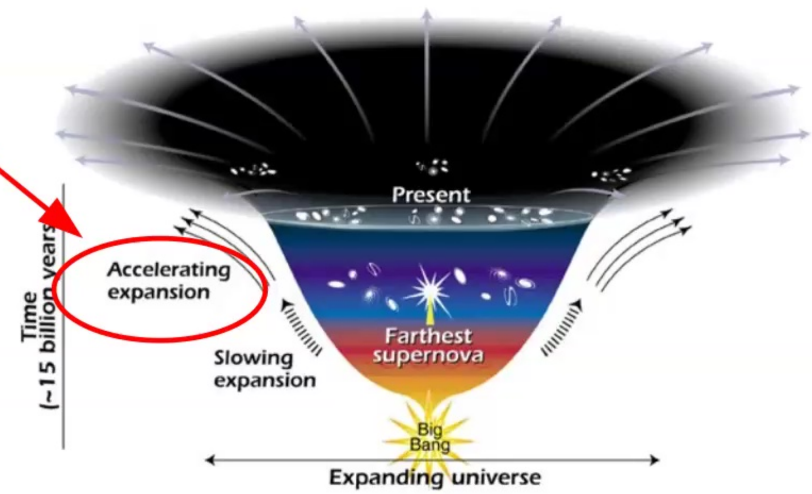
- Where do we need to go?
  - Galaxy clustering → go beyond linear bias
  - Add baryonic effects → post processing, baryonification algorithms
  - 3x2pt analysis

# Motivation

- Standard Model




$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

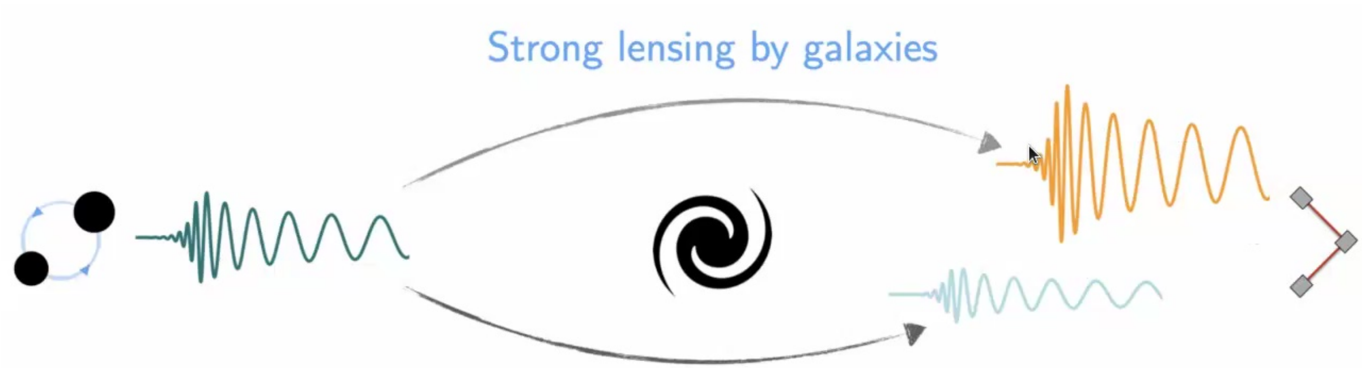


# GW lensing - Introduction

– Gravitational Waves Lensing:

- Similar to electromagntic waves, GWs are lensed when propagating through an object

- The wavelength of GWs is given by the mass of the coalescing objects, which can have masses ranging from stellar mass to a few percent of the mass of galaxies



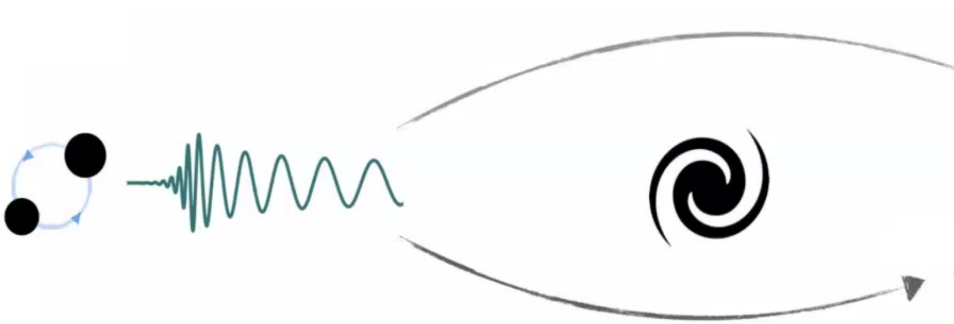
# GW lensing - Introduction

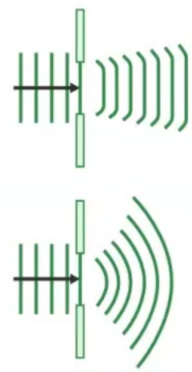
- Gravitational Waves Lensing:

  - But the wavelenght of GWs can be of the same order of magnitude of the size of the lens object.

  - Propagation no longer obeys the geometrical optics expansion → Wave Optics Effects (diffraction, intereference, ...)

S. Savastano, + 2306.05282
M. Calışkan, + 2206.02803
R. Takahashi, + 0305055





# Motivation

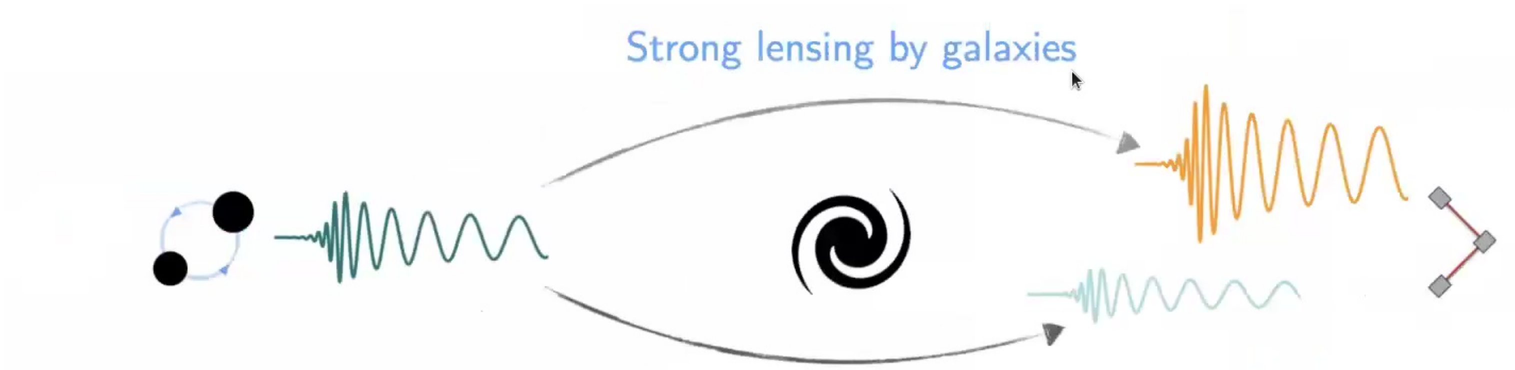
- Why look for beyond-LCDM theories?
  - Cosmological Constant problem → orders of magnitude of discrepancy
  - Cosmological tensions
  - Stress-tests of the concordance model
  - Cosmological tests of gravity

# GW lensing - Introduction

- Gravitational Waves Lensing:

  - Similar to electromagntic waves, GWs are lensed when propagating through an object

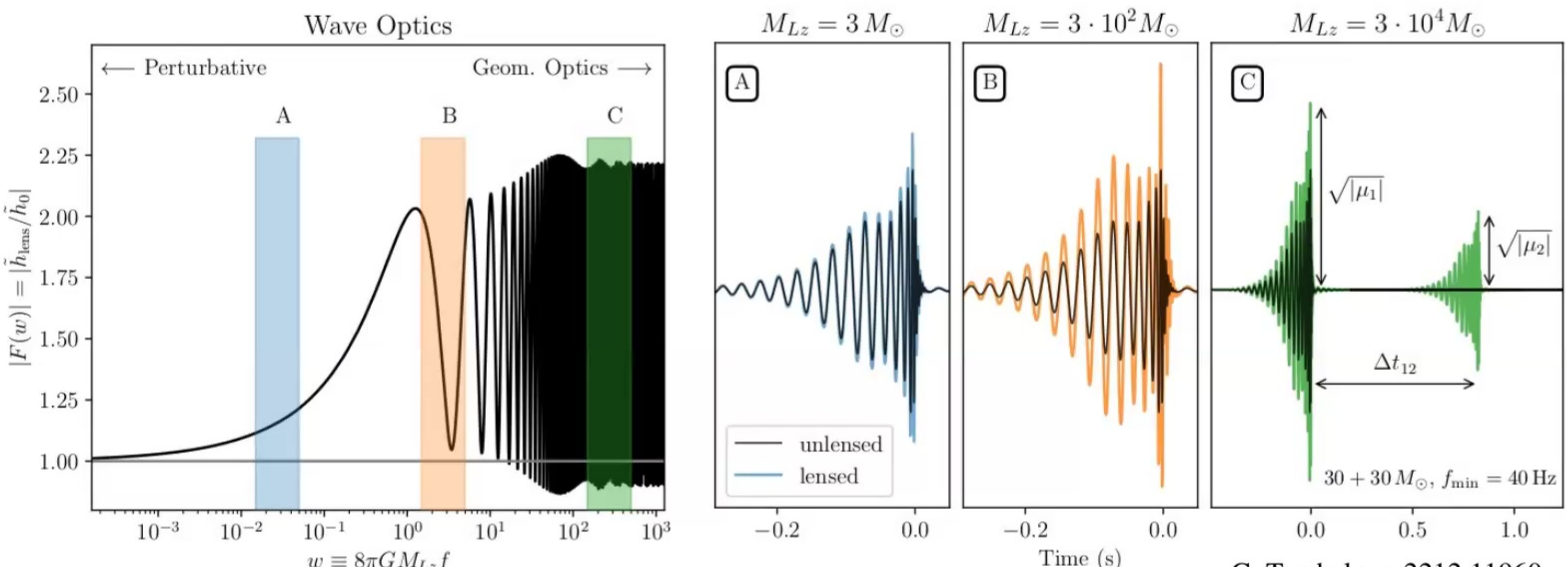
  - The wavelength of GWs is given by the mass of the coalescing objects, which can have masses ranging from stellar mass to a few percent of the mass of galaxies



# GW lensing - Introduction

– Gravitational Waves Lensing:

- To go beyond geometric optics, we need to compute the Amplification Factor: $F(f) = \dfrac{h_L(f)}{h(f)}$




G. Tambalo, + 2212.11960

# Modelling Small Scales

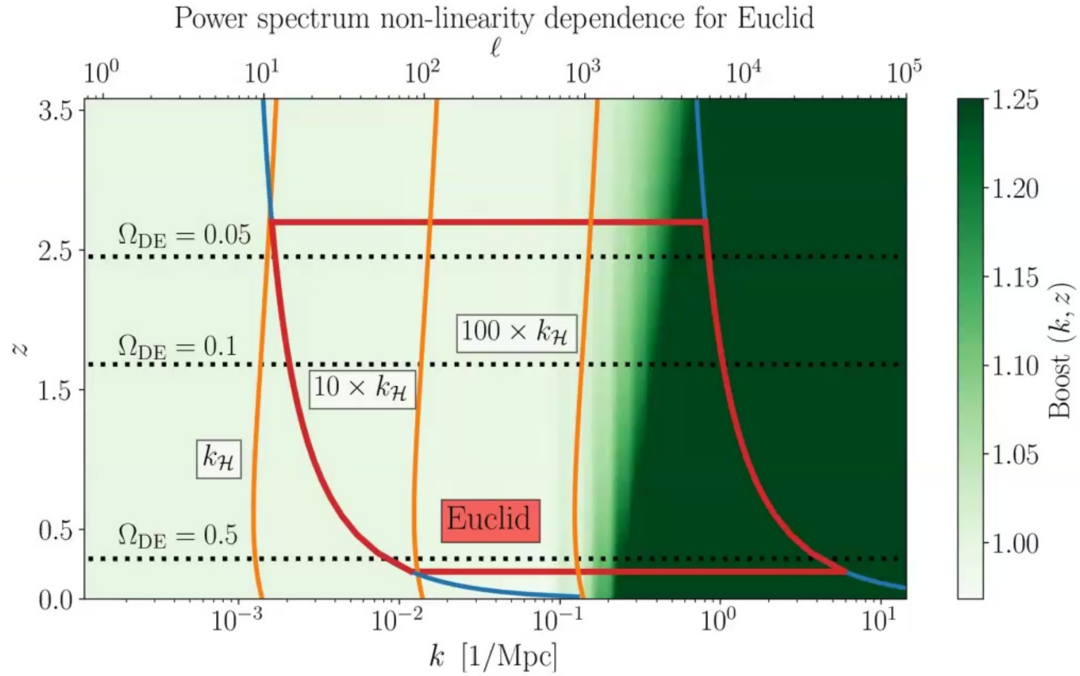
- Large scale structure cosmology → modelling of beyond-LCDM theories in the non-linear regime (small scales)

