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Dark Matters 2022* | *Université Libre de Bruxelles

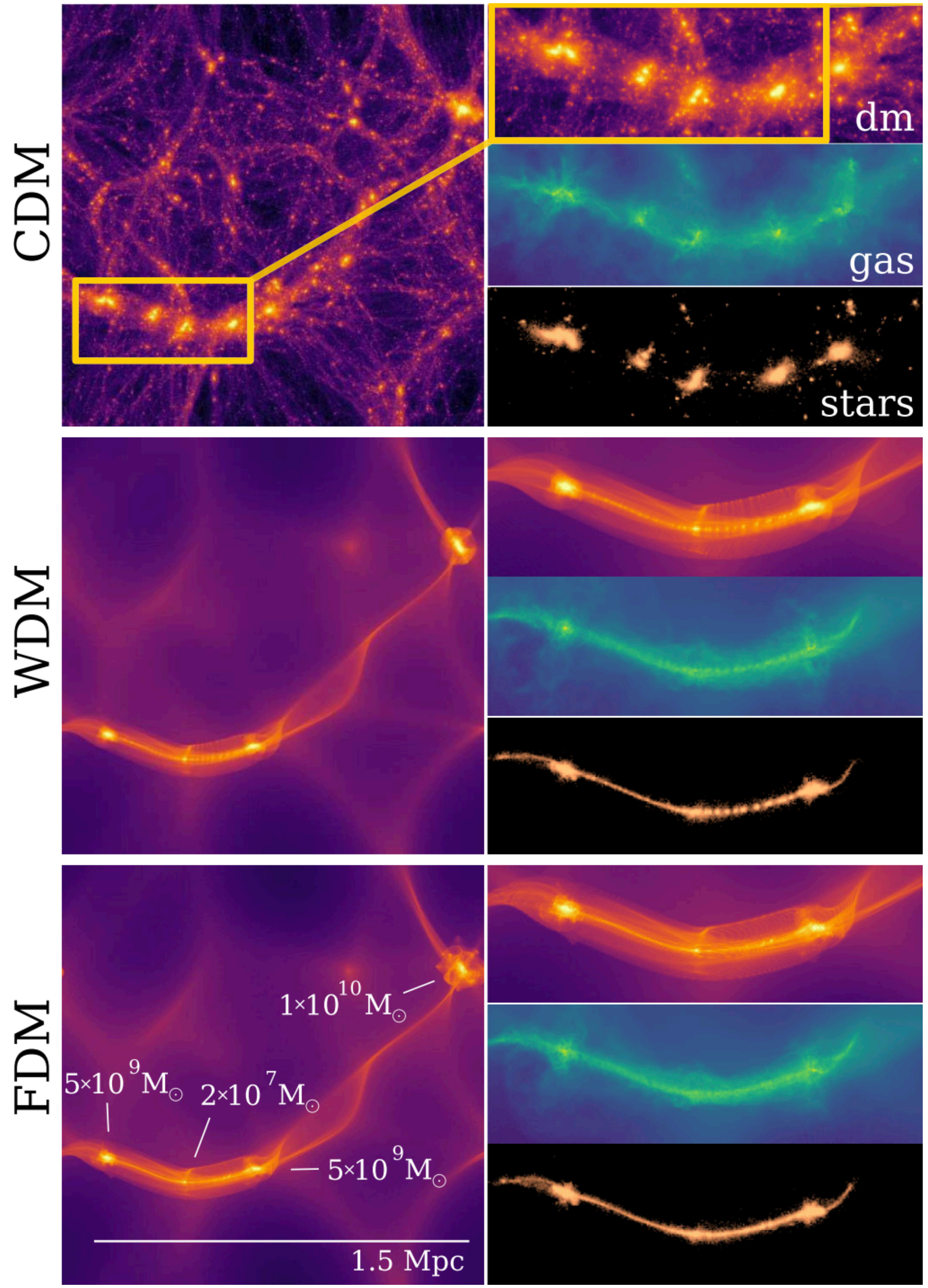
Gravitational-wave event rates as a new probe of DM microphysics

Based on arXiv 2207.14126 [astro-ph.CO]
with Markus Mosbech, Sownak Bose, Celine Boehm, Mairi Sakellariadou, & Yvonne Wong

