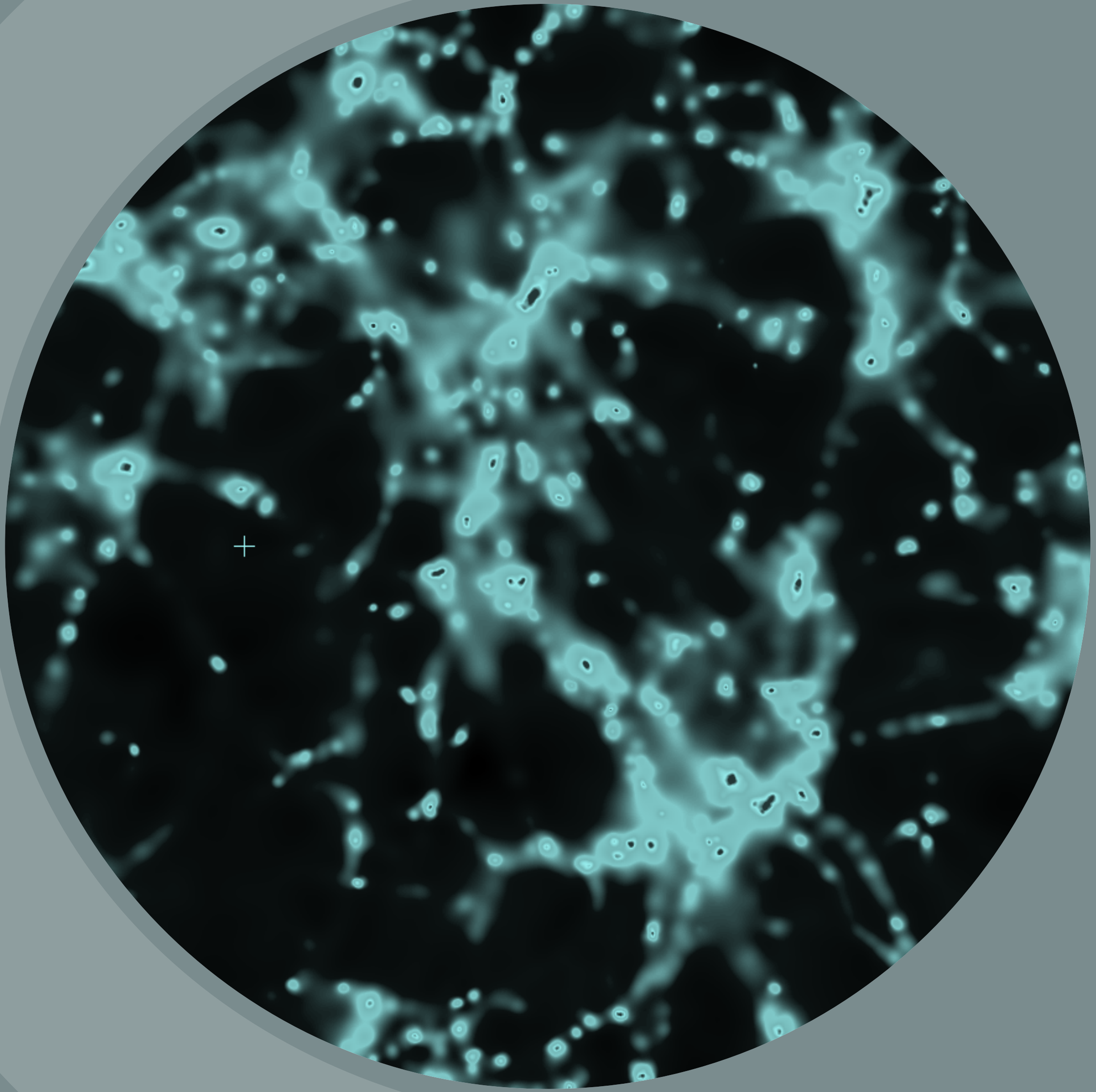


CURRENT AND FUTURE COSMOLOGICAL PROBES OF DARK MATTER MICROPHYSICS

MARKUS R. MOSBECH

Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

December 7, 2023, CosKASI seminar

Overview

- Quick intro
- Our test case model
- Gravitational waves as a novel type of constraint
- Supplementary constraints

- Thanks to collaborators:
  - Alex Jenkins, Sownak Bose, Celine Boehm, Mairi Sakellariadou, and Yvonne Wong

M. Mosbech, A. Jenkins, S. Bose, C. Boehm, M. Sakellariadou, & Y^3 Wong
Gravitational-wave event rates as a new probe for dark matter microphysics
arXiv:2207.14126

M. Mosbech, C. Boehm, S. Hannestad, O. Mena, J. Stadler, & Y^3 Wong
The full Boltzmann hierarchy for dark matter-massive neutrino interactions
arXiv:2011.04206

M. Mosbech, C. Boehm, & Y^3 Wong
Probing dark matter interactions with SKA
arXiv:2207.03107

WHAT DO WE KNOW ABOUT DARK MATTER?

- Quite a lot of it out there
- Zero, or very limited, interactions with the standard model
- Clusters gravitationally, at least on large scales

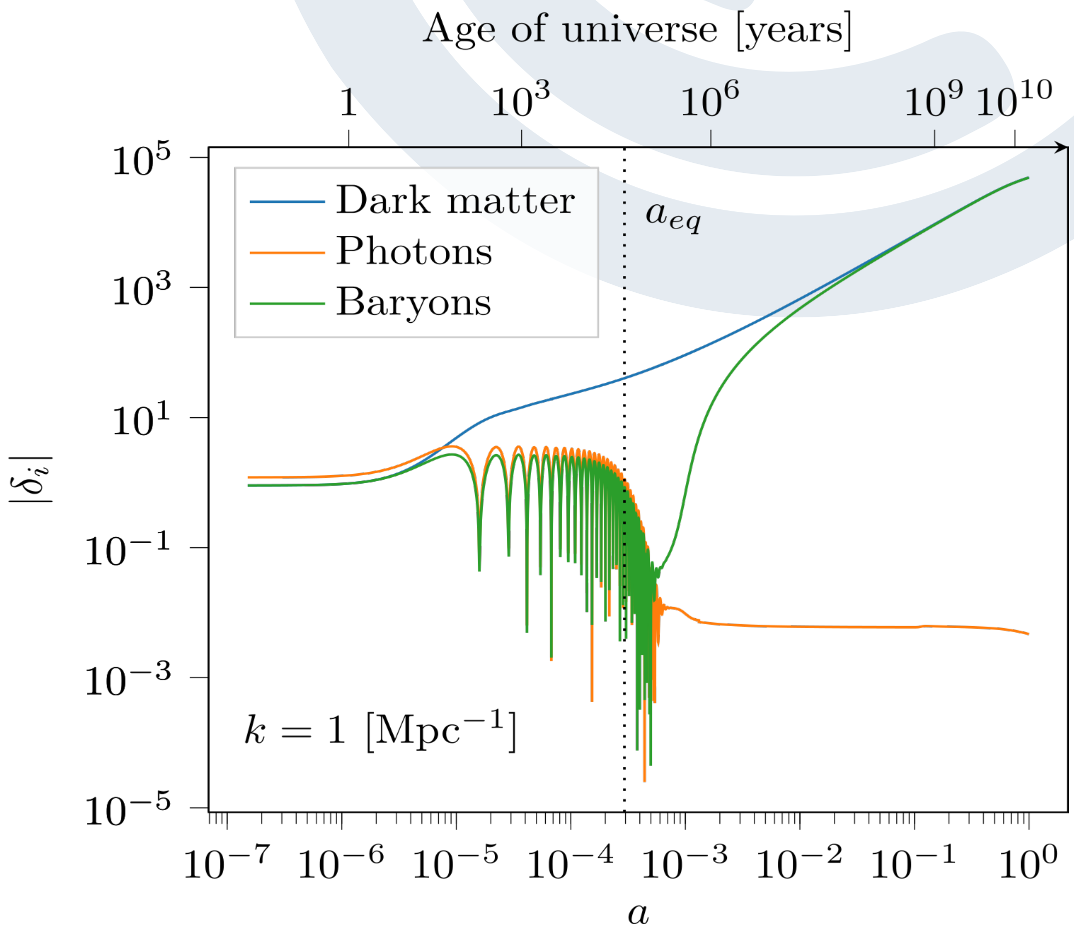
- Essentially: we know a lot about what it is *not*, but not a lot about what it *is*
  - So what can gravitational waves tell us?

How can we learn more?