  - Current fast and accurate tools

    Einstein-Boltzmann solvers

    ↓

    <u>Only valid in linear scales!!</u>

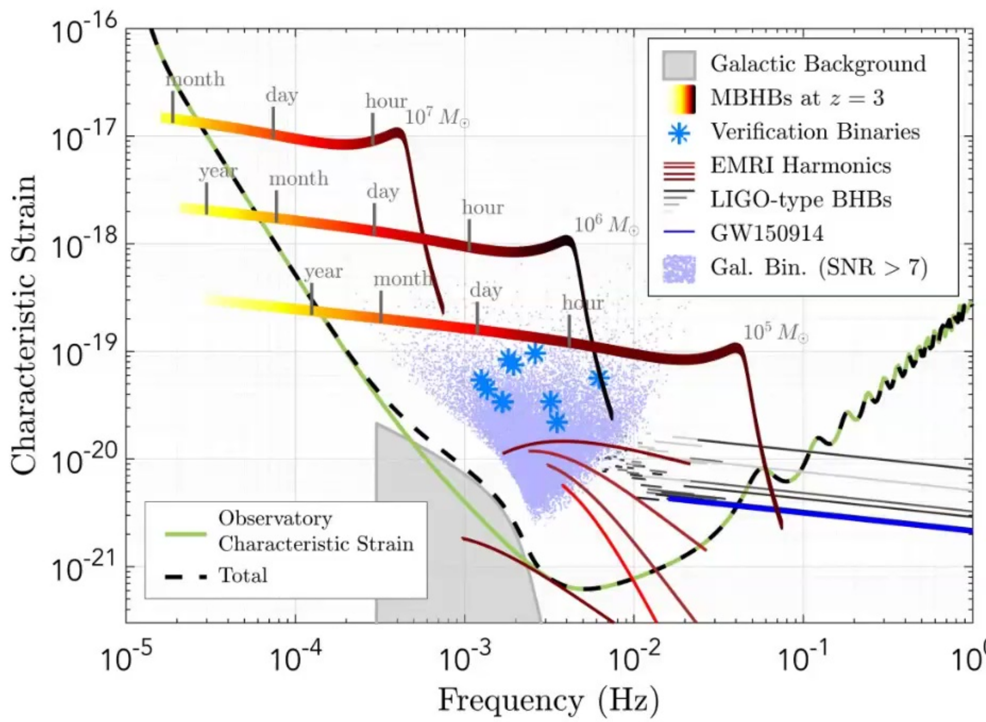


# GW lensing – LISA

- Gravitational Waves Lensing:
  - Wave Optics Features (WOFs)
  - Detectability: low frequencies

$$w \sim \left(\frac{M_{Lz}}{100\,M_\odot}\right)\left(\frac{f}{100\,\mathrm{Hz}}\right) = \left(\frac{M_{Lz}}{10^6\,M_\odot}\right)\left(\frac{f}{10\,\mathrm{mHz}}\right)$$

$$M_{Lz} = 10 - 1000 M_\odot, \quad \text{LIGO}$$
$$M_{Lz} = 10^5 - 10^8 M_\odot, \quad \text{LISA}$$




K. Danzmann, et al, 1702.00786

# Modelling Small Scales

- Large scale structure cosmology → modelling of beyond-LCDM theories in the non-linear regime (small scales)

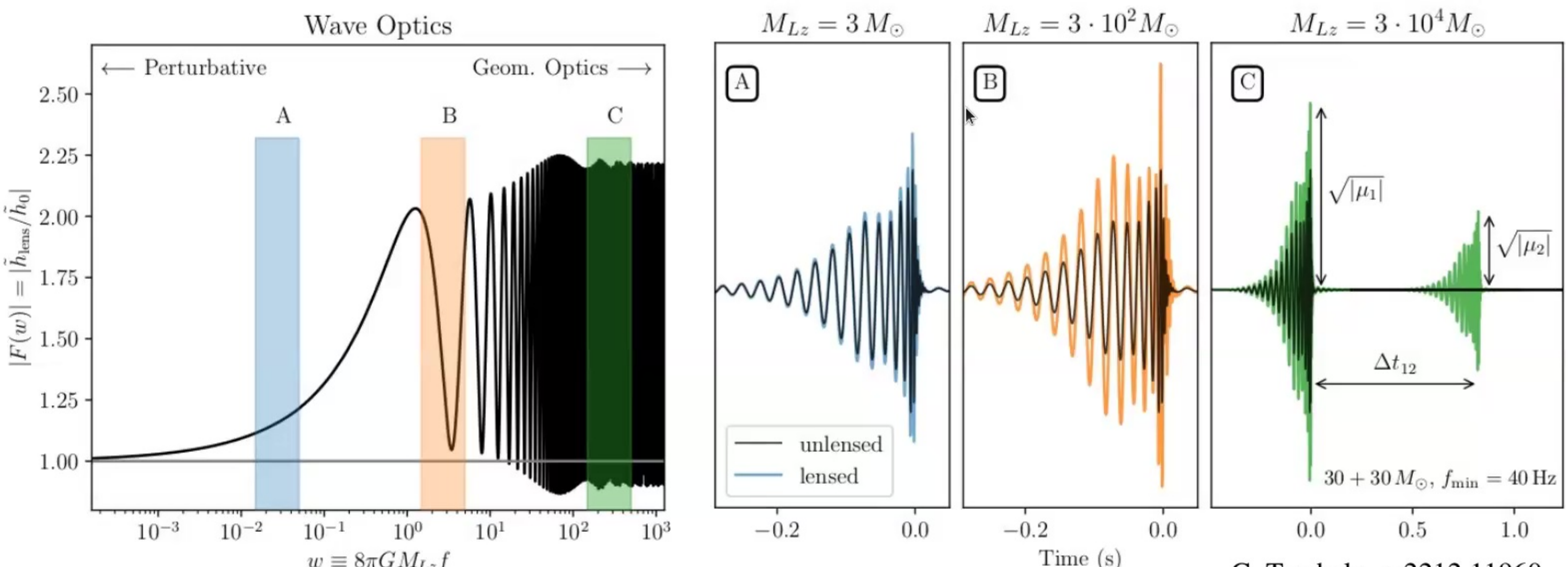
  - Difficulties of modelling non-linear scales in these models:

    - Most predictive way is non-perturbatively → N-body simulations
    - Time-consuming and computationally expensive → even worse for beyond-LCDM
    - Tradeoff between: **predictive power x cost**
    - One viable alternative: COmoving Lagrangian Approximation method (COLA)

# GW lensing - Introduction

– Gravitational Waves Lensing:

- To go beyond geometric optics, we need to compute the Amplification Factor: $F(f) = \dfrac{h_L(f)}{h(f)}$




G. Tambalo, + 2212.11960

# GW lensing – LISA

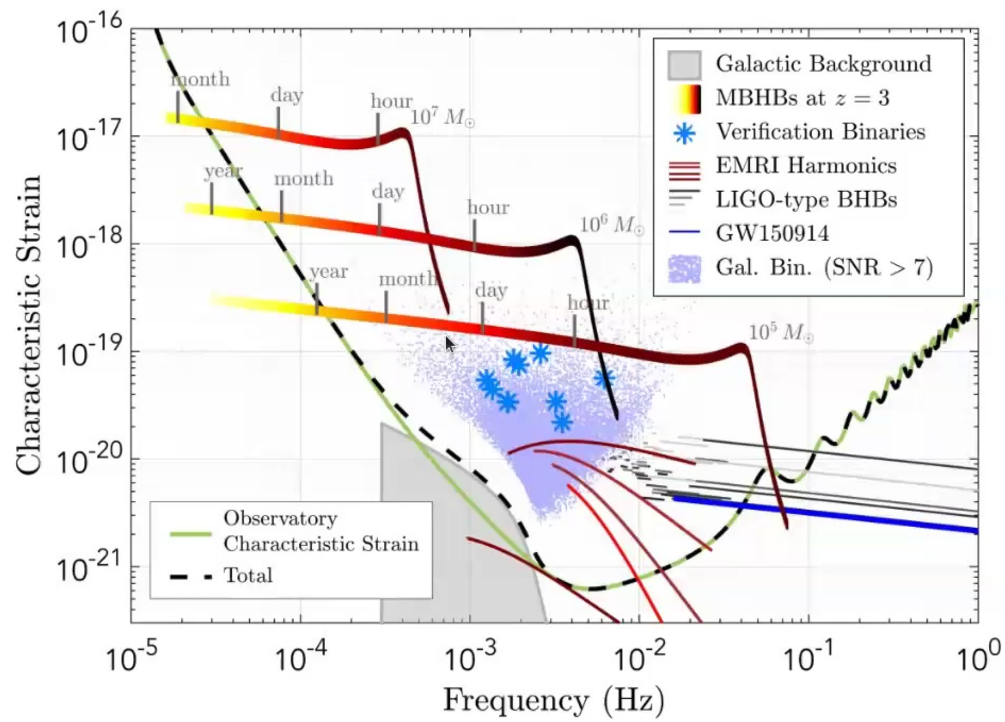
– Gravitational Waves Lensing:

- Wave Optics Features (WOFs)
- Detectability: low frequencies

$$w \sim \left(\frac{M_{Lz}}{100\, M_\odot}\right)\left(\frac{f}{100\,\text{Hz}}\right) = \left(\frac{M_{Lz}}{10^6\, M_\odot}\right)\left(\frac{f}{10\,\text{mHz}}\right)$$

$$M_{Lz} = 10 - 1000 M_\odot, \quad \text{LIGO}$$

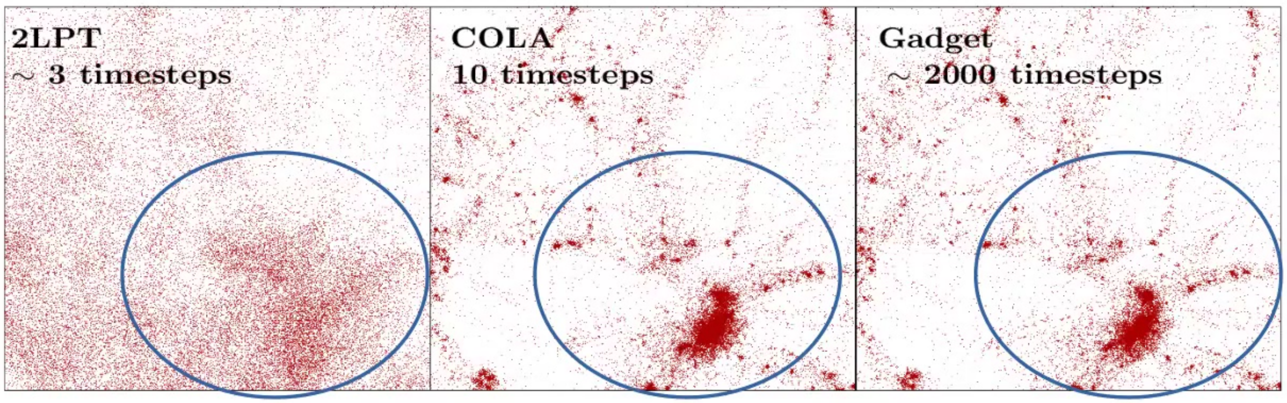
$$M_{Lz} = 10^5 - 10^8 M_\odot, \quad \text{LISA}$$




K. Danzmann, et al, 1702.00786

# Modelling Small Scales

- One viable alternative: COmoving Lagrangian Approximation method
  - Combines 2LPT to describe large scales with a Particle-Mesh algorithm to solve for small scales
    - ✔ Fast realizations of the density field → two orders of magnitude faster than full N-body

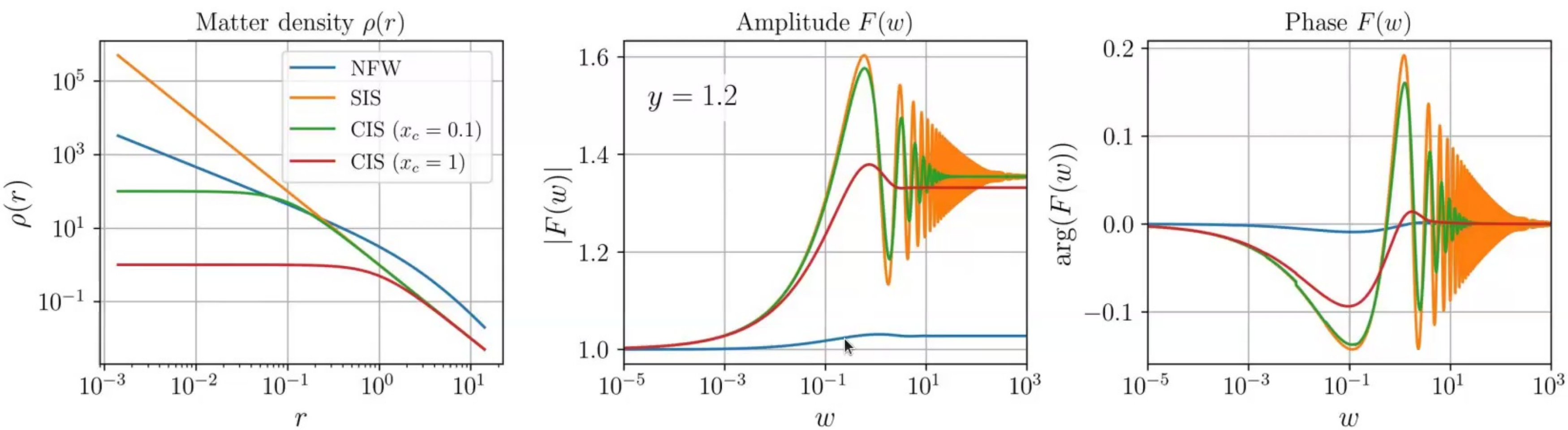



S. Tassev et al - 1301.0322

# GW lensing – LISA

- Gravitational Waves Lensing:

  - Detectability: height of WOF peak, depends on lens mass profile and impact parameter:



# Modelling Small Scales

- One viable alternative: COmoving Lagrangian Approximation method
  - Combines 2LPT to describe large scales with a Particle-Mesh algorithm to solve for small scales
    - ✔ Computationally less costly → reduced wall clock