Dark matter substructure

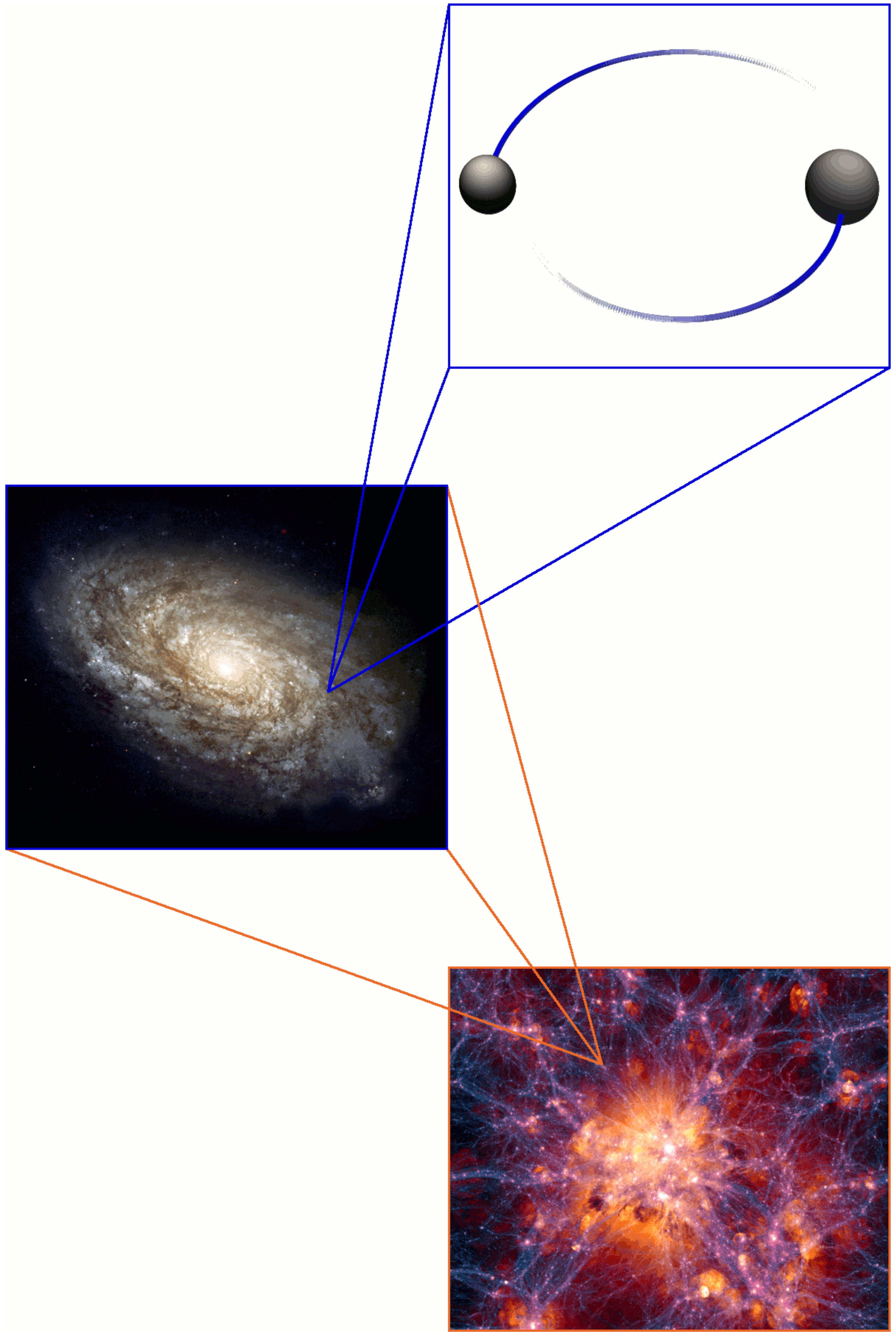
- Is dark matter actually *cold*? (collisionless, noninteracting, nonrelativistic)
- If so, gravitational collapse forms structures on very small scales (Jeans wavelength is zero)
- Many alternatives, e.g. scattering off other particles (IDM), mildly relativistic velocities (WDM), or “quantum pressure” (FDM)
- All these effects prevent collapse on small scales and *suppress substructure*