- Laboratory experiments
  - Direct Detection
  - Colliders
- Astrophysical signals
  - Indirect detection – annihilation/decay
  - Structure formation

Dark matter as the seeds of structure

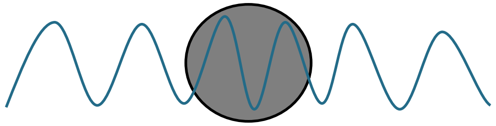
- The universe begins in a very homogeneous state
- Baryons are strongly coupled to photons, whose pressure prevent collapse
- Non-interacting dark matter feels no such pressure, letting it form structures early



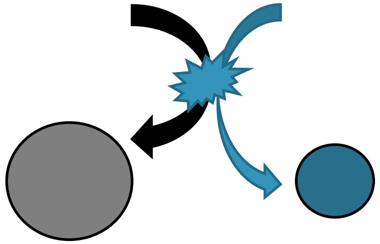
Dark matter models with suppressed structure

- Three broad categories:
  - Warm dark matter
    - Supresses structure due to thermal velocity, if thermally produced $M \sim \mathcal{O}(\mathrm{keV})$

  - Ultra-light dark matter
    - Suppresses structure due to wavelike behaviour, $M \sim \mathcal{O}(10^{-22}\mathrm{eV})$

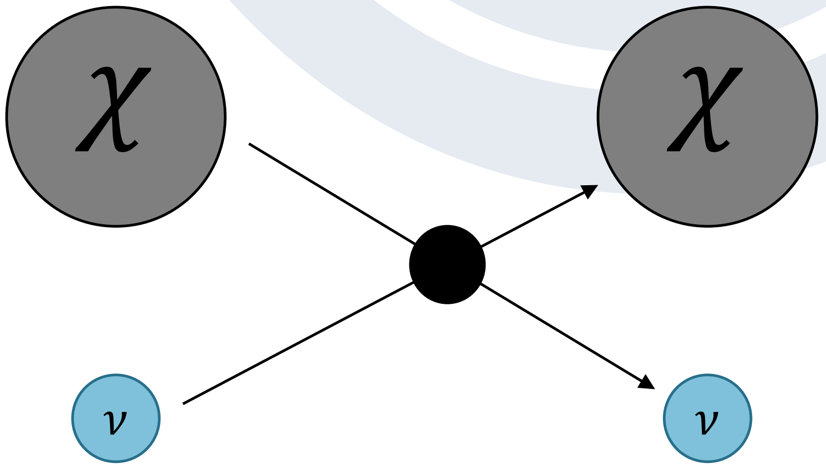


  - Interacting dark matter
    - Suppresses structure due to scattering



Our example model: DM-ν scattering

- Good baseline model – baryonic and photon physics remain unaffected
- Neutrino physics has remaining open questions, e.g. masses
- For simplicity: velocity independent scattering



Linear evolution

- Linear Boltzmann equations are useful for describing early evolution ($z \geq 50$), and large scales (e.g. BAO)
- Super good for CMB predictions
- Produces initial conditions for nonlinear simulations

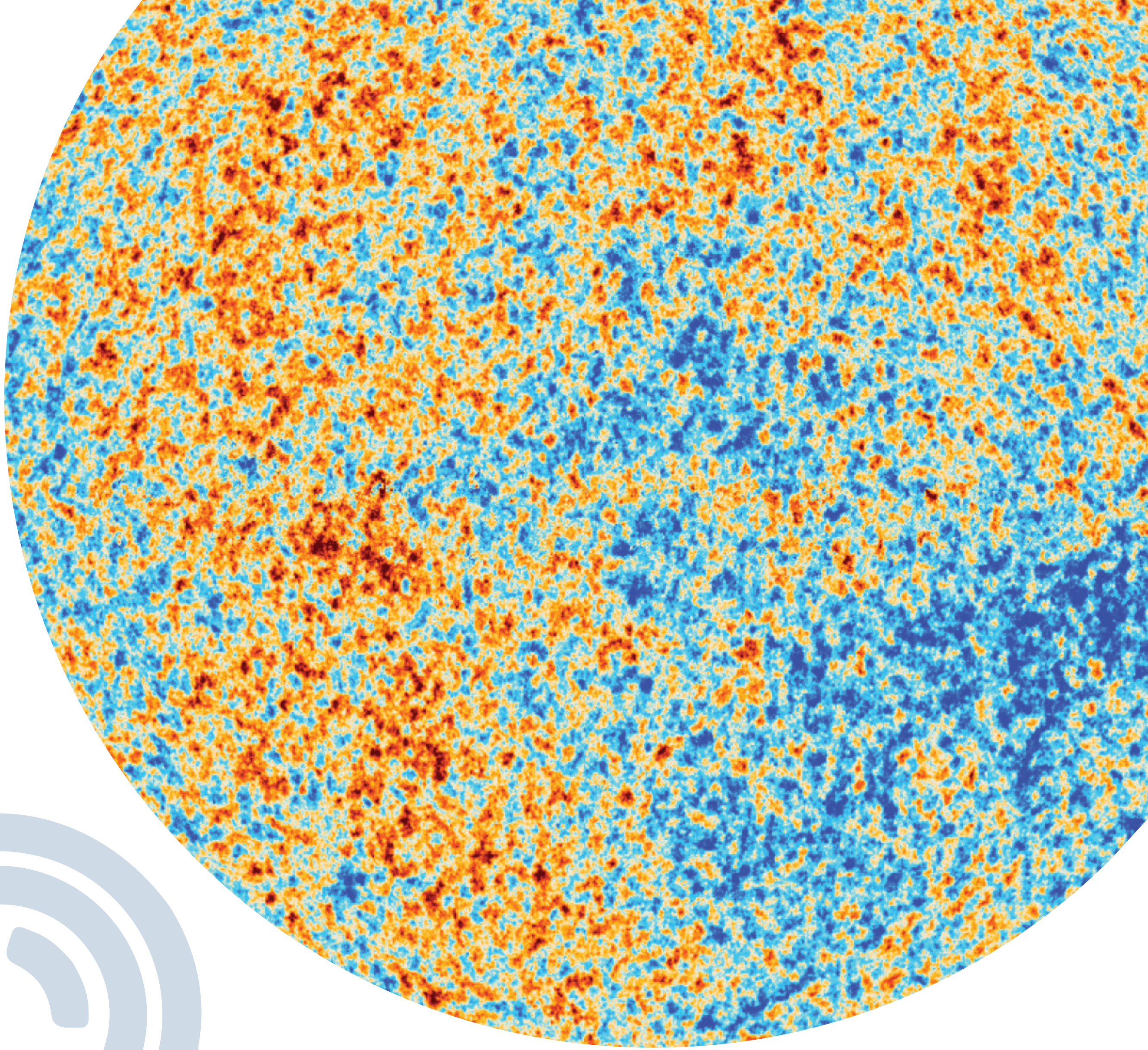


Image: ESA and the Planck Collaboration

Linear evolution equations

- Dark matter:

$$\dot{\delta}_\chi = -\theta_\chi + 3\dot{\phi}$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta + k^2\psi + K_\chi \dot{\mu}_\chi(\theta_\nu - \theta_\chi)$$

$$C_\chi = a\, u_{\nu\chi} \frac{\sigma_{\mathrm{Th}}\rho_\chi}{100\ \mathrm{GeV}} \frac{p^2}{E_\nu^2}$$

$$u_{\nu\chi} = \frac{\sigma_0}{\sigma_{\mathrm{Th}}} \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^{-1}$$

$$\dot{\mu}_\chi \equiv \frac{3k}{4} \frac{\int p^2 dp\, p\, f^{(0)}(p)\, C_\chi(p) \left(\frac{\theta_\chi E_\nu(p)}{3k\, f^{(0)}(p)} \frac{df^{(0)}(p)}{dp} + \Psi_{\nu,1} \right)}{\int p^2 dp\, p\, f^{(0)}(p)}$$

$$K_\chi \equiv \frac{\rho_\nu + P_\nu}{\rho_\chi}$$

- Neutrinos (non-zero mass)

$$\dot{\Psi}_{\nu 0} = -\frac{pk}{E_\nu(p)}\Psi_{\nu 1} - \dot{\phi}\frac{d\ln f^{(0)}(p)}{d\ln p}$$

$$\dot{\Psi}_{\nu 1} = \frac{pk}{3E_\nu(p)}(\Psi_{\nu 0} - 2\Psi_{\nu 2}) - \frac{E_\nu(p)k}{3p}\psi\frac{d\ln f^{(0)}(p)}{d\ln p}$$