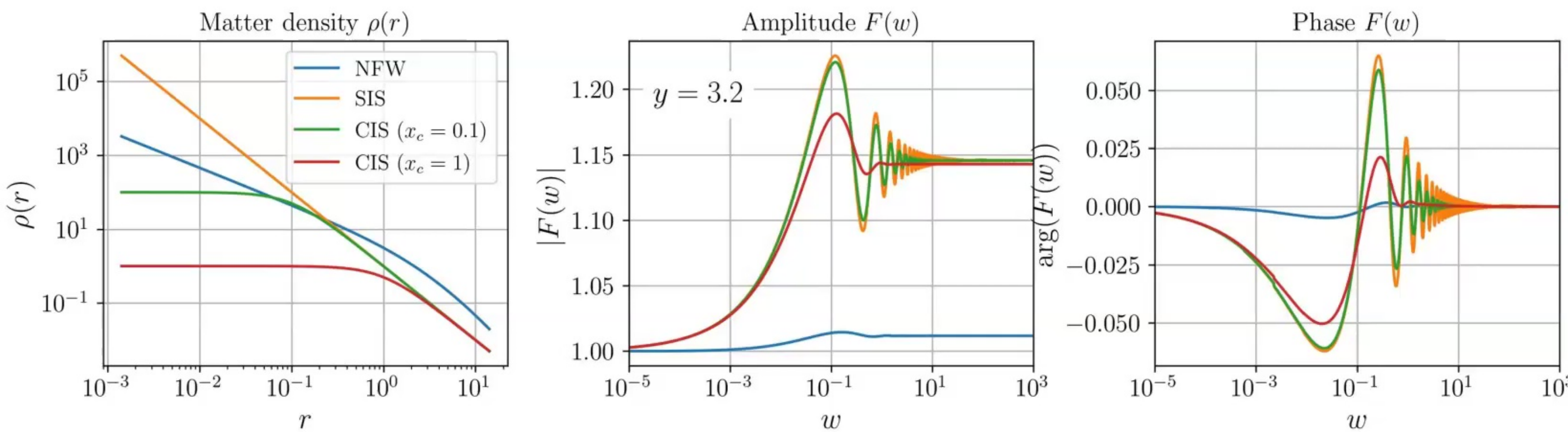
| SimType | Box size ($h^{-3}\mathrm{Mpc}^3$) | $N_{\mathrm{par}}$ | $z_{\mathrm{init}}$ | $a_{\mathrm{init}}$ | $a_{\mathrm{final}}$ | $da$ | $N_{\mathrm{step}}$ | CPUs | Wall-clock time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| GADGET-2 | $800^3$ | $1024^3$ | 49 | 1/50 | 1 | – | 3676 | 252 | 149.7 |
| COLA | $800^3$ | $1024^3$ | 29 | 1/30 | 1 | 1/30 | 30 | 256 | 0.39 |
| COLA | $800^3$ | $1024^3$ | 49 | 1/50 | 1 | 1/50 | 50 | 256 | 0.75 |
| COLA | $800^3$ | $1024^3$ | 59 | 1/60 | 1 | 1/60 | 60 | 256 | 0.76 |
| COLA | $800^3$ | $1024^3$ | 119 | 1/120 | 1 | 1/120 | 120 | 256 | 1.51 |

J. Ding et al - 2311.00981

# GW lensing – LISA

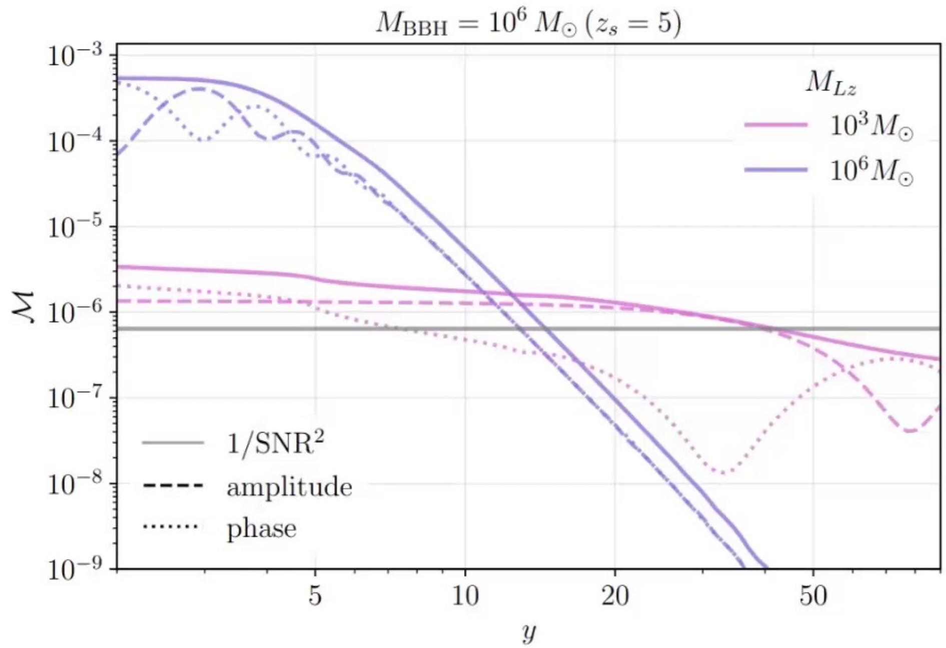
- Gravitational Waves Lensing:

  - Detectability: height of WOF peak, depends on lens mass profile and impact parameter:



# GW lensing – LISA

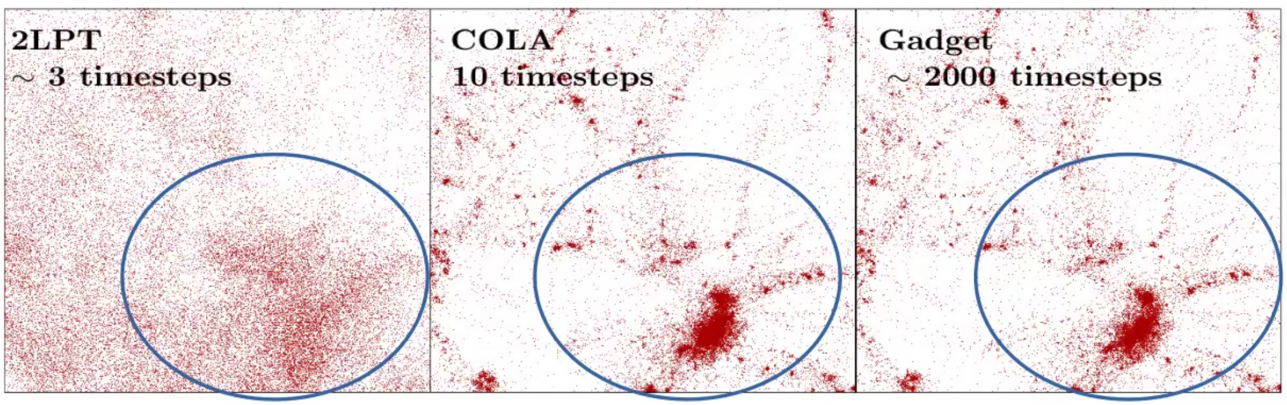
- Gravitational Waves Lensing:
  - Detecatability of WOFs:
    - Lens geometry x Detectability criterion
    - Critical impact parameter:
      - How far can we detect WOFs?
        in units of Einstein radii




S. Savastano, + 2306.05282

# Modelling Small Scales

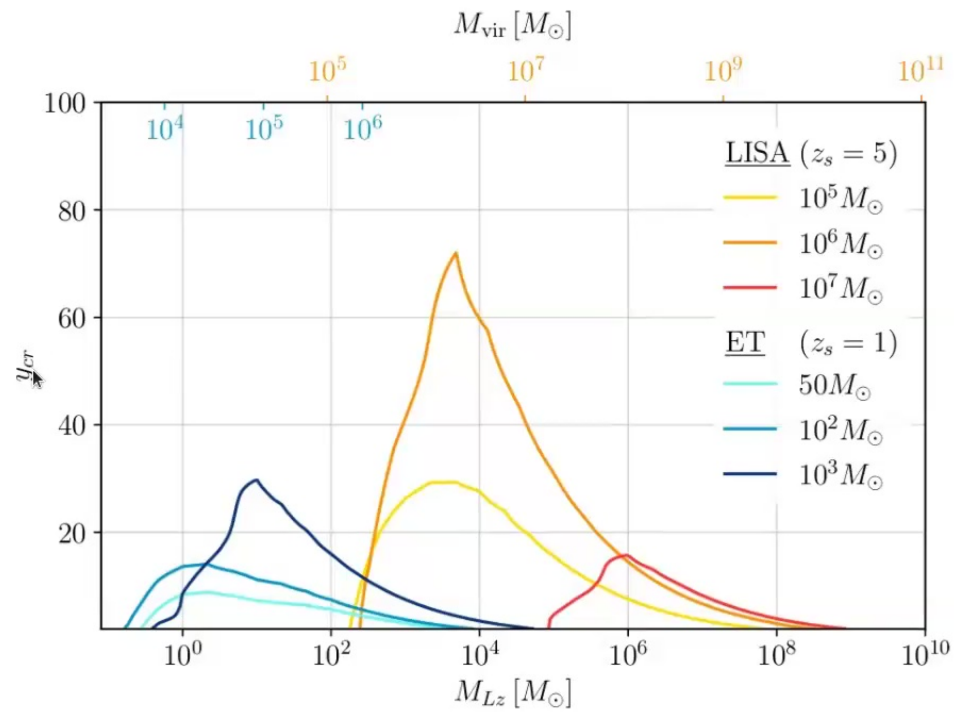
- One viable alternative: COmoving Lagrangian Approximation method
  - Combines 2LPT to describe large scales with a Particle-Mesh algorithm to solve for small scales
    - ✔ Fast realizations of the density field → two orders of magnitude faster than full N-body




S. Tassev et al - 1301.0322

# GW lensing – LISA

- Gravitational Waves Lensing:
  - Detecatability of WOFs:
    - Lens geometry x Detectability criterion
    - Critical impact parameter:
      - How far can we detect WOFs?
        in units of Einstein radii



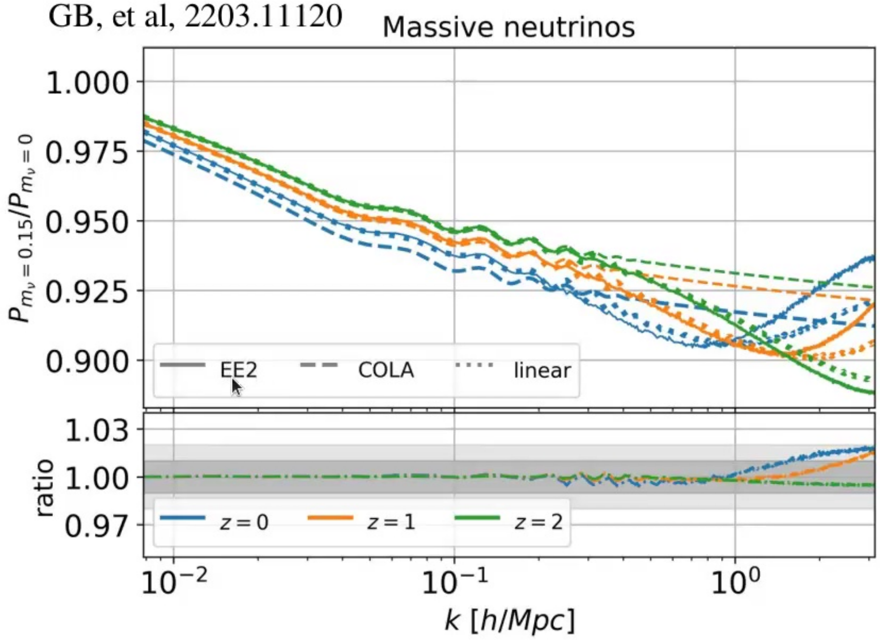

S. Savastano, + 2306.05282

# Modelling Small Scales

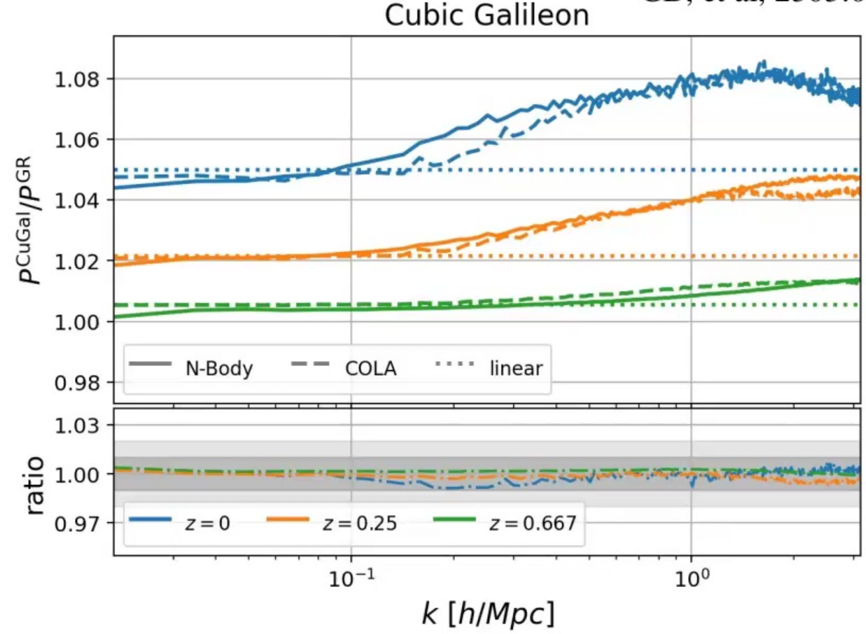
- One viable alternative: COmoving Lagrangian Approximation method

  ✔ Examples of extensions to LCDM in COLA

GB, et al, 2203.11120

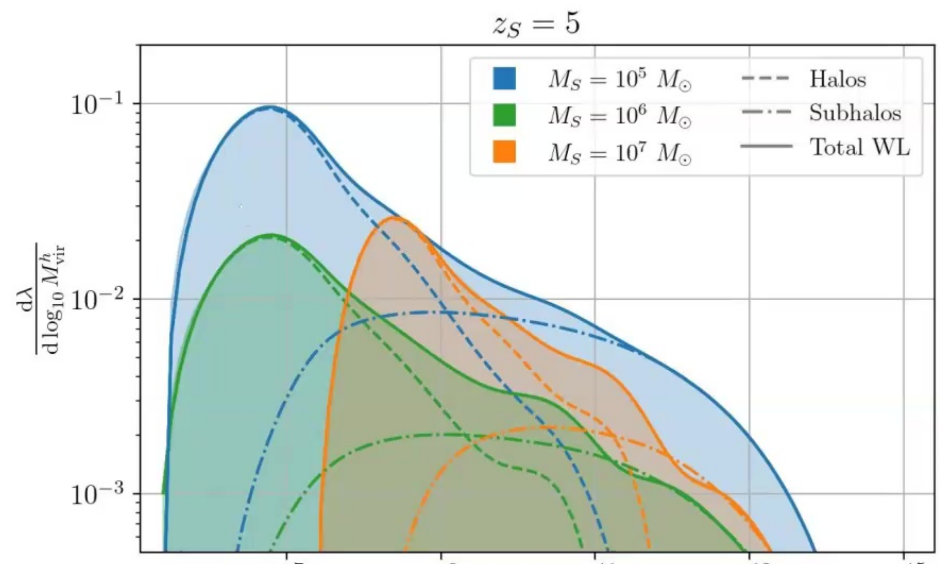



GB, et al, 2303.09549



# GW lensing – LISA

- Gravitational Waves Lensing:
  - Probability (optical depth): $\frac{\mathrm{d}\tau_h}{\mathrm{d}\log M_{\mathrm{vir}}^h} = \int_0^{z_S} \mathrm{d}z_L \frac{c\,(1+)^2}{H(z_L)} \sigma\left(z_S, M_S, z_L, M_{\mathrm{vir}}^h\right) \times \frac{\mathrm{d}n_l\left(z_L, M_{\mathrm{vir}}^h\right)}{\mathrm{d}\log M_{\mathrm{vir}}^h}$
  - Distribution of lenses:
    - Halo mass function
    - Subhalo mass function