Mocz+, 1910.01653



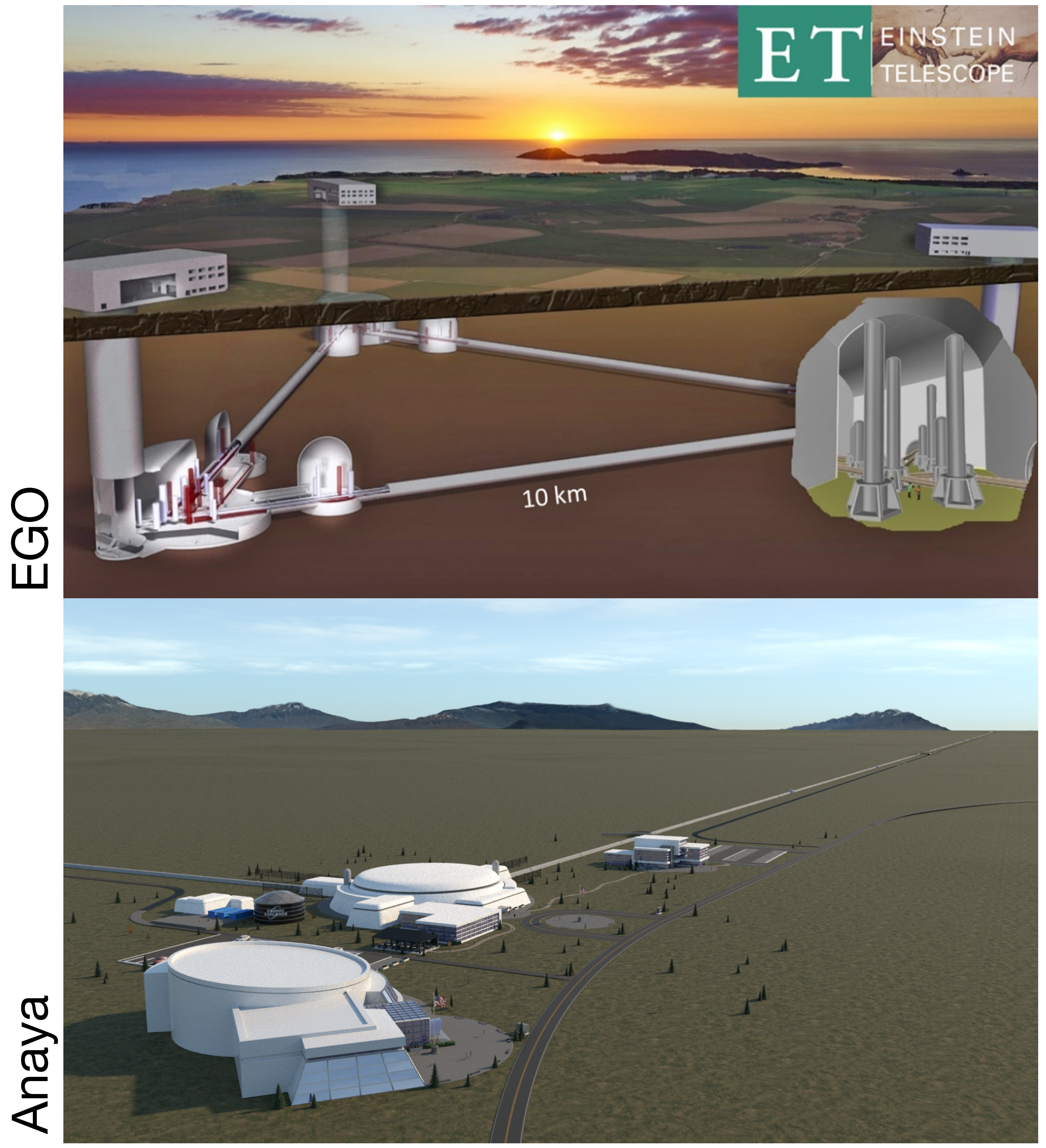
Gravitational waves are an ideal probe of this!