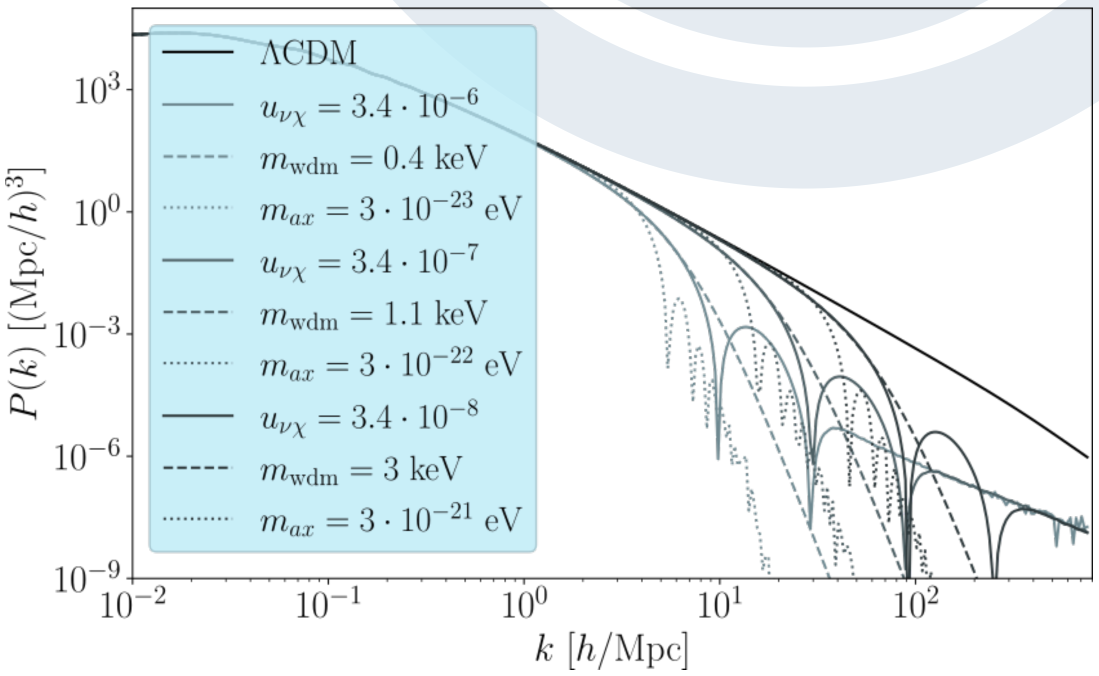
$$+C_\chi \frac{v_\chi E_\nu(p)}{3f^{(0)}(p)} \frac{df^{(0)}(p)}{dp} - C_\chi \Psi_{\nu 1}$$

$$\dot{\Psi}_{\nu l} = \frac{1}{2l+1}\frac{pk}{E_\nu(p)}\left(\Psi_{\nu(l-1)} - (l+1)\Psi_{\nu(l+1)}\right) - C_\chi \Psi_{\nu l}$$

$$\dot{\Psi}_{\nu 2} = [\ldots] - \frac{9}{10} C_\chi \Psi_{\nu 2}$$

"All roads lead to Rome": The suppressed matter power spectrum

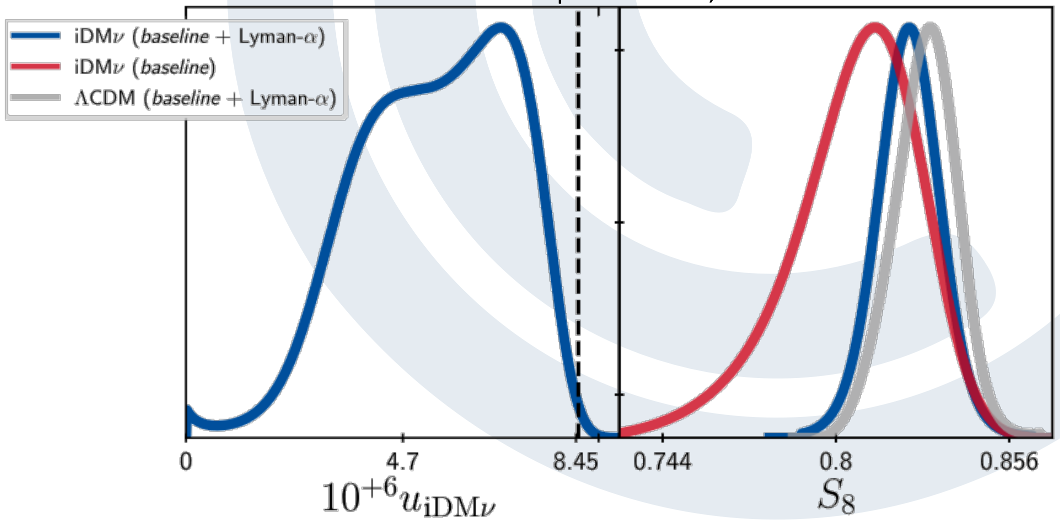
- The three "types" of models are easily tuned to suppress structure at similar scales
- Different models may have qualitatively different signals below the suppression scale

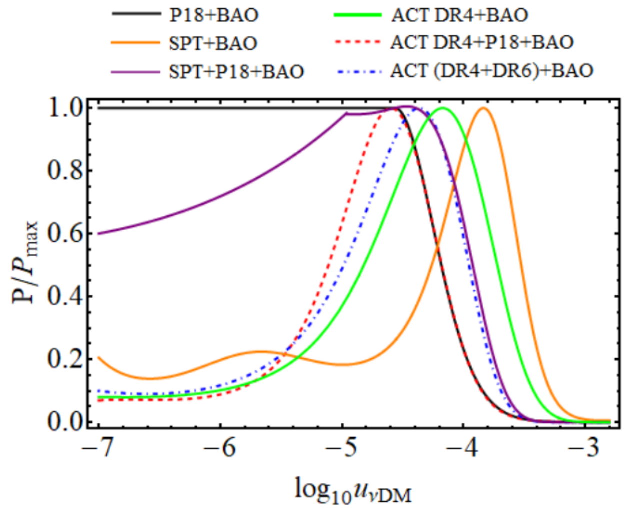


Promising hints

- Lyman-α data prefers a non-zero interaction strength
- Preferred value $u_{\nu\chi} \sim 5 \cdot 10^{-6}$
- New analyses of SPT and ACT CMB data also reveals preference for non-zero interaction