Host halo mass → $M_{\mathrm{vir}}^h\ [M_\odot]$

GB, + 2402.XXXXX

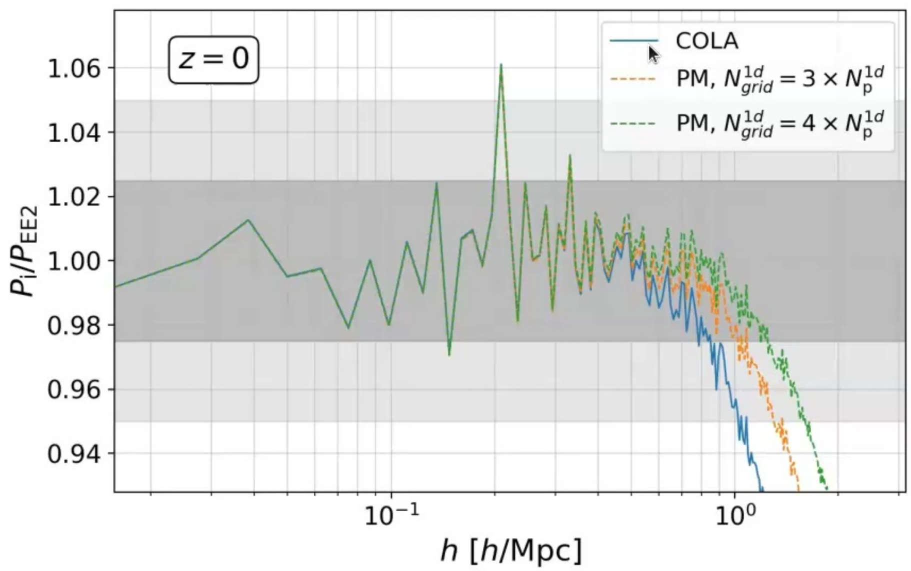
# Conclusions

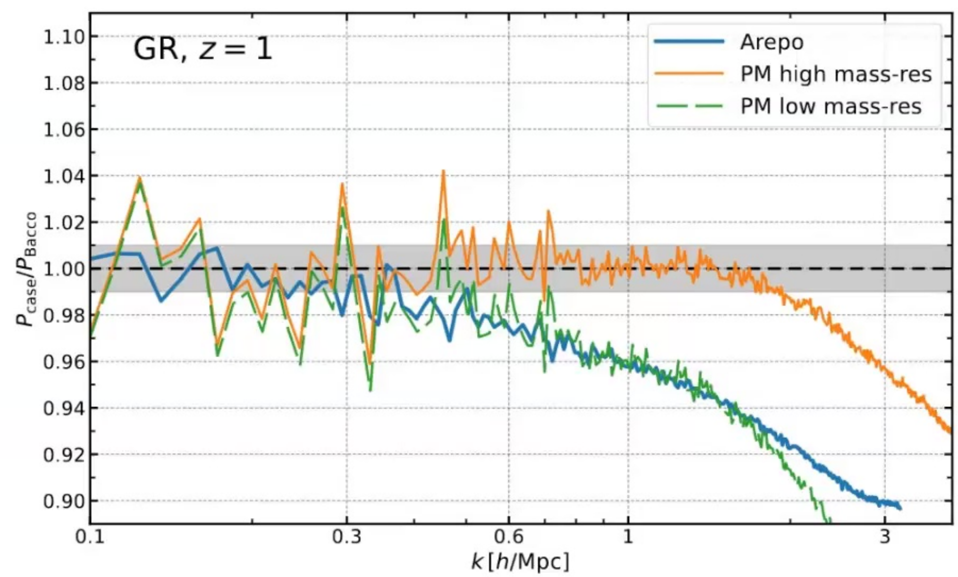
- Gravitational Waves Lensing:
  - GWs can have frequency-dependent lensing effects → Wave Optics Features (Diffraction)
  - LVK is already searching for multiply imaged events, but very limited exploration of wave optics and weak lensing
  - I have shown that for LISA sources we will be able to probe the (sub)substructure of our Universe, with with enhanced probabilities depending on the modelling of the lens.

# Modelling Small Scales

- One viable alternative: COmoving Lagrangian Approximation method

  ✔ Validated and benchmarked



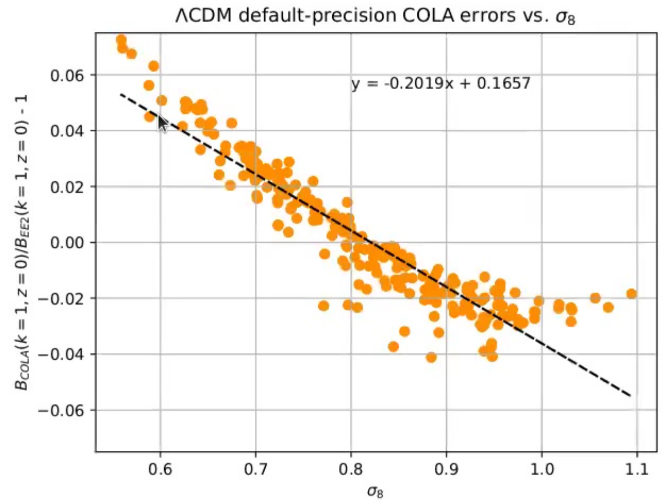



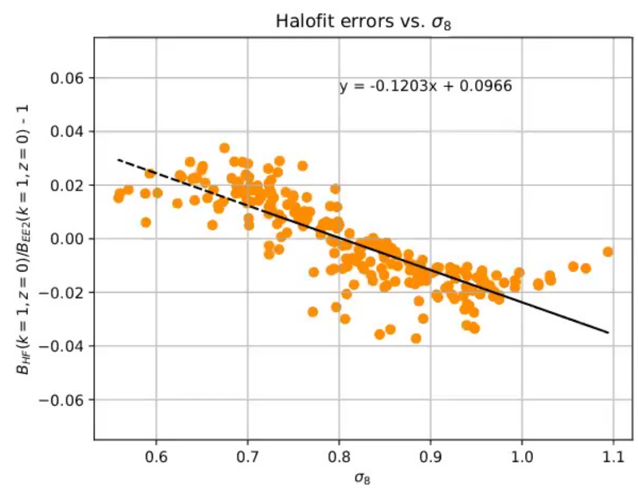

B. Fiorini et al - 2310.05786

### nonlinear matter power spectrum emulator

| | | | |
|---|---|---|---|
| `omega_cold` | 0.23 | 0.4 | $\Omega_{cb} = \Omega_{cdm} + \Omega_b$ (cdm+baryons) |
| `omega_baryon` | 0.04 | 0.06 | $\Omega_b$ |
| `sigma8_cold` | 0.73 | 0.9 | $\sigma_{8,cb}$ (cdm+baryons) |
| `ns` | 0.92 | 1.01 | $n_s$ |
| `hubble` | 0.6 | 0.8 | $h = H_0/100$ |
| `neutrino_mass` | 0 | 0.4 | $M_\nu = \sum m_{\nu,i}[\mathrm{eV}]$ |
| `w0` | -1.15 | -0.85 | $w_0$ |
| `wa` | -0.3 | 0.3 | $w_a$ |
| `expfactor` | 0.4 | 1 | $a = 1/(1+z)$ |

https://baccoemu.readthedocs.io/en/latest/



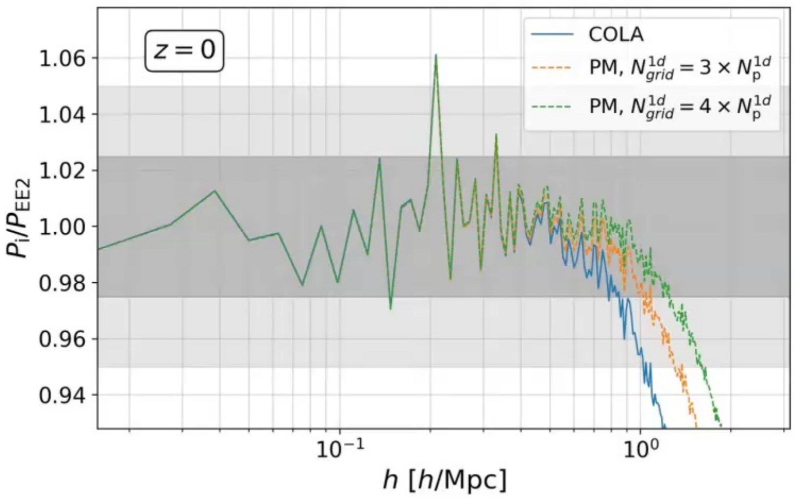
Thank you!

# Modelling Small Scales

- Emulation methods for the matter power spectrum → emulation of the boost

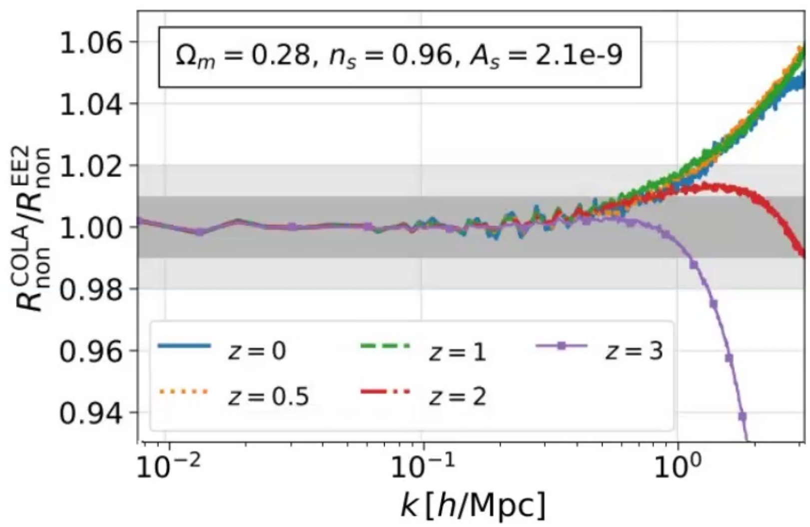
$$B = \frac{P_{\rm non}}{P_{\rm lin}} \qquad B^{\rm case} = B^{\rm ref}\frac{R^{\rm case}_{\rm non}}{R^{\rm case}_{\rm lin}} \qquad R_{\rm lin/non} = \frac{P^{\rm case}_{\rm lin/non}}{P^{\rm ref}_{\rm lin/non}}$$

EuclidEmulator2




COLA

GB et al - 2203.11120



# Modelling Small Scales

- Large scale strcture cosmology → modelling of beyond-LCDM theories in the non-linear regime (small scales)

  - I have shown examples of COLA for certain fixed cosmologies and theories.

  - To go further we need:

    - Construct a COLA-based emulator → wCDM (validation!)
    - Perform a full parameter estimation for a stage-IV survey

| | Default-precision | High-precision |
|---|---|---|
| $N_{\text{particles}}$ | $1024^3$ | $1024^3$ |
| L [Mpc/h] | 1024 | 512 |
| $N_{\text{mesh}}$ | $2048^3$ | $3072^3$ |
| $z_{\text{initial}}$ | 19 | 19 |
| $\ell_{\text{force}}$ [Mpc/h] | 0.5 | 0.17 |

| Parameter | Min. | Max. | Ref. |
|---|---|---|---|
| $\Omega_m$ | 0.24 | 0.40 | 0.319 |
| $\Omega_b$ | 0.04 | 0.06 | 0.049 |
| $n_s$ | 0.92 | 1.00 | 0.96 |
| $A_s \times 10^{-9}$ | 1.7 | 2.5 | 2.1 |
| $h$ | 0.61 | 0.73 | 0.67 |
| $w$ | $-1.3$ | $-0.7$ | $-1.0$ |

# LSSTY1 – like survey

- Cosmic shear:
  - Shear angular power spectrum:

$$C_{\kappa\kappa}^{ij}(\ell) = \int \frac{d\chi}{\chi^2} q_\kappa^i(\chi) q_\kappa^j(\chi) P_{\rm NL}\left(k = \frac{\ell + 1/2}{\chi}, z(\chi)\right)$$

  - 5 tomographic bins with source and lens galaxies drawn from:

$$n(z) \propto z^2 \exp[-(z/z_0)^\alpha]$$
$$(z_0, \alpha) = (0.191, 0.870)$$

  - Different masks (scale cuts) per bin

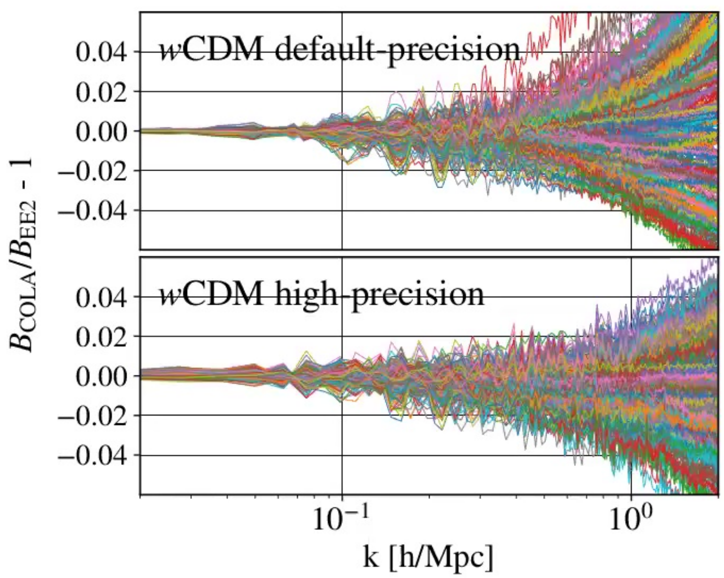
| **Parameter** | **Fiducial** | **Prior** |
|---|---|---|
| **Survey specifications** | | |
| Area | 12300 $\deg^2$ | – |
| Shape noise per component | 0.26 | – |
| $n_{\rm eff}^{\rm sources}$ | 11.2 arcmin$^{-2}$ | – |
| $n_{\rm eff}^{\rm lens}$ | 18 arcmin$^{-2}$ | – |
| **Photometric redshift offsets** | | |
| $\Delta z_{\rm source}^i$ | 0 | $\mathcal{N}[0, 0.02]$ |
| **Intrinsic alignment (NLA)** | | |
| $A^1$ | 0.7 | $\mathcal{U}[-5, 5]$ |
| $\eta^1$ | -1.7 | $\mathcal{U}[-5, 5]$ |
| **Shear calibration** | | |
| $m^i$ | 0 | $\mathcal{N}[0, 0.005]$ |
| **Baryon PCA amplitude** | | |
| $Q^1$ | 3 | $\mathcal{U}[0, 4]$ |
| $Q^2$ | 0 | $\mathcal{U}[-2.5, 2.5]$ |