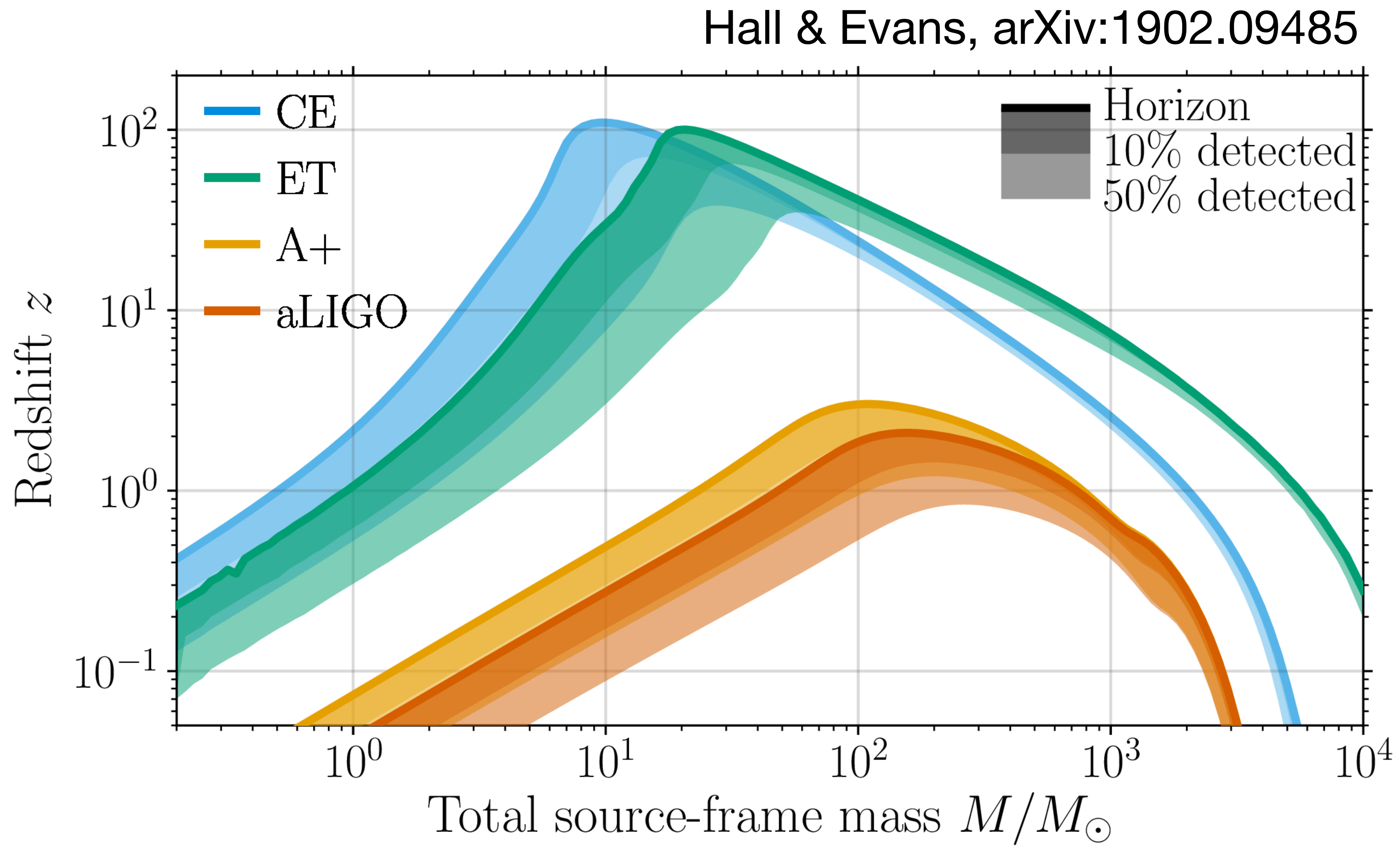
- Suppression strongest on small scales (lightest haloes) and at high redshift (structure formation is “bottom-up”)
- Challenging to access with traditional observations
- **Key idea:** use *binary black holes* (BBHs) as tracers of these haloes
- Break CDM —> fewer light, early haloes —> fewer high-z BBHs