Hooper & Lucca, arXiv:2110.04024

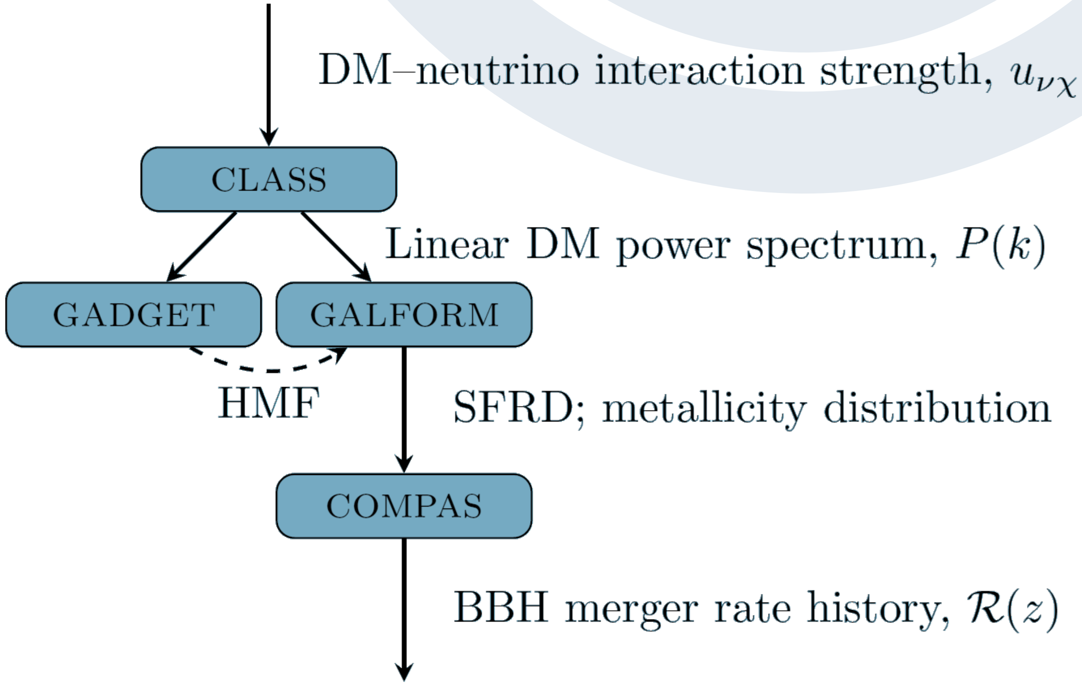




Giarè et al., arXiv:2311.09116

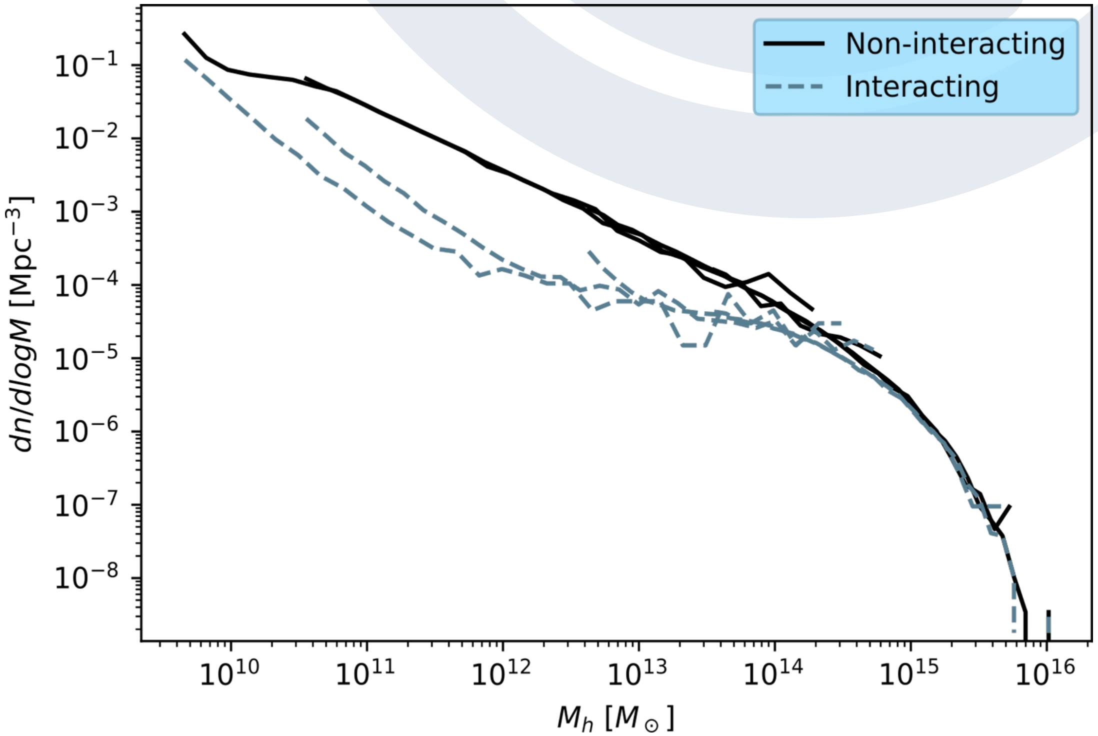
From suppressed structure to gravitational waves

1. Suppressed structure
2. Less/delayed galaxy/progenitor formation
3. Less/delayed star formation
4. Fewer/delayed black hole binaries formed
5. Fewer binary black hole mergers detected



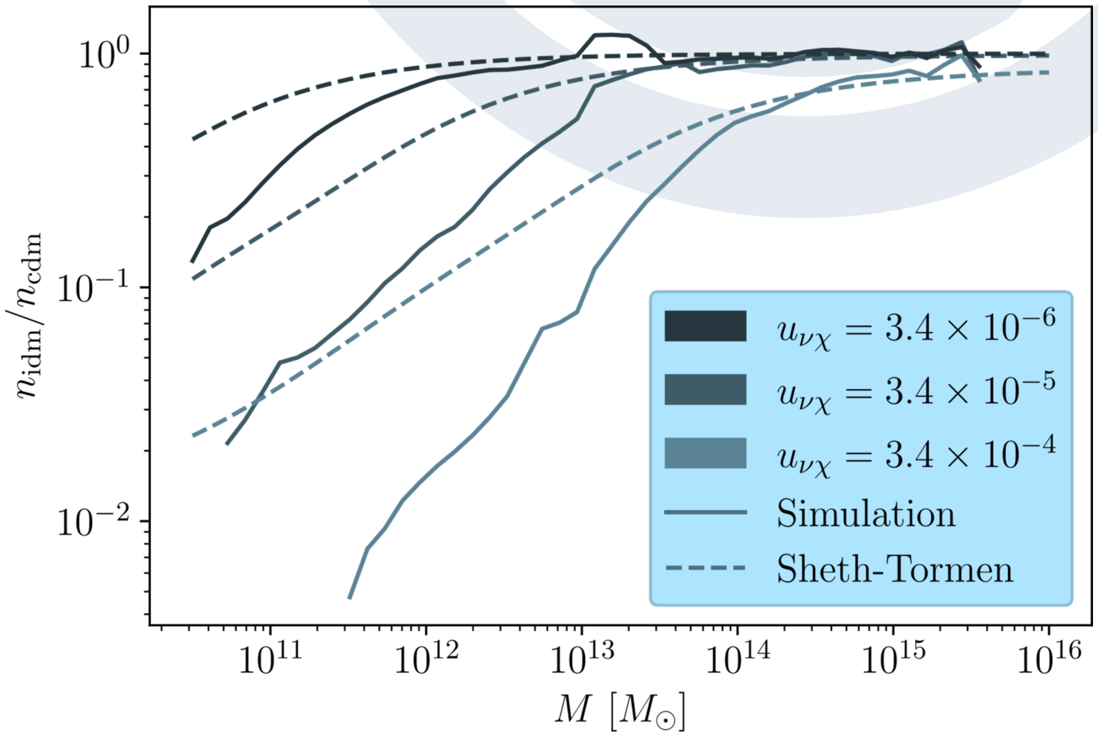
Simulating suppressed structure

- For the purpose of the GW signal, our main interest is in the halo mass function
- Problem: unphysical fragmentation causes upturn at low masses for suppressed structure cosmologies

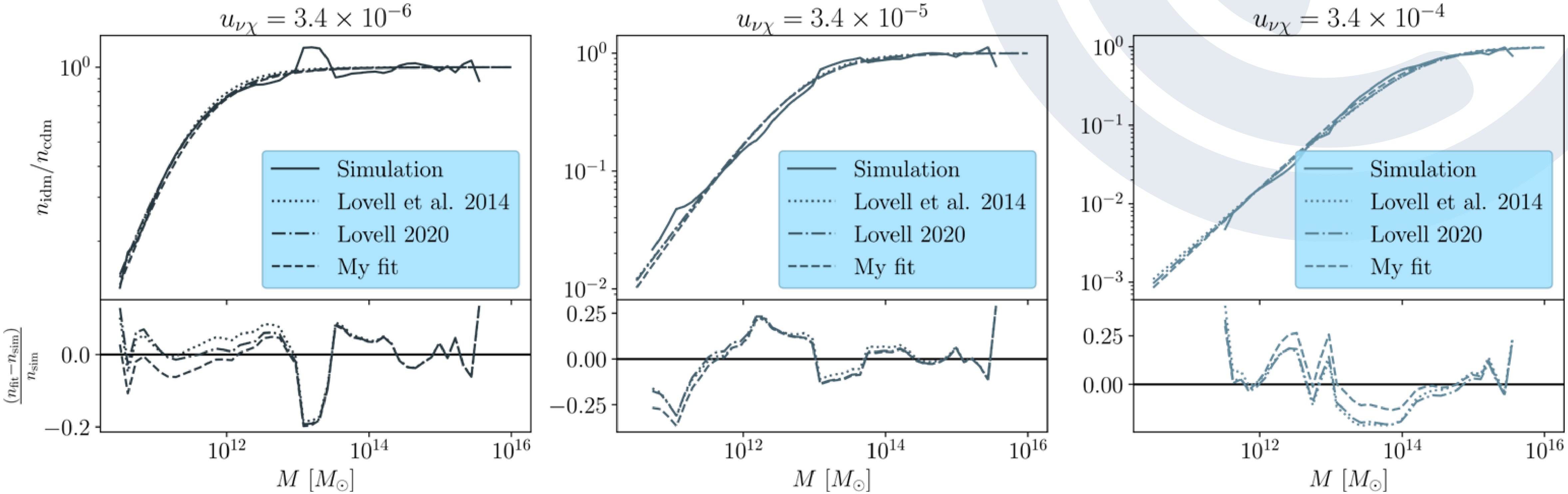


Avoiding fragmentation: Analytic HMF?