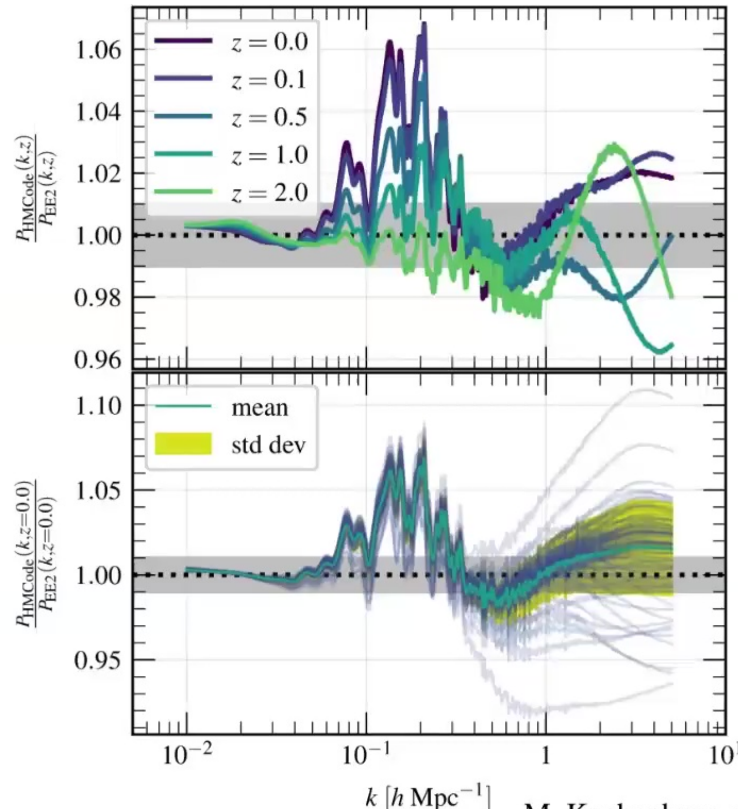
| | bin 0 | bin 1 | bin 2 | bin 3 | bin 4 |
|---|---|---|---|---|---|
| M2 | 5.7 | 4.3 | 3.7 | 3.4 | 0.5 |
| M3 | 2.9 | 2.1 | 1.9 | 1.7 | 0.2 |
| M4 | 1.4 | 1.1 | 0.9 | 0.8 | 0.1 |

Maximum scale $k_{\rm max}[h/Mpc]$

# Emulator

- Comparison between COLA and HMCode:




M. Knabenhans, et al - 2010.11288

# Modelling Small Scales

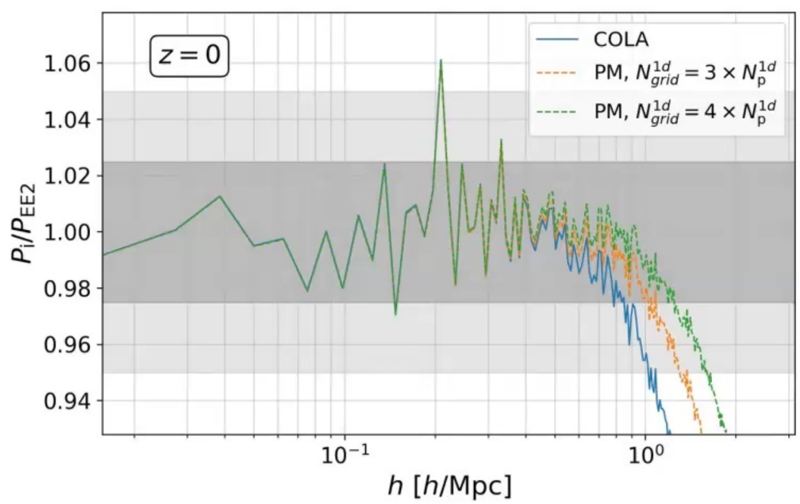
- Emulation methods for the matter power spectrum → emulation of the boost

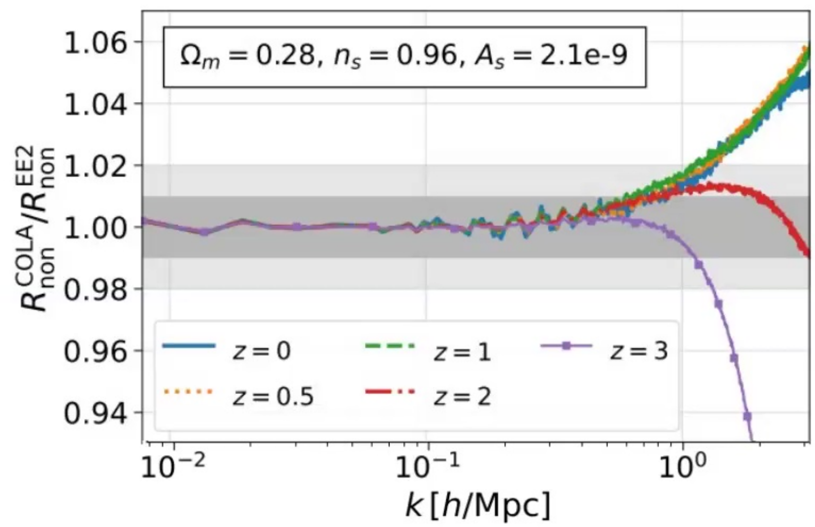
$$B = \frac{P_{\rm non}}{P_{\rm lin}} \qquad B^{\rm case} = B^{\rm ref} \frac{R^{\rm case}_{\rm non}}{R^{\rm case}_{\rm lin}} \qquad R_{\rm lin/non} = \frac{P^{\rm case}_{\rm lin/non}}{P^{\rm ref}_{\rm lin/non}}$$

EuclidEmulator2

COLA

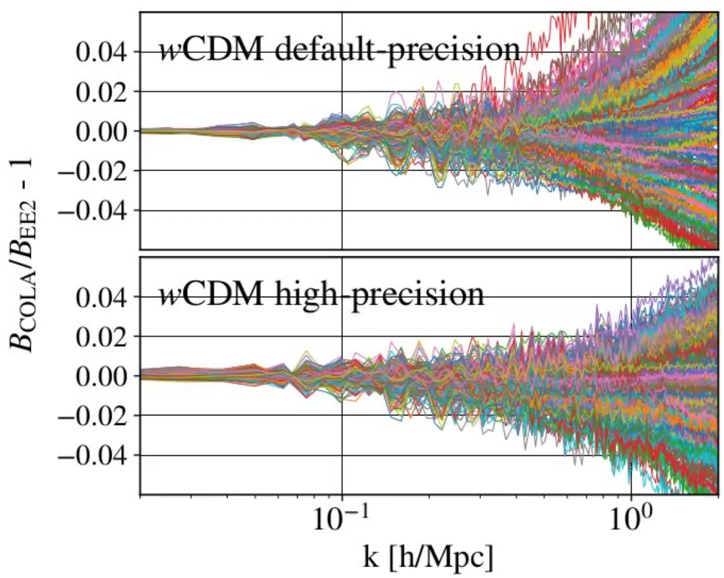
GB et al - 2203.11120

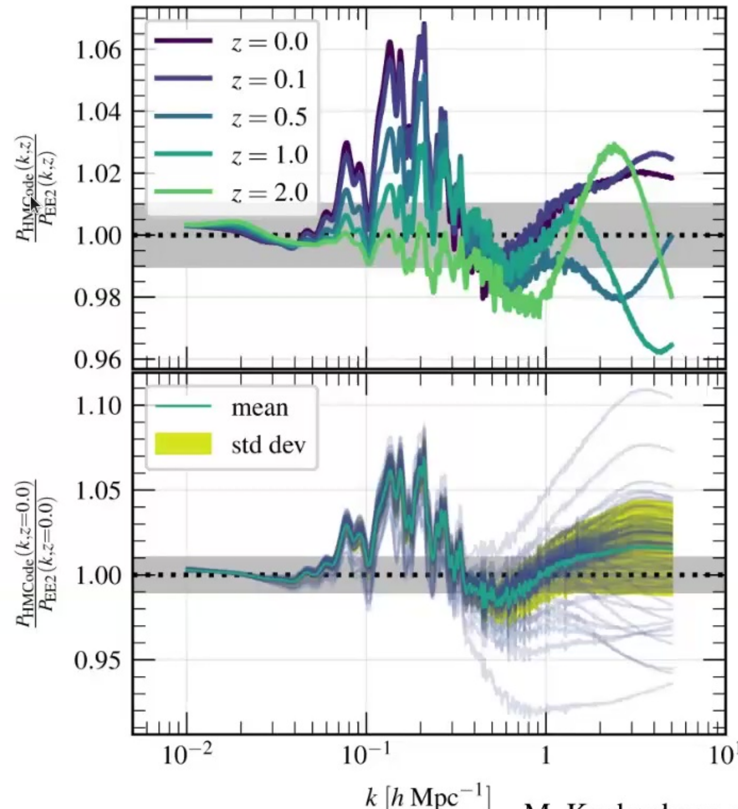


# Emulator

- Comparison between COLA and HMCode:

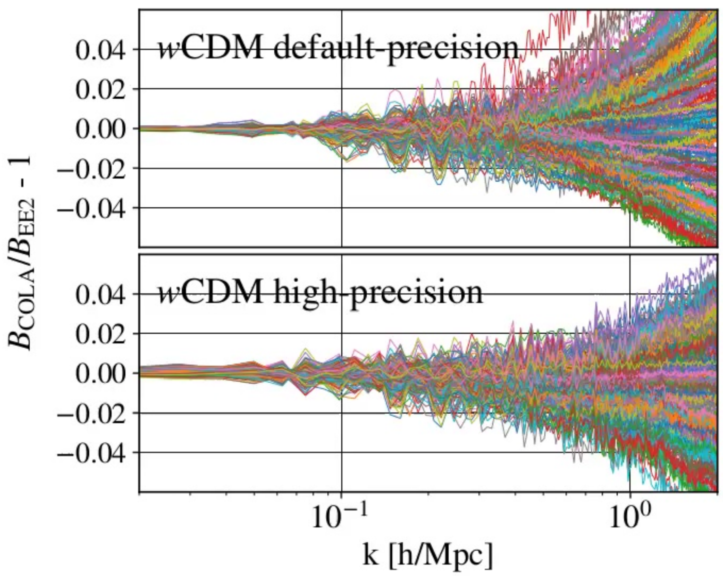



M. Knabenhans, et al - 2010.11288

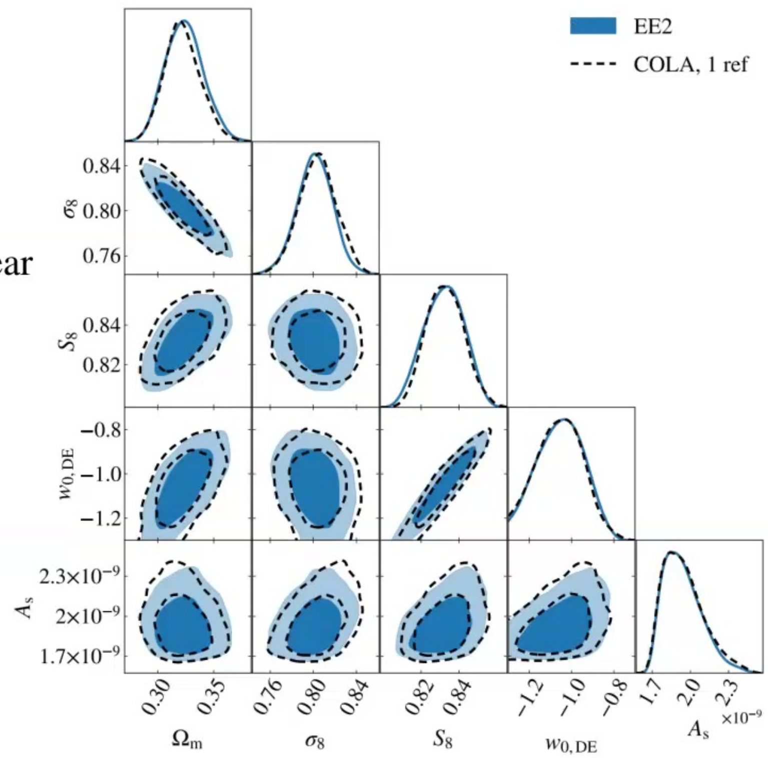
# Results

- Results:



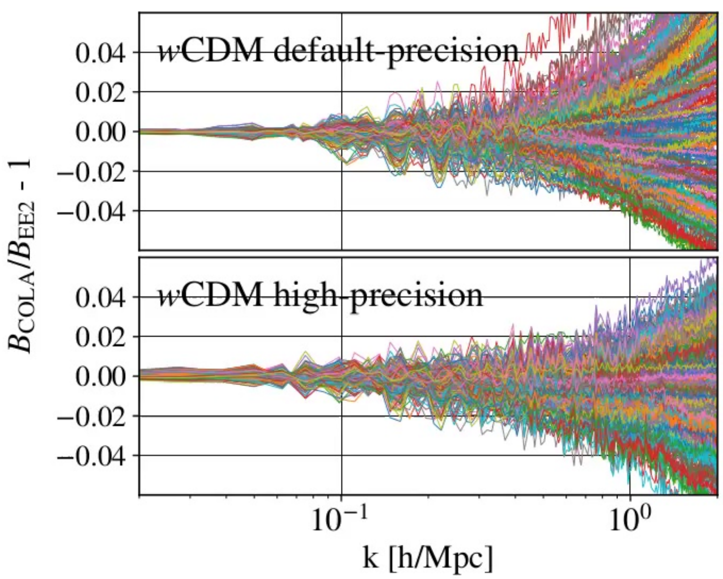

LSST-Y1 Cosmic Shear forecast

Fiducial data vector: EE2 ref + M2 mask

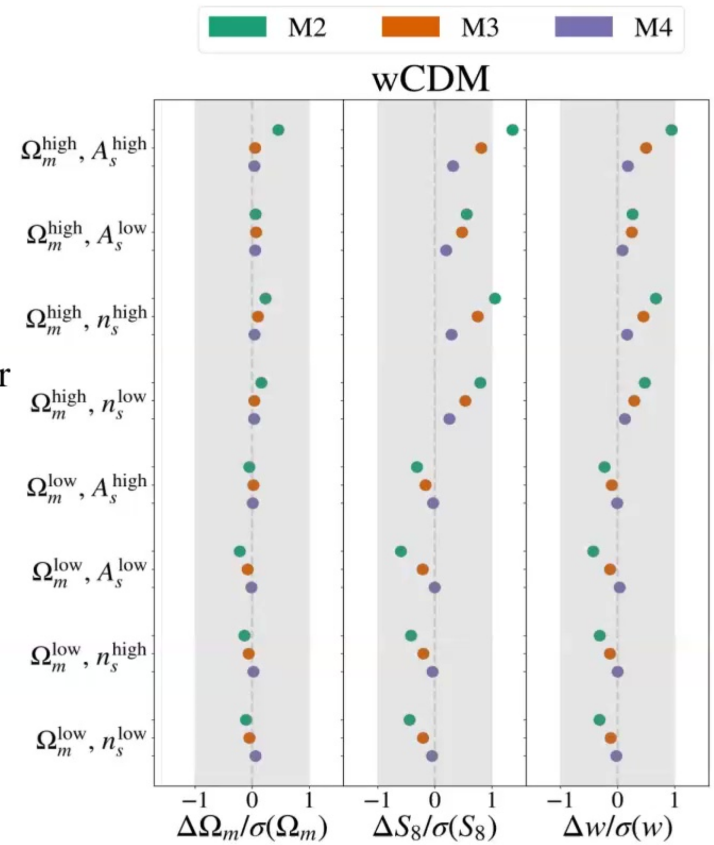


# Results

- Results:




LSST-Y1 Cosmic Shear forecast →



# Results

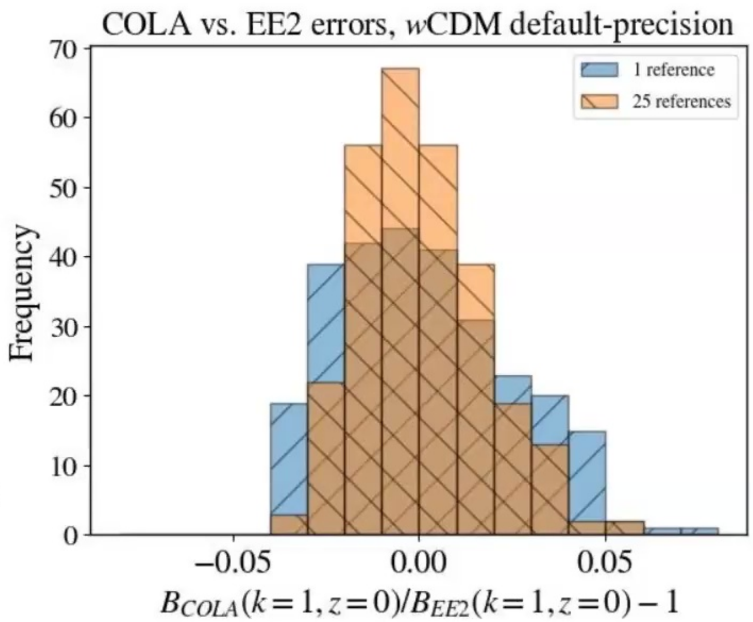
- Results:

  - Emulated boost has considerable scatter at high k

  - A possible solution is to increase the number of reference boosts:

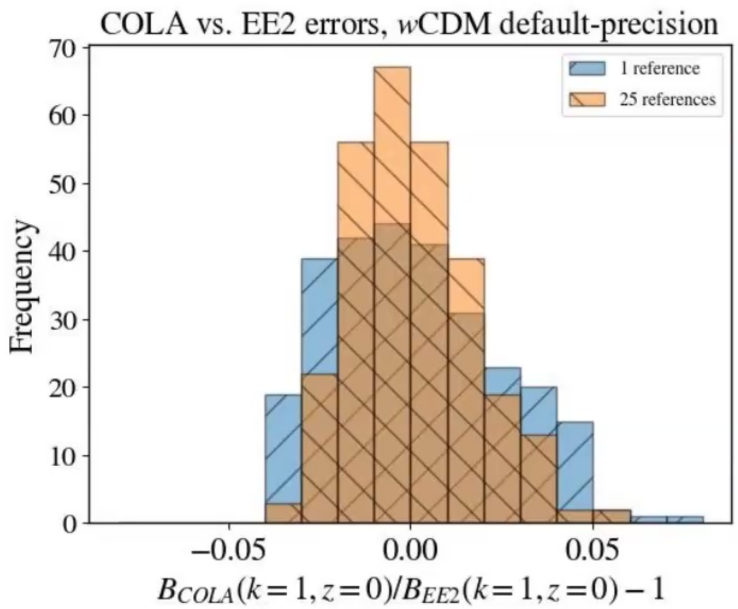
$$B^{\text{case}} = B^{\text{ref}} \frac{R^{\text{case}}_{\text{non}}}{R^{\text{case}}_{\text{lin}}} \qquad B^{\text{case}}(k,z) = \sum_{i=1}^{N_{\text{refs}}} w_i B^{\text{case}}_i(k,z)$$

  - Increases the calibration process, reduces the distanc between points to be emulated

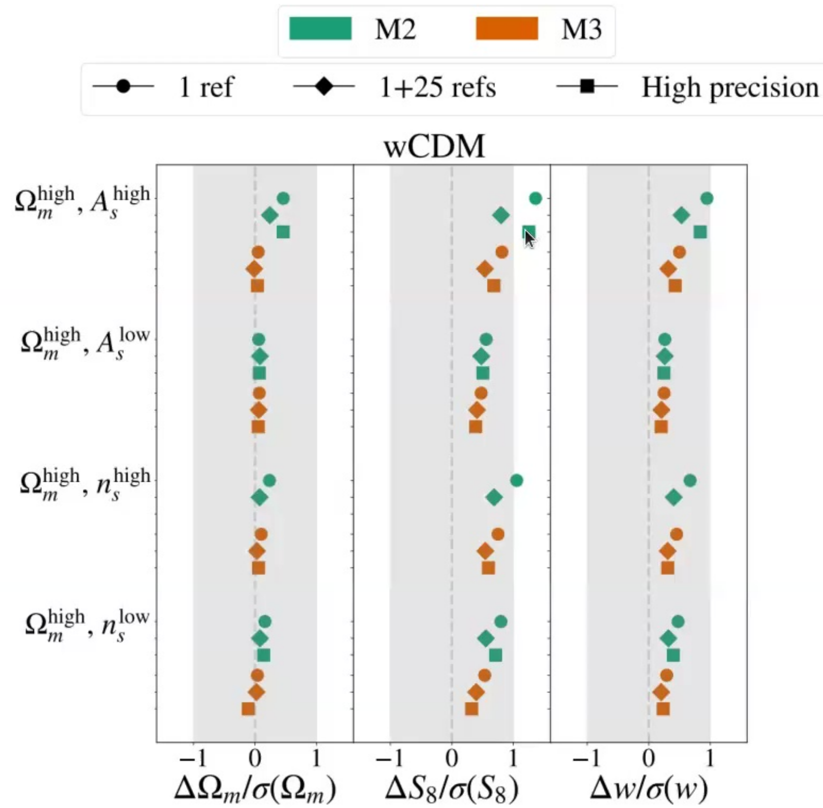


# Results

- Results:

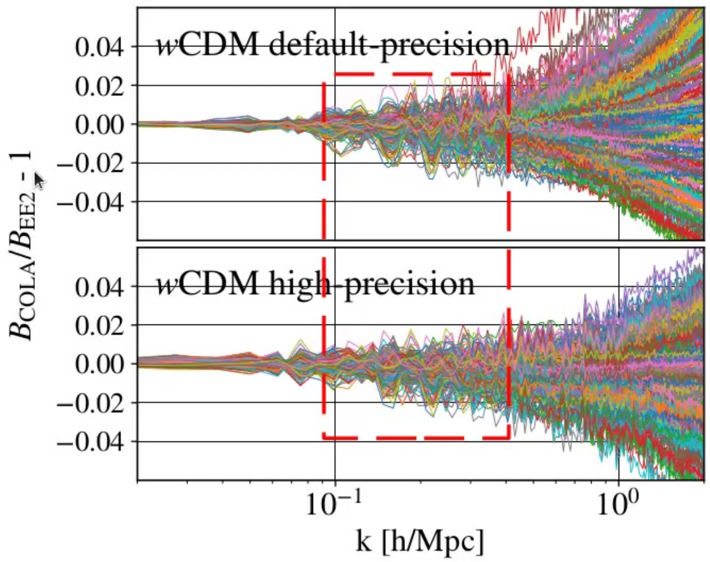


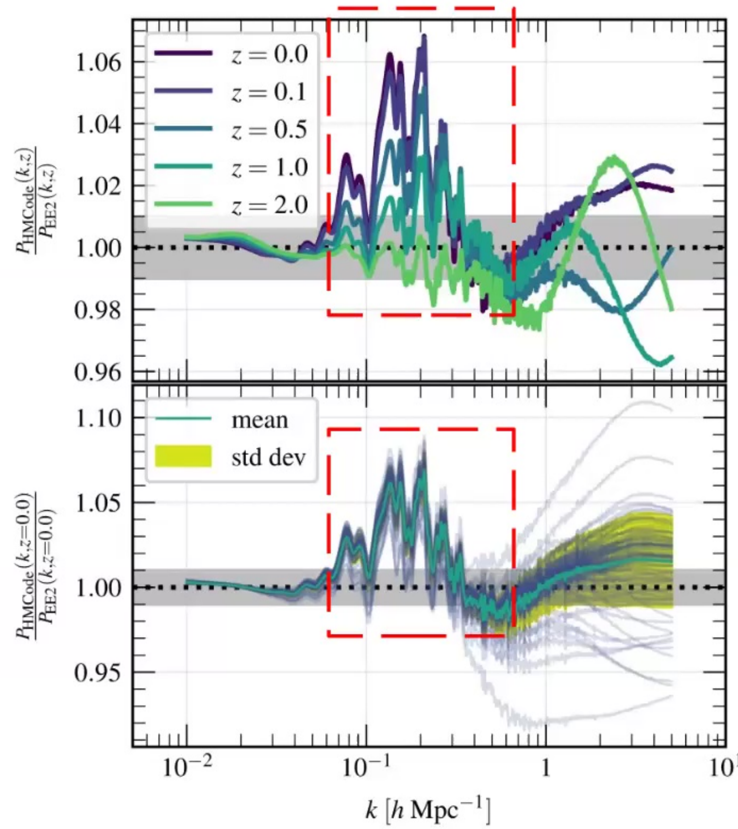

LSST-Y1 Cosmic Shear forecast



# Future

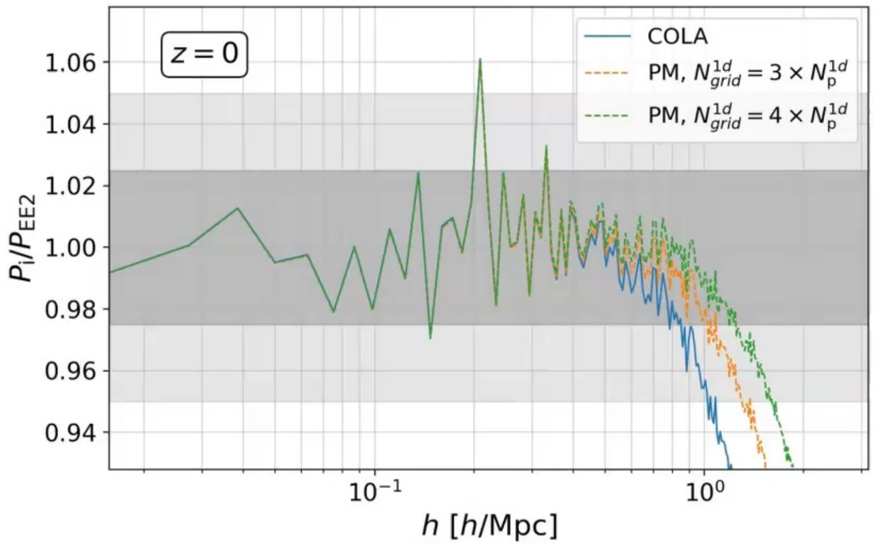
- Where do we need to improve?
  - Reduce BAO-scale scatter:

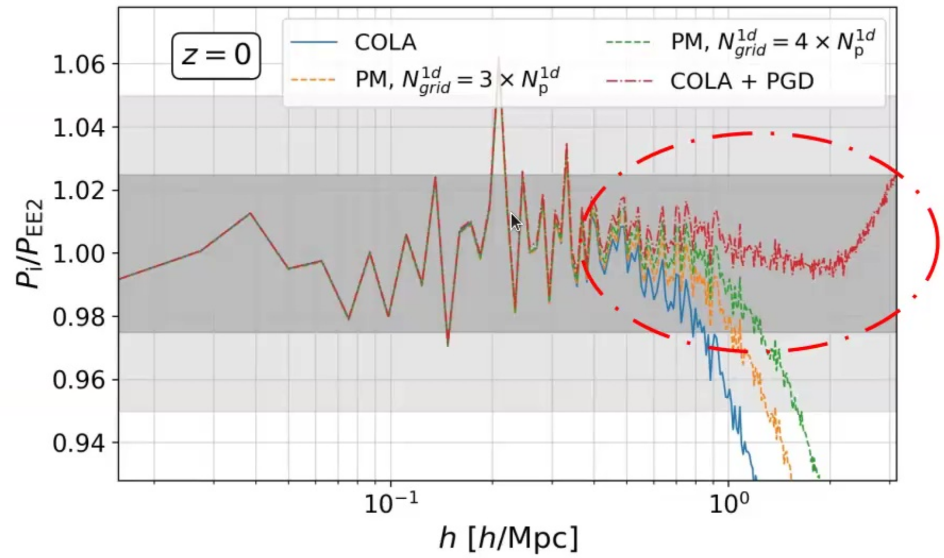


# Future

- Where do we need to improve?
  - Tame high-k behaviour
    - Potential Gradient Descent (PGD): Biwei Dai, Yu Feng and Uros Seljak – 1804.00671