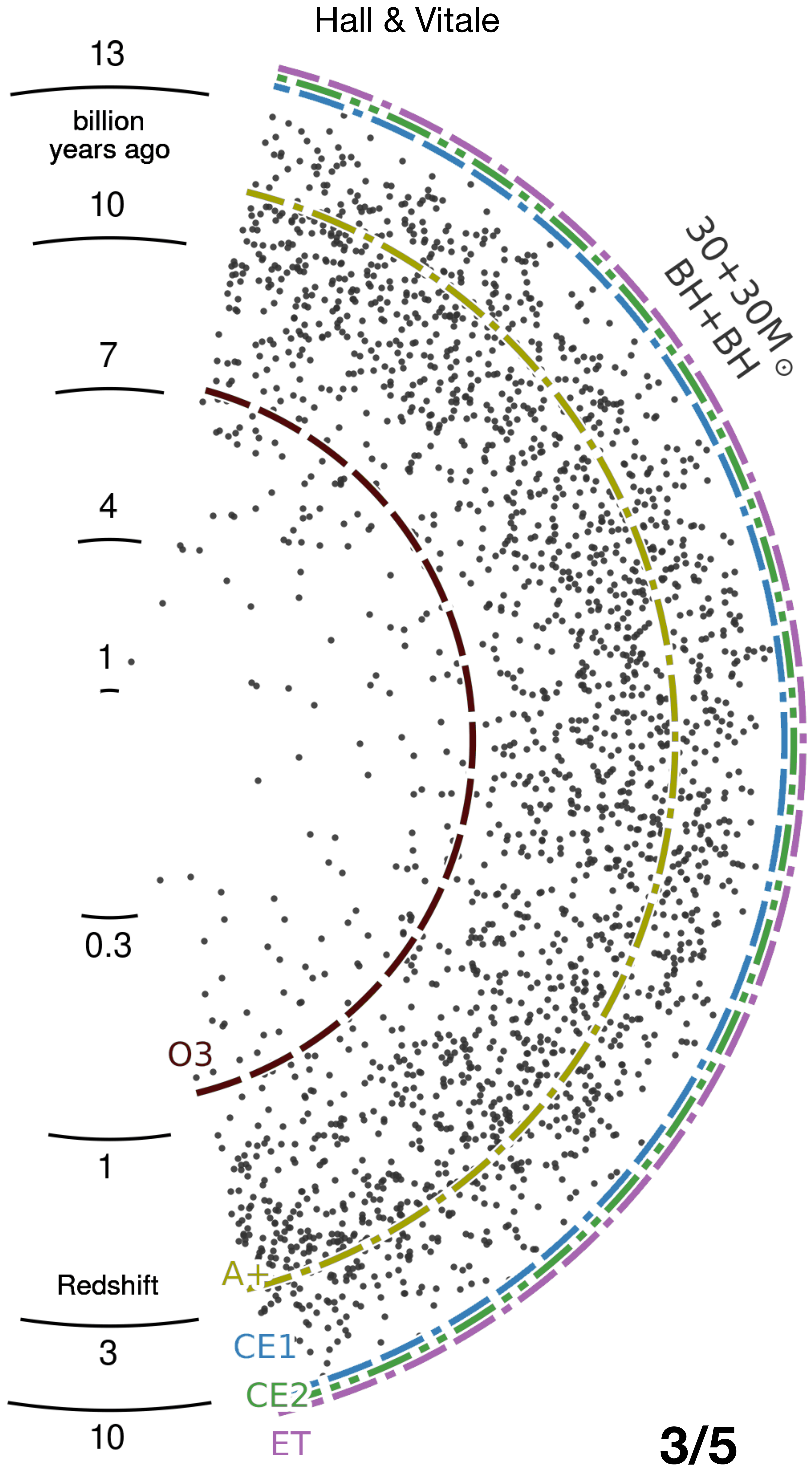


3rd-gen GW interferometers

- Einstein Telescope (EU) and Cosmic Explorer (US) will detect essentially *all* BBHs in the observable Universe! (*thousands per yr* at $z > 7$)