- Standard Sheth-Tormen HMF does not accurately capture suppression
- Boxes stitched together with unphysical tail removed – not suitable for generating galaxy populations



Avoiding fragmentation: Analytic HMF?



$$\frac{n_{\rm idm}}{n_{\rm cdm}} = \frac{1}{1 + \left(\frac{M_\beta}{M}\right)^\alpha} \qquad \beta = 10\%, \qquad \alpha = 0.9$$

Generating galaxy populations

- We generate realistic galaxy populations for our model with Galform
- To avoid issues with artificial fragmentation, we generate galaxy populations with a Monte Carlo method.
- Extended Press-Schechter method reproduced our fitted HMF

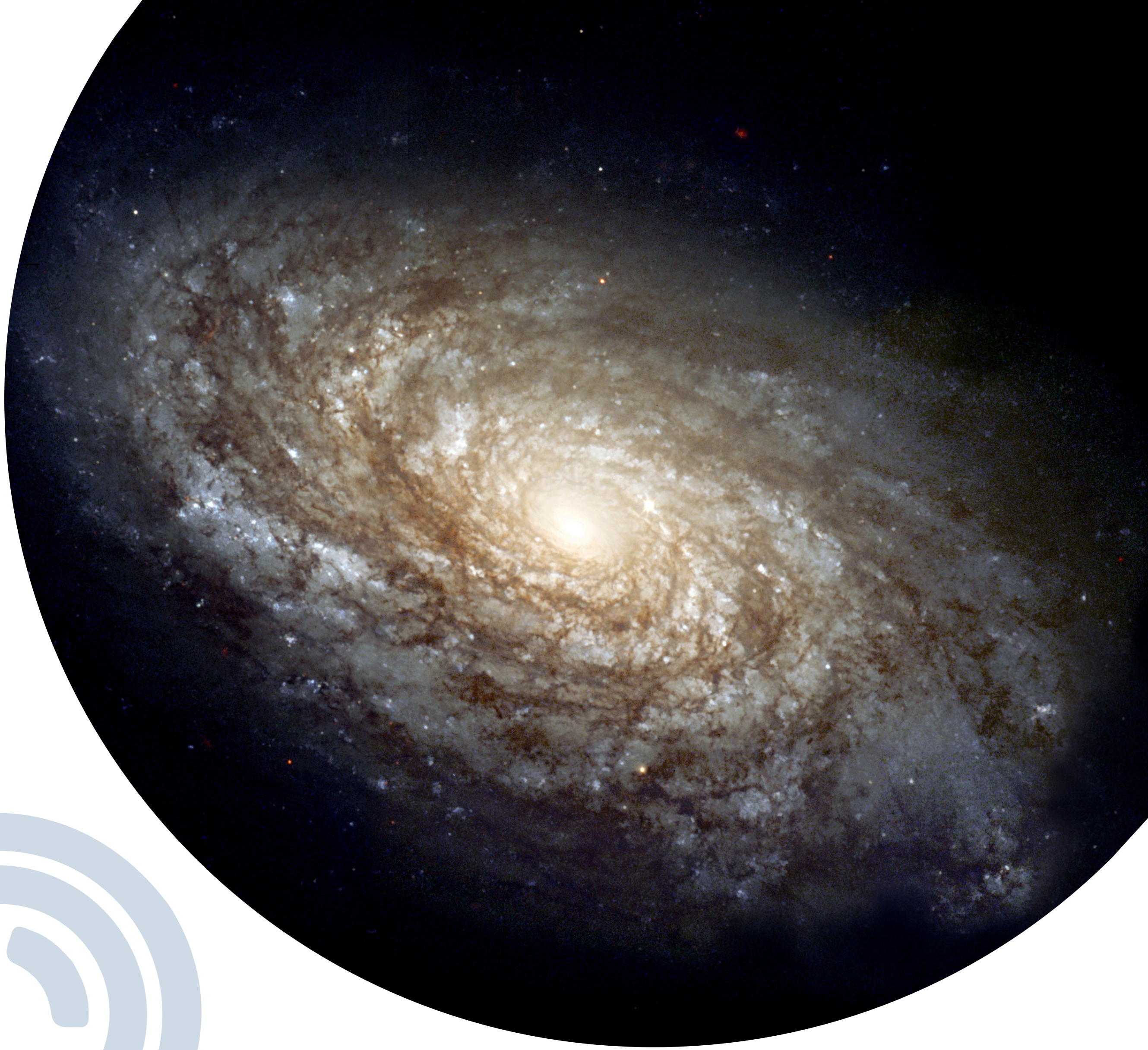
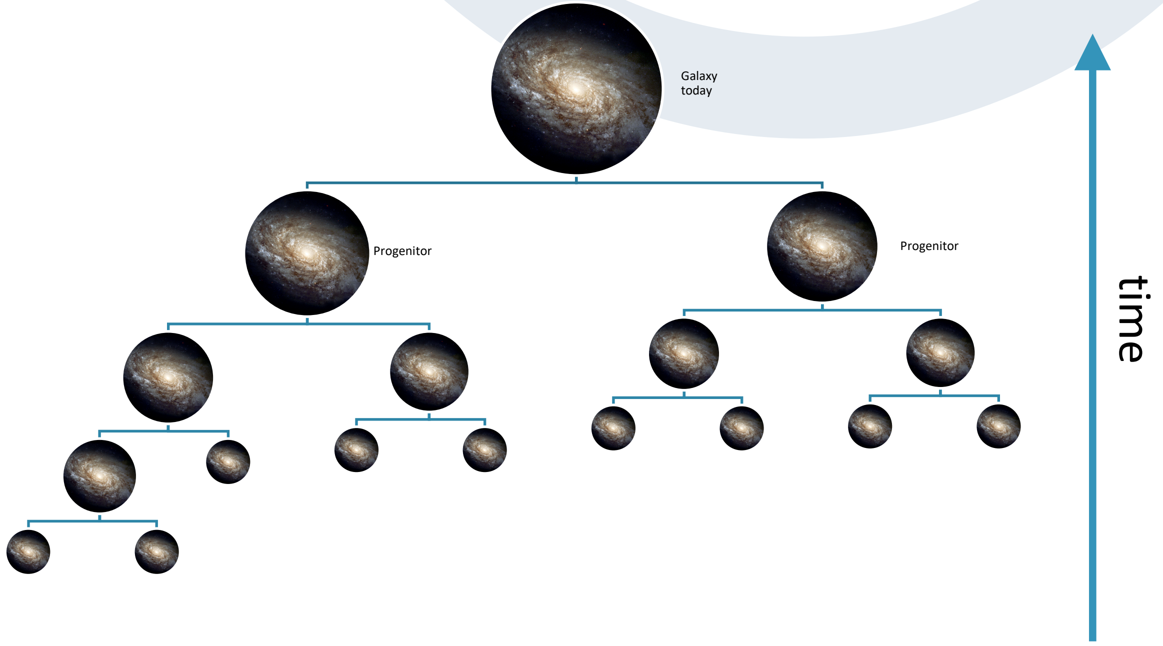


Image: NASA Hubble heritage team

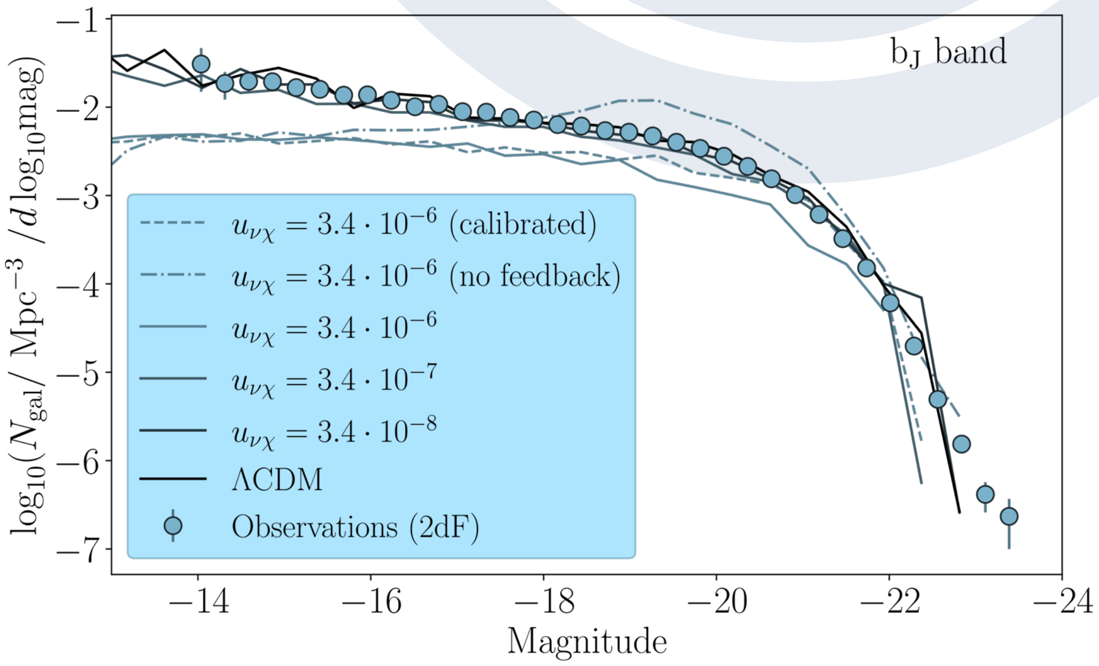
Hierarchical Merger tree

- Progenitors generated through Monte Carlo
- Galaxy merger physics determines star formation, metallicity etc
- Resolution set by smallest tracked progenitor