# Conclusions

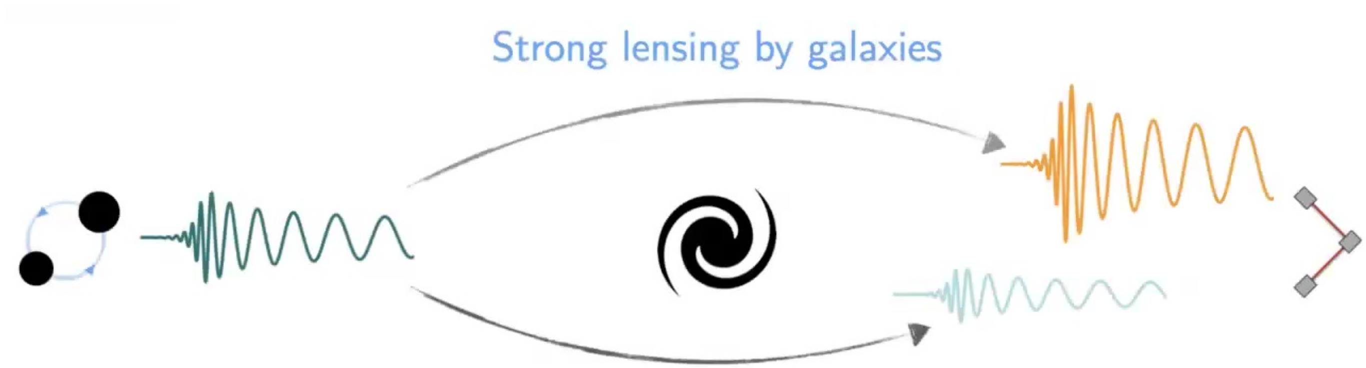
- Where do we need to go?
  - Galaxy clustering → go beyond linear bias
  - Add baryonic effects → post processing, baryonification algorithms
  - 3x2pt analysis

# GW lensing - Introduction

- Gravitational Waves Lensing:

  - Similar to electromagntic waves, GWs are lensed when propagating through an object

  - The wavelength of GWs is given by the mass of the coalescing objects, which can have masses ranging from stellar mass to a few percent of the mass of galaxies



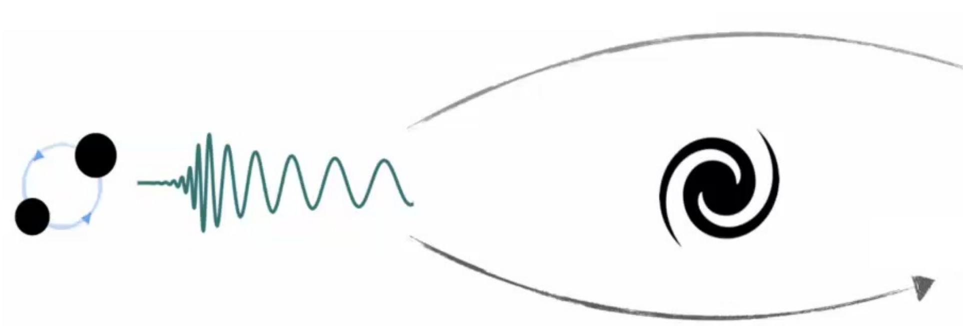
# GW lensing - Introduction

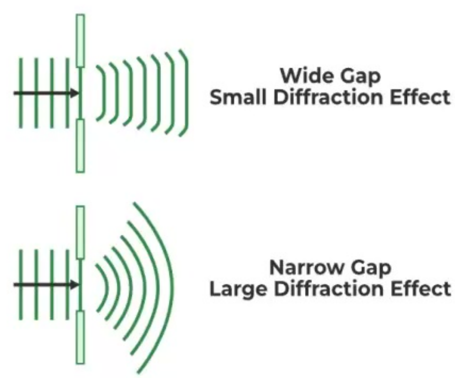
– Gravitational Waves Lensing:

- But the wavelenght of GWs can be of the same order of magnitude of the size of the lens object.

- Propagation no longer obeys the geometrical optics expansion → Wave Optics Effects (diffraction, intereference, ...)

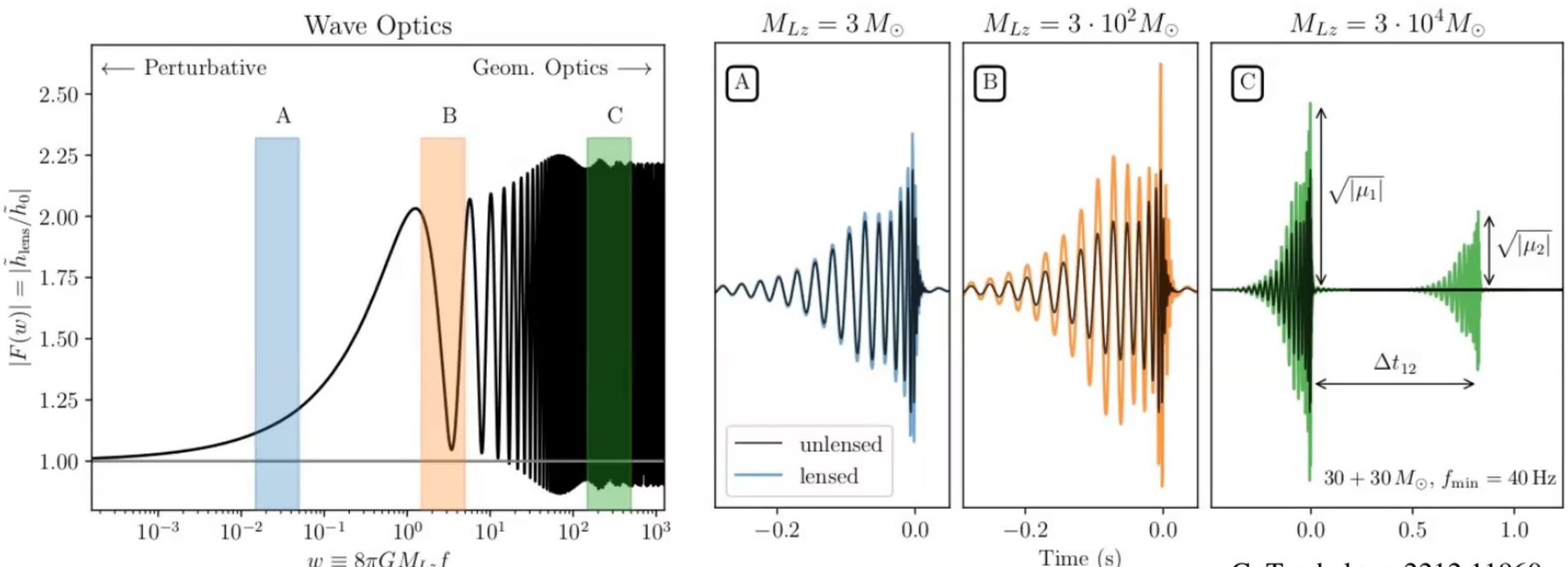
S. Savastano, + 2306.05282
M. Calışkan, + 2206.02803
R. Takahashi, + 0305055





# GW lensing - Introduction

- Gravitational Waves Lensing:
  - To go beyond geometric optics, we need to compute the Amplification Factor: $F(f) = \dfrac{h_L(f)}{h(f)}$




G. Tambalo, + 2212.11960

# GW lensing – LISA

- Gravitational Waves Lensing:

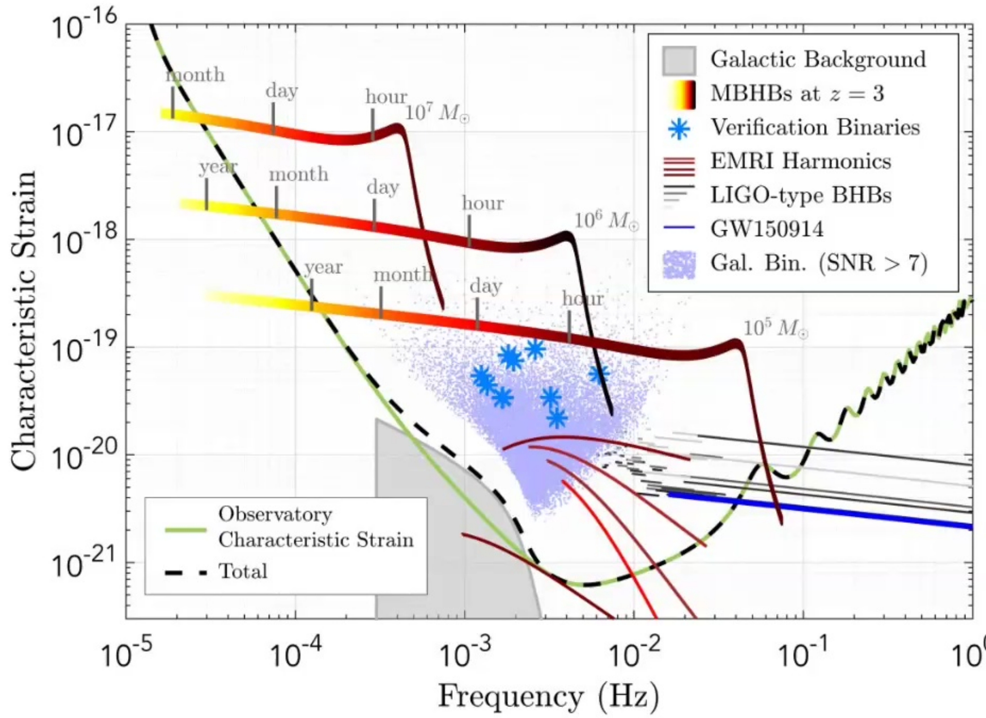
  - Wave Optics Features (WOFs)

  - Detectability: low frequencies

$$w \sim \left(\frac{M_{Lz}}{100\,M_\odot}\right)\left(\frac{f}{100\,\mathrm{Hz}}\right) = \left(\frac{M_{Lz}}{10^6\,M_\odot}\right)\left(\frac{f}{10\,\mathrm{mHz}}\right)$$

$$M_{Lz} = 10 - 1000 M_\odot, \quad \text{LIGO}$$

$$M_{Lz} = 10^5 - 10^8 M_\odot, \quad \text{LISA}$$

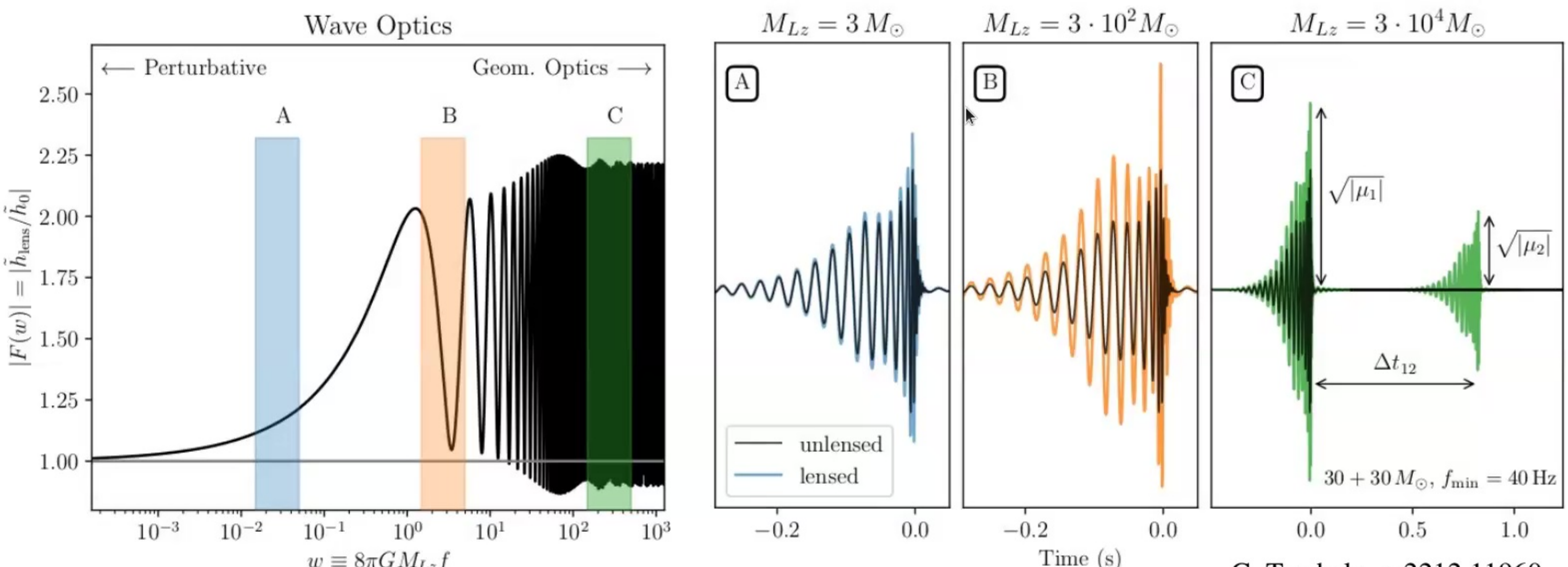



K. Danzmann, et al, 1702.00786

# GW lensing - Introduction

– Gravitational Waves Lensing:

- To go beyond geometric optics, we need to compute the Amplification Factor: $F(f) = \dfrac{h_L(f)}{h(f)}$