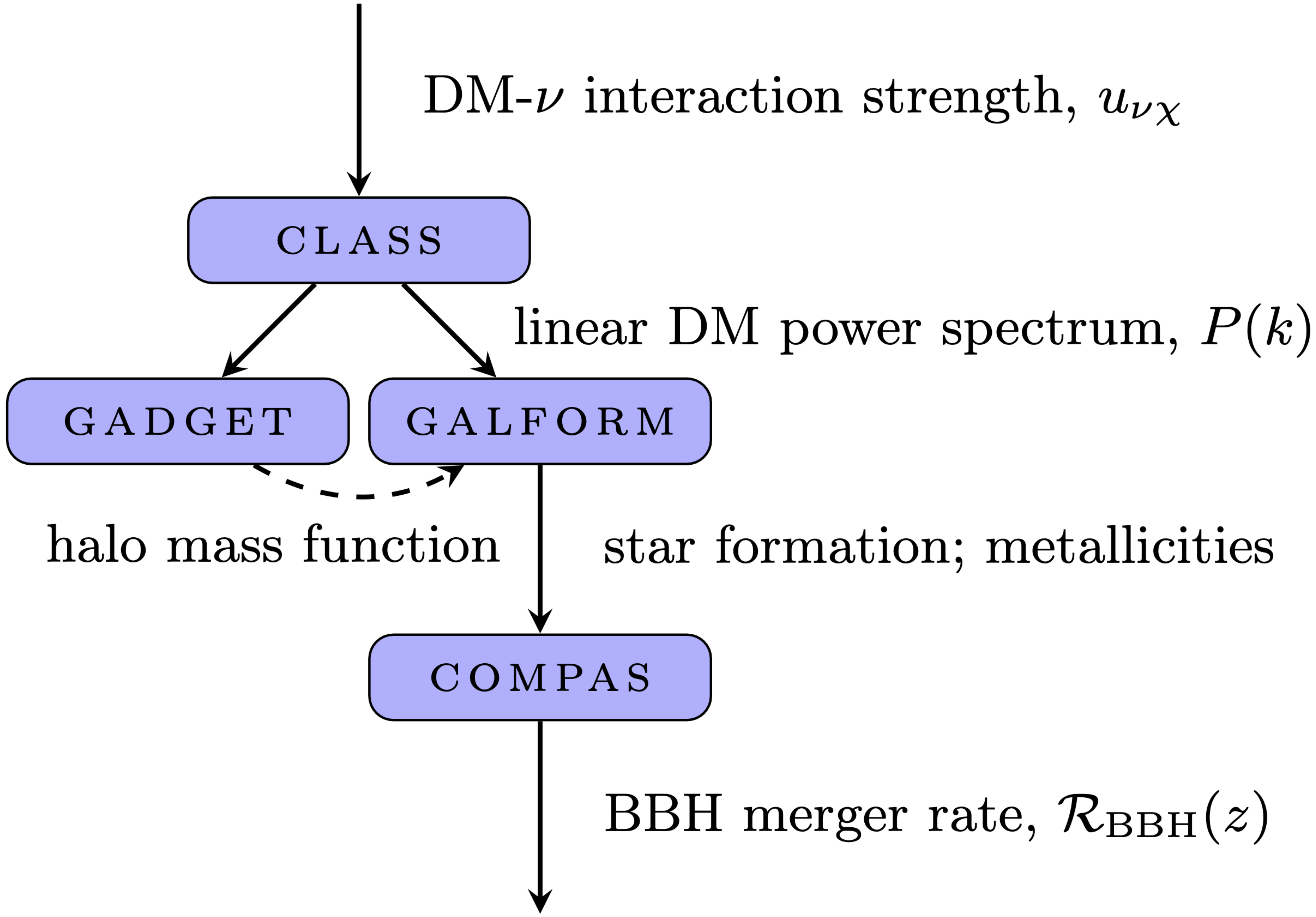


Our simulation pipeline

- Example DM model: elastic scattering with (massive) neutrinos
- Single new parameter:

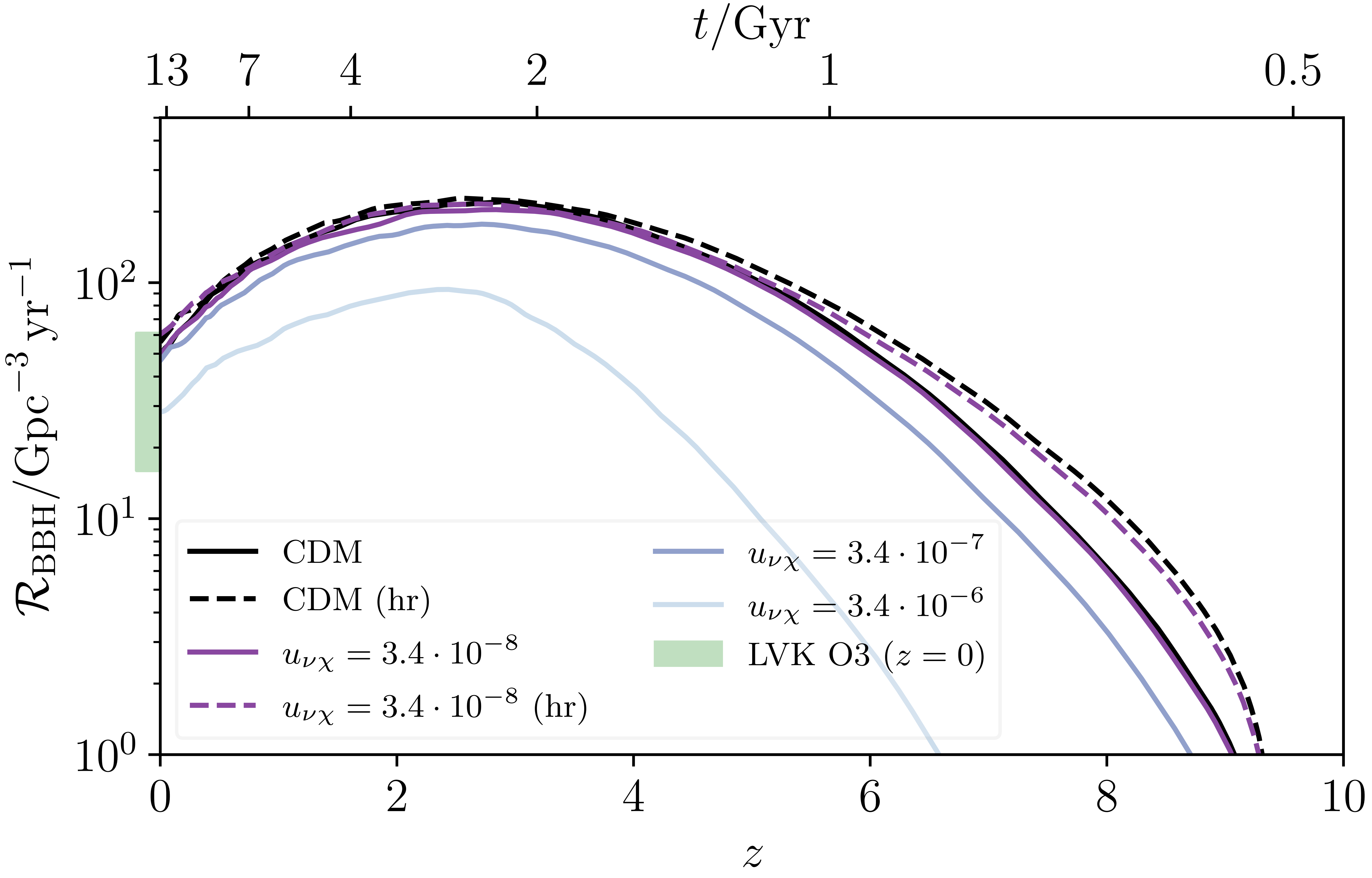
$$u_{\nu\chi} = \frac{\sigma_0}{\sigma_{\mathrm{Th}}} \left(\frac{m_\chi}{100\,\mathrm{GeV}} \right)^{-1}$$

- Current constraints: $u_{\nu\chi} \lesssim 10^{-4}$ (CMB), $u_{\nu\chi} \lesssim 10^{-5}$ (Ly-α forest)
- Imprinted only on initial conditions (late-Universe dynamics identical to CDM)



Results for BBH merger rate

- All models consistent with current LIGO/Virgo/KAGRA results at $z = 0$
- Suppression strongest at high z (as expected)
- Significant even for $u_{\nu\chi} \sim 10^{-7}$
- Corresponds to haloes $M \lesssim 10^{10} M_{\odot}$, scales $k \gtrsim 10\,\mathrm{Mpc}^{-1}$



Summary

- Suppression of cosmic structure on small scales is a promising avenue for unravelling the microphysics of dark matter

- Binary black holes provide a unique probe of this effect

- 1yr of observations with a next-gen GW detector network will beat existing constraints by *two orders of magnitude*

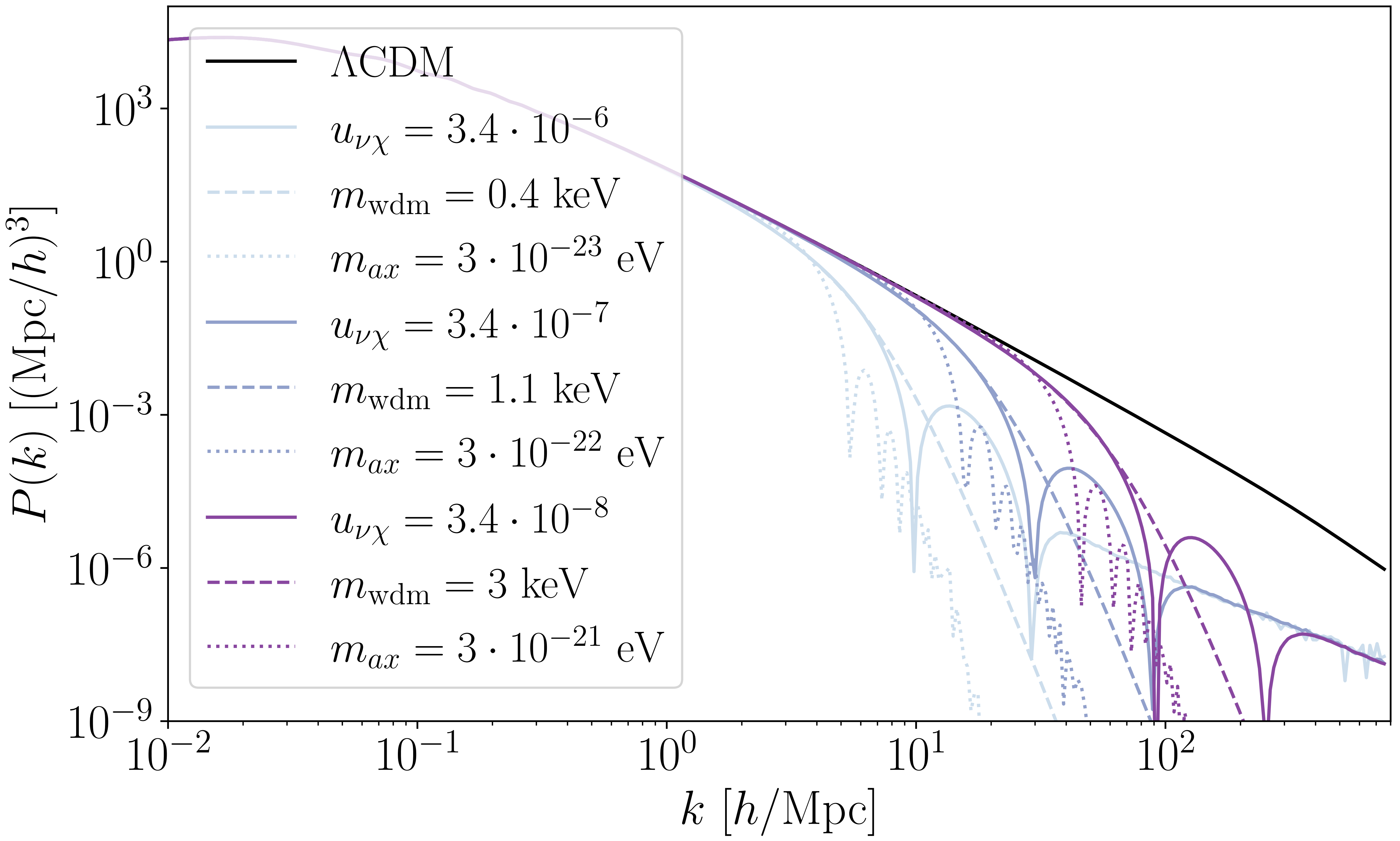
- This is true even with astrophysical uncertainties (see bonus slides)

Thanks for listening!

Backup Slides