Impact on galaxy populations

- Strong interactions ruled out already
- Sets strongest bounds yet on this interaction – rules out Ly-α preferred value



Generating compact binary population

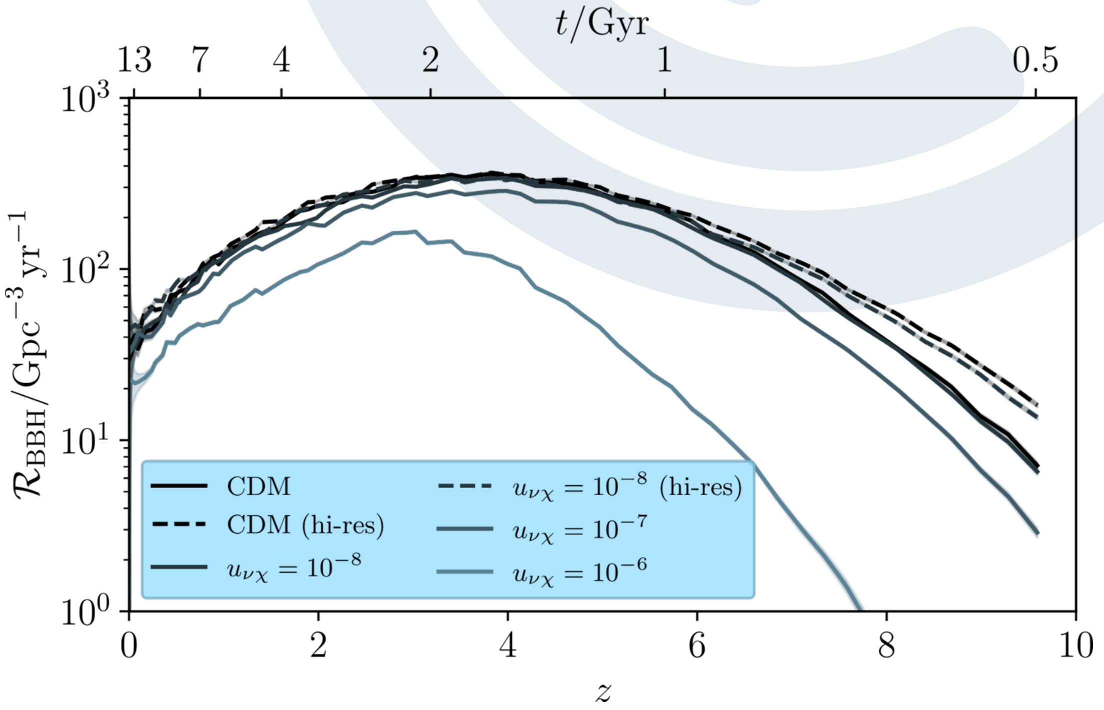
- Compact binaries form from massive binary star systems
- Compact binary formation rate → delayed tracer of star formation
- Not so simple: conversion from binary star to compact binary depends on metallicity

Image: COMPAS team, compas.science

See:
arXiv:2109.10352
arXiv:2010.00002
arXiv:1806.05820
arXiv:1906.08136

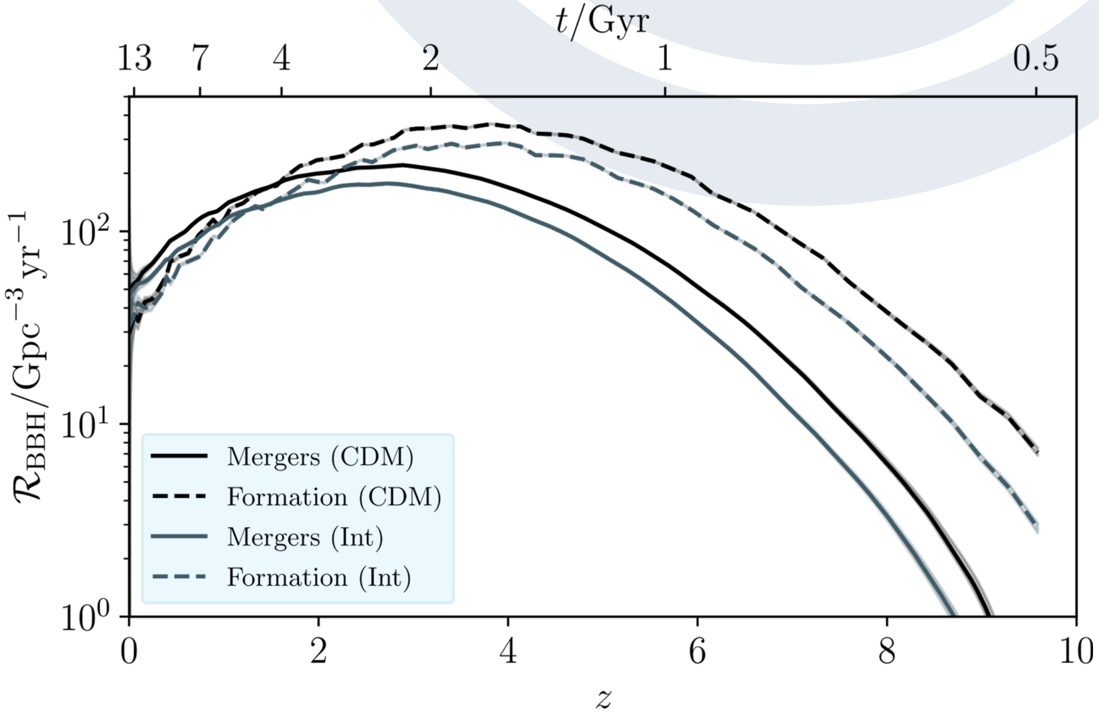
Binary formation rate

- Computed by Compas from Galform output
- Generates binaries over cosmic time using differential star formation rate and metallicity
- Draws from stellar tracks computed with stellar evolution code MESA



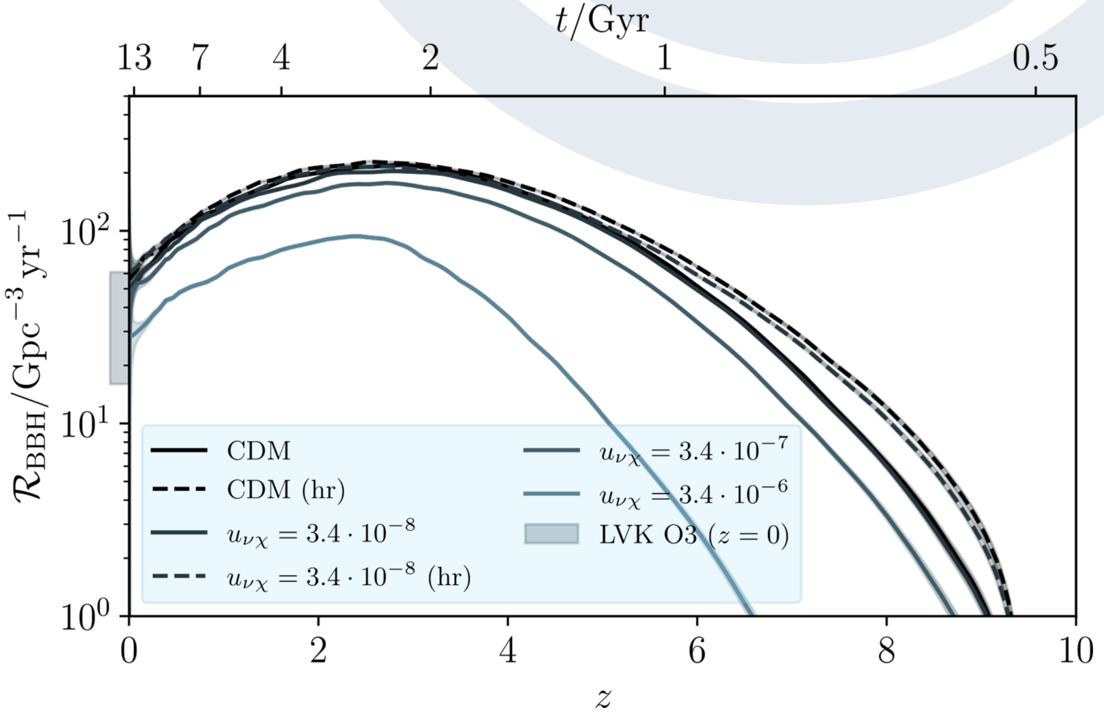
Formation and coalescence

- Coalescence time also drawn from Compas based on generated population
- Essentially a time-folding of the formation rate



Constraining DM with LIGO/VIRGO/Kagra

- Current generation of GW observatories "only" constrain the rate well at low z.
- Current constraints on local GW rate not strong enough to rule interacting DM out (or in)
- With our modelling, ΛCDM is at the upper end of the allowed range.



Beyond LVK: The next generation

- The rate is strongly affected by delayed structure formation
- High-redshift observations will be ideal for constraining these models
- Einstein Telescope + Cosmic Explorer provides high-redshift sensitivity

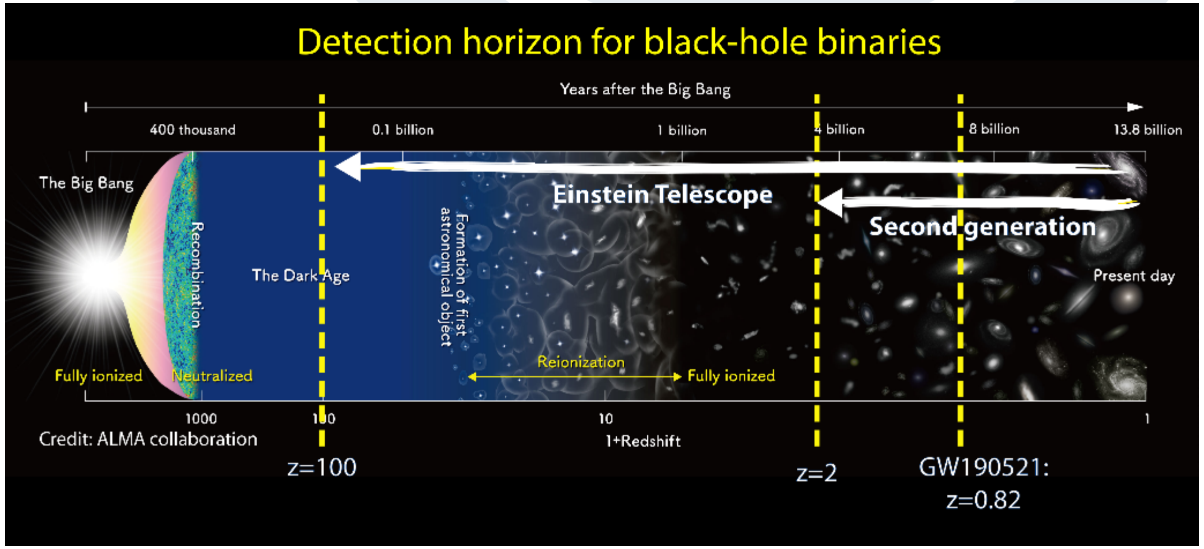
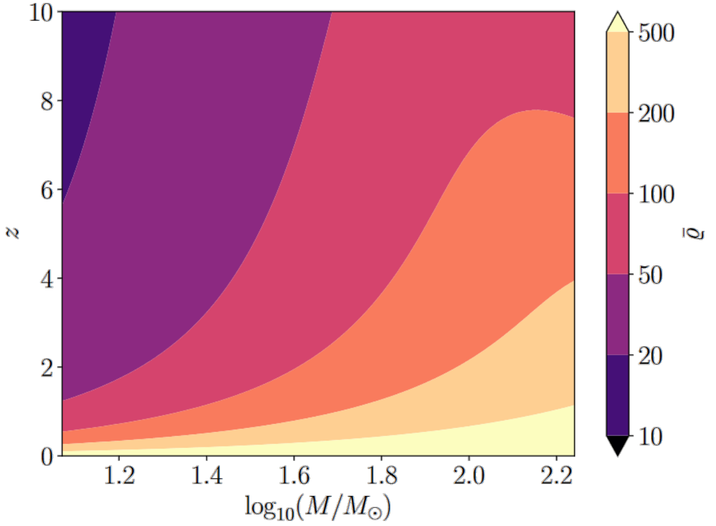
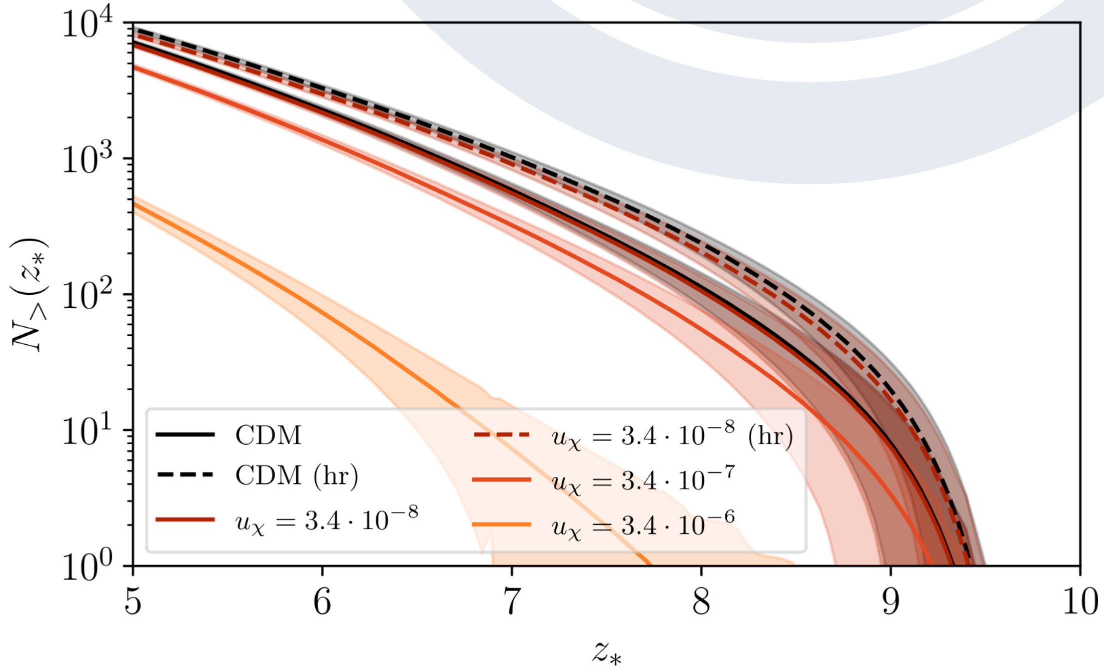


Image: Einstein Telescope, https://www.et-gw.eu/

Next generation detection forecast

- The next generation can see almost every event

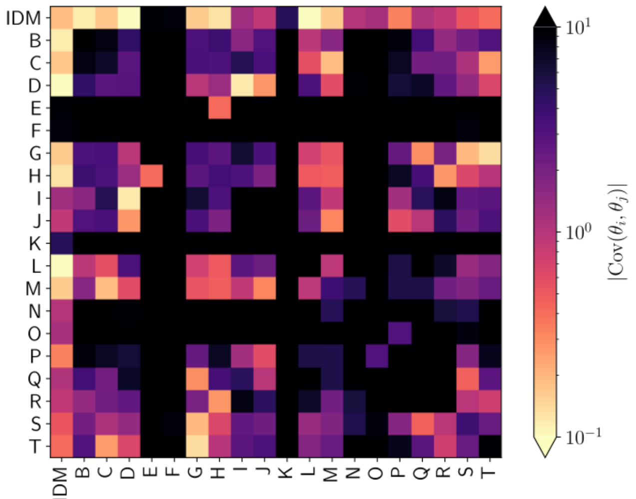


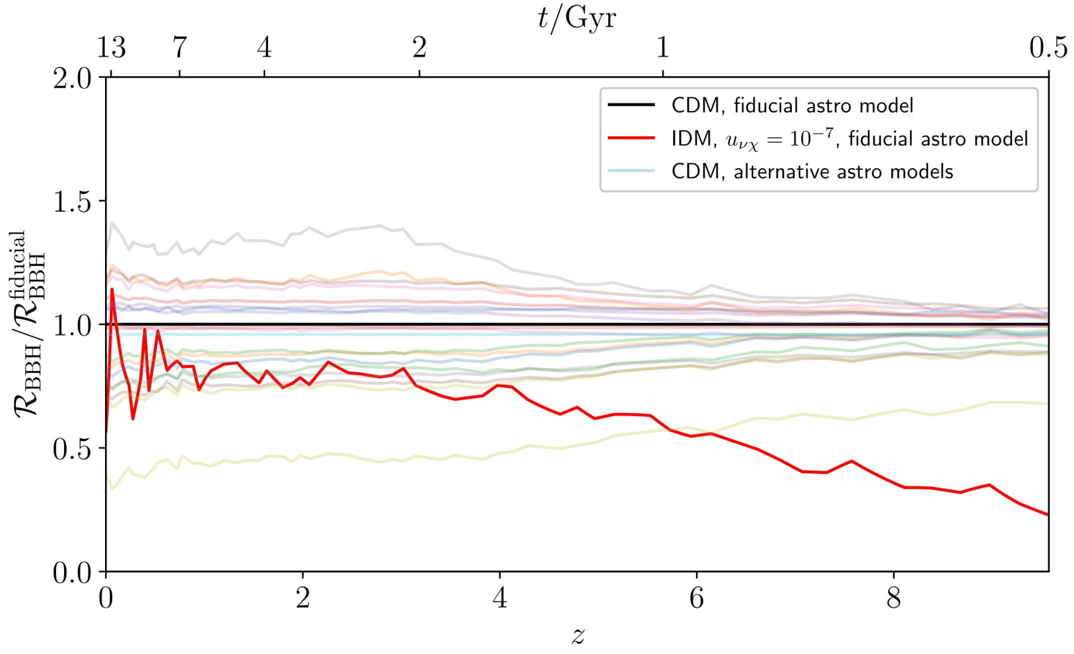


- This will be able to set powerful constraints

Binary formation uncertainty

- Binary formation/merger model relies on set of astro parameters
- Qualitative effect on formation/merger rate different than interacting DM

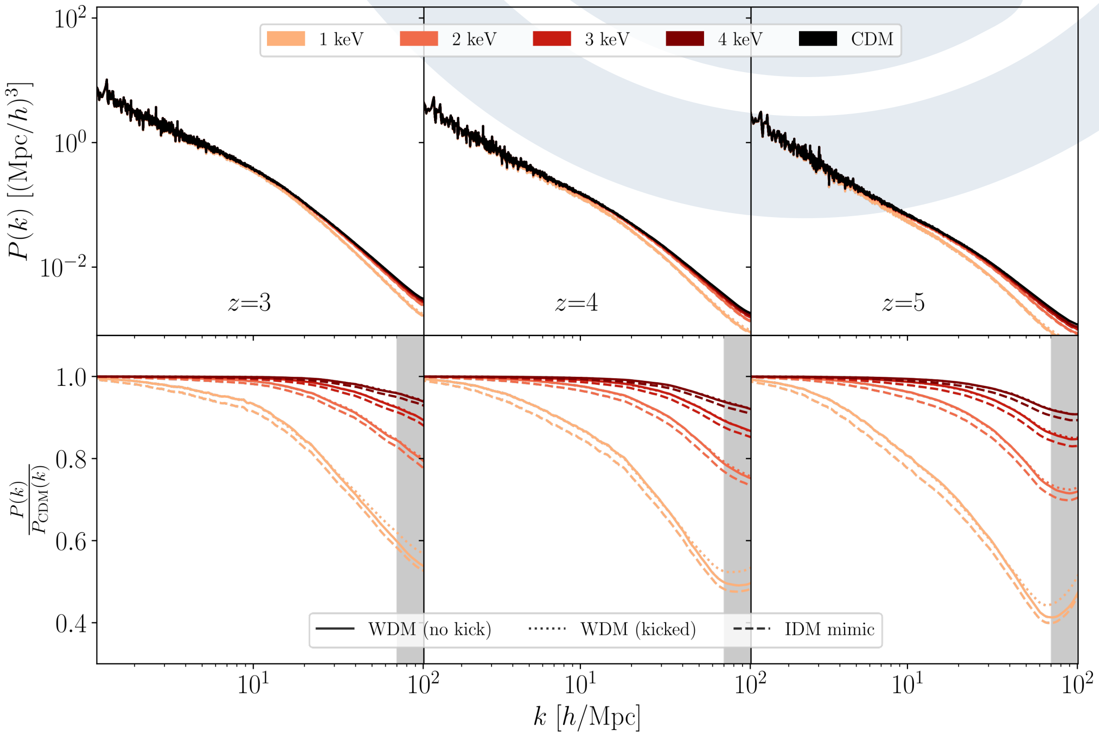




Compare and contrast: warm dark matter

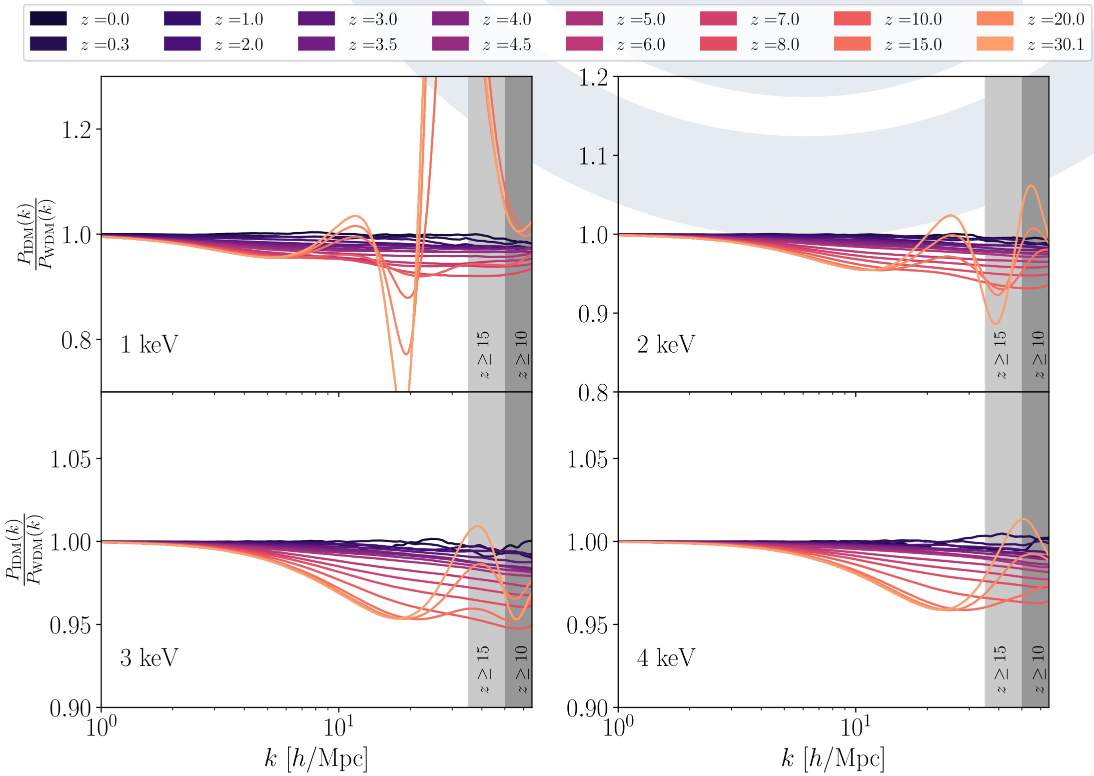
- Our interacting models are indistinguishable from warm dark matter at $z \leq 10$
- The upside of which: constraints on warm dark matter can be directly mapped to interacting models

m_{wdm}	$u_{\nu DM}$	$u_{\gamma DM}$
1 keV	8.5×10^{-7}	4.0×10^{-7}
2 keV	1.75×10^{-7}	9.0×10^{-8}
3 keV	7×10^{-8}	3.5×10^{-8}
4 keV	3.6×10^{-8}	1.8×10^{-8}



Complementary constraints: 21cm with SKAO

- SKAO forecasts on WDM constraint can be mapped to interacting DM
- At early times, nonlinear evolution has not yet erased oscillations
- High-precision, high redshift measurements at high k needed to distinguish
- SKAO can in principle measure the 21 cm line at these redshifts.



Conclusions

- Next generation GW observatories can be used constraining suppressed structure, improving limits
- SKA will be able to similarly constrain DM models with suppressed structure
- High redshift measurements will be key to distinguishing between models suppressing small scale power

Data	Max $u_{\nu DM}$	Source
Planck + SDSS	$\sim 3 \times 10^{-4}$	Mosbech et al. arXiv:2011.04206
Planck + SDSS+Lyα	$\sim 10^{-5}$	Hooper & Lucca arXiv:2110.04024
ACT/SPT + BAO (+ Planck)	$\sim 10^{-4}$	Giarè et al. arXiv:2311.09116
SKA 21cm line intensity map	$\sim 4 \times 10^{-8}$*	Mosbech, Boehm, & Wong arXiv.2207.03107
2dF galaxy counts	$\sim 3 \times 10^{-6}$-10^{-7}	Mosbech et al. arXiv:2207.14126
Einstein Telescope + Cosmic Explorer	$\sim 4 \times 10^{-7}$*	Mosbech et al. arXiv:2207.14126

*: Forecast – constraint assuming non-detection