G. Tambalo, + 2212.11960

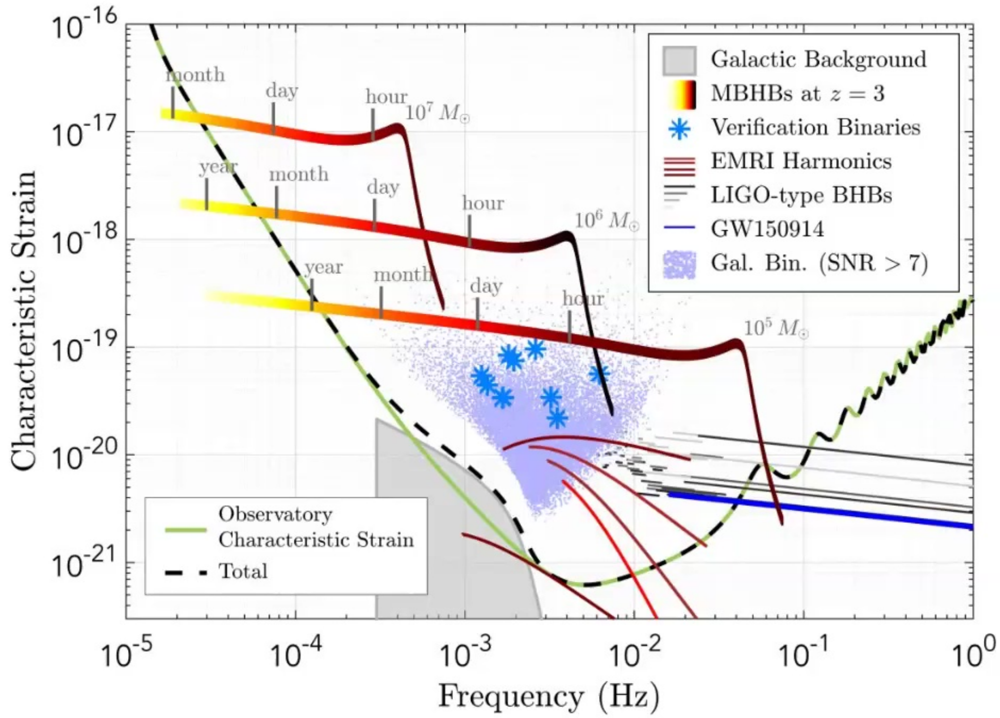
# GW lensing – LISA

– Gravitational Waves Lensing:

- Wave Optics Features (WOFs)
- Detectability: low frequencies

$$w \sim \left(\frac{M_{Lz}}{100\,M_\odot}\right)\left(\frac{f}{100\,\text{Hz}}\right) = \left(\frac{M_{Lz}}{10^6\,M_\odot}\right)\left(\frac{f}{10\,\text{mHz}}\right)$$

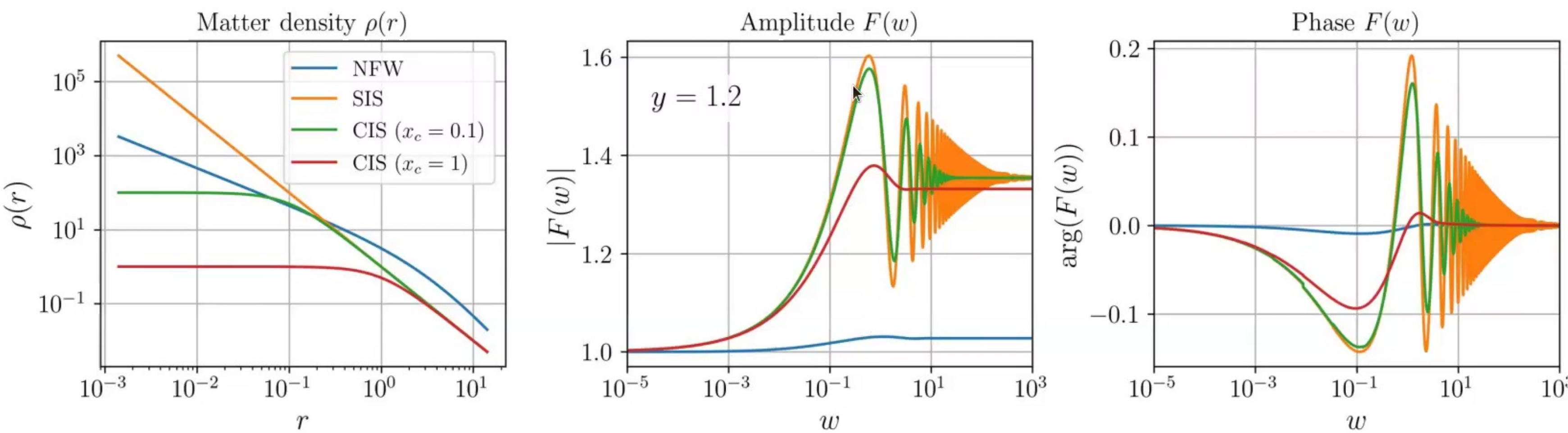
$$M_{Lz} = 10 - 1000 M_\odot, \quad \text{LIGO}$$
$$M_{Lz} = 10^5 - 10^8 M_\odot, \quad \text{LISA}$$




K. Danzmann, et al, 1702.00786

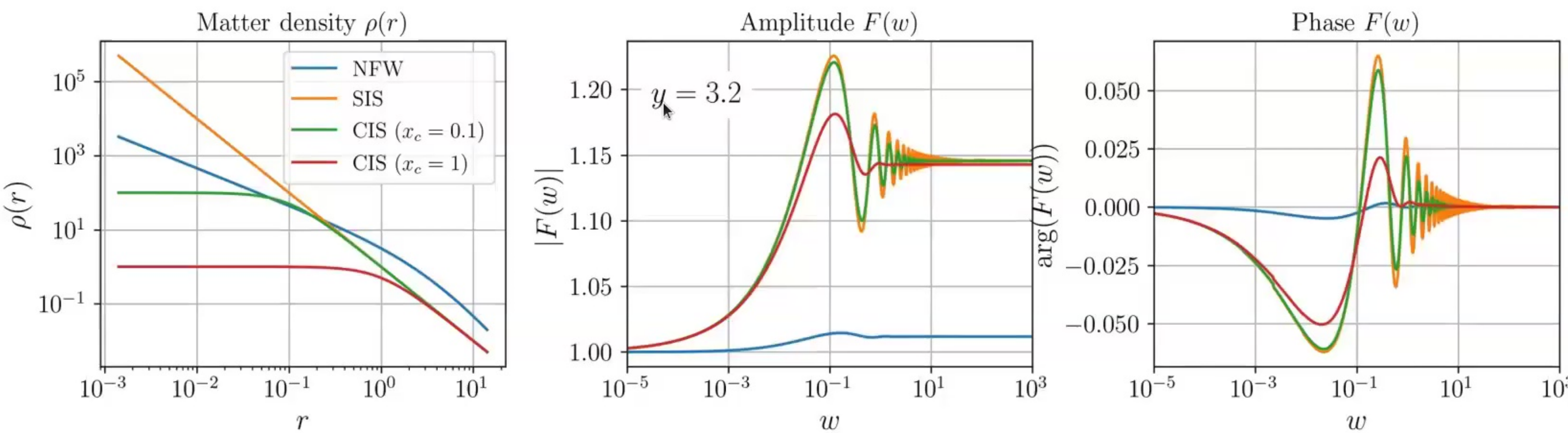
# GW lensing – LISA

- Gravitational Waves Lensing:
  - Detectability: height of WOF peak, depends on lens mass profile and impact parameter:



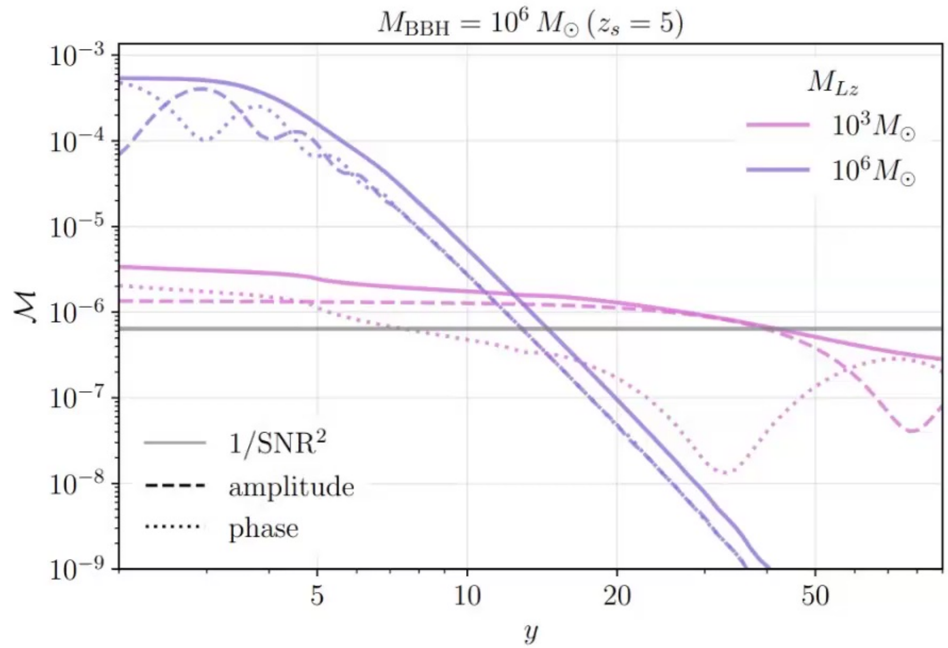
# GW lensing – LISA

- Gravitational Waves Lensing:
  - Detectability: height of WOF peak, depends on lens mass profile and impact parameter:



# GW lensing – LISA

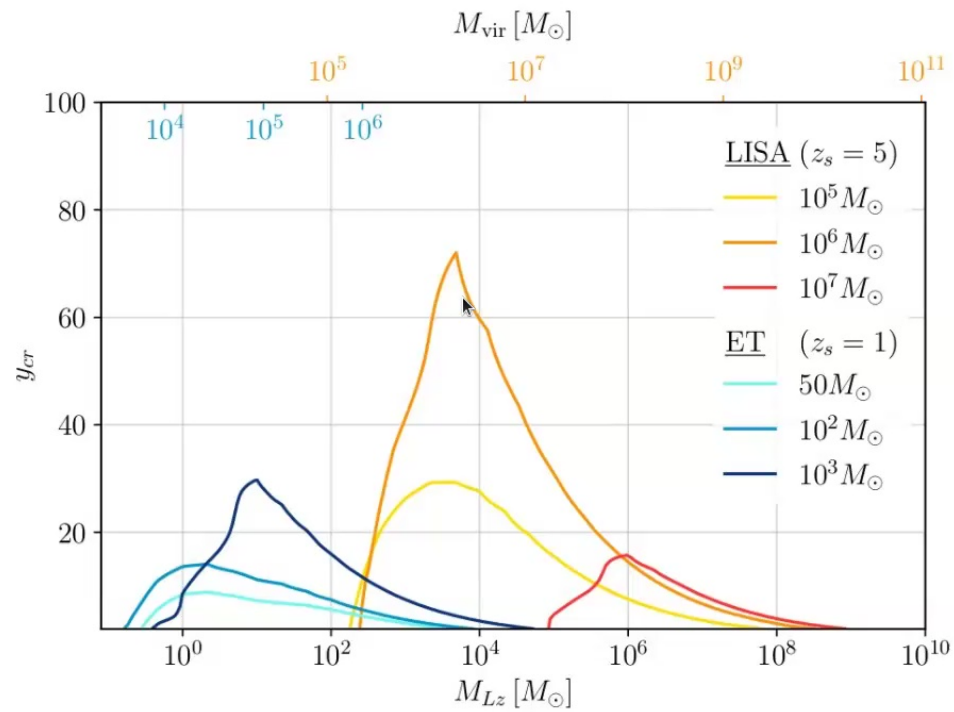
- Gravitational Waves Lensing:
  - Detecatability of WOFs:
    - Lens geometry x Detectability criterion
    - Critical impact parameter:
      - How far can we detect WOFs?
        in units of Einstein radii




S. Savastano, + 2306.05282

# GW lensing – LISA

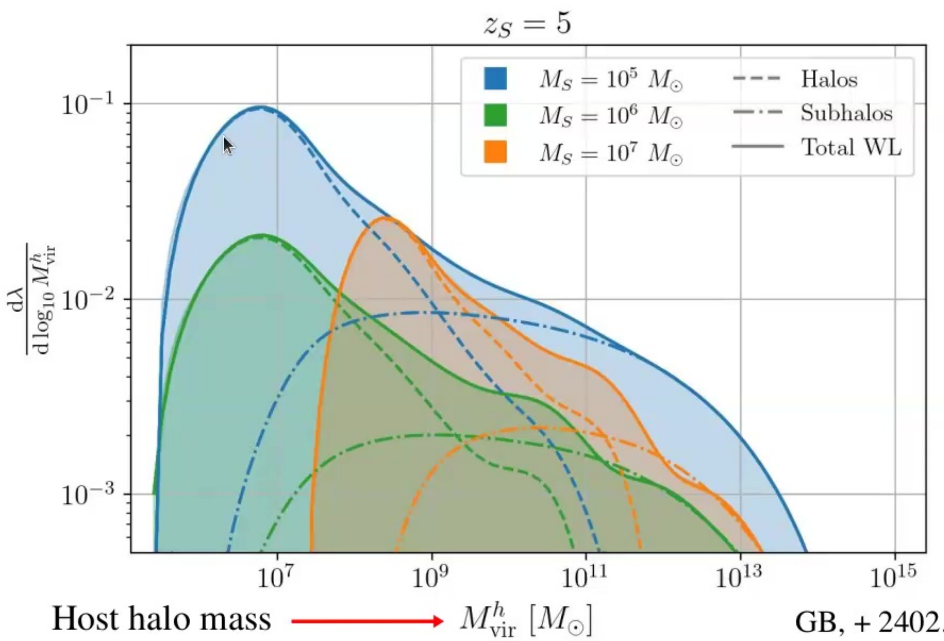
- Gravitational Waves Lensing:
  - Detecatability of WOFs:
    - Lens geometry x Detectability criterion
    - Critical impact parameter:
      - How far can we detect WOFs? in units of Einstein radii




S. Savastano, + 2306.05282

# GW lensing – LISA

- Gravitational Waves Lensing:
  - Probability (optical depth): $\frac{\mathrm{d}\tau_h}{\mathrm{d}\log M_{\mathrm{vir}}^h} = \int_0^{z_S} \mathrm{d}z_L \frac{c\,(1+)^2}{H(z_L)} \sigma\left(z_S, M_S, z_L, M_{\mathrm{vir}}^h\right) \times \frac{\mathrm{d}n_l\left(z_L, M_{\mathrm{vir}}^h\right)}{\mathrm{d}\log M_{\mathrm{vir}}^h}$
  - Distribution of lenses:
    - Halo mass function
    - Subhalo mass function




Host halo mass → 

GB, + 2402.XXXXX

# Conclusions

– Gravitational Waves Lensing:

- GWs can have frequency-dependent lensing effects → Wave Optics Features (Diffraction)

- LVK is already searching for multiply imaged events, but very limited exploration of wave optics and weak lensing

- I have shown that for LISA sources we will be able to probe the (sub)substructure of our Universe, with with enhanced probabilities depending on the modelling of the lens.

Thank you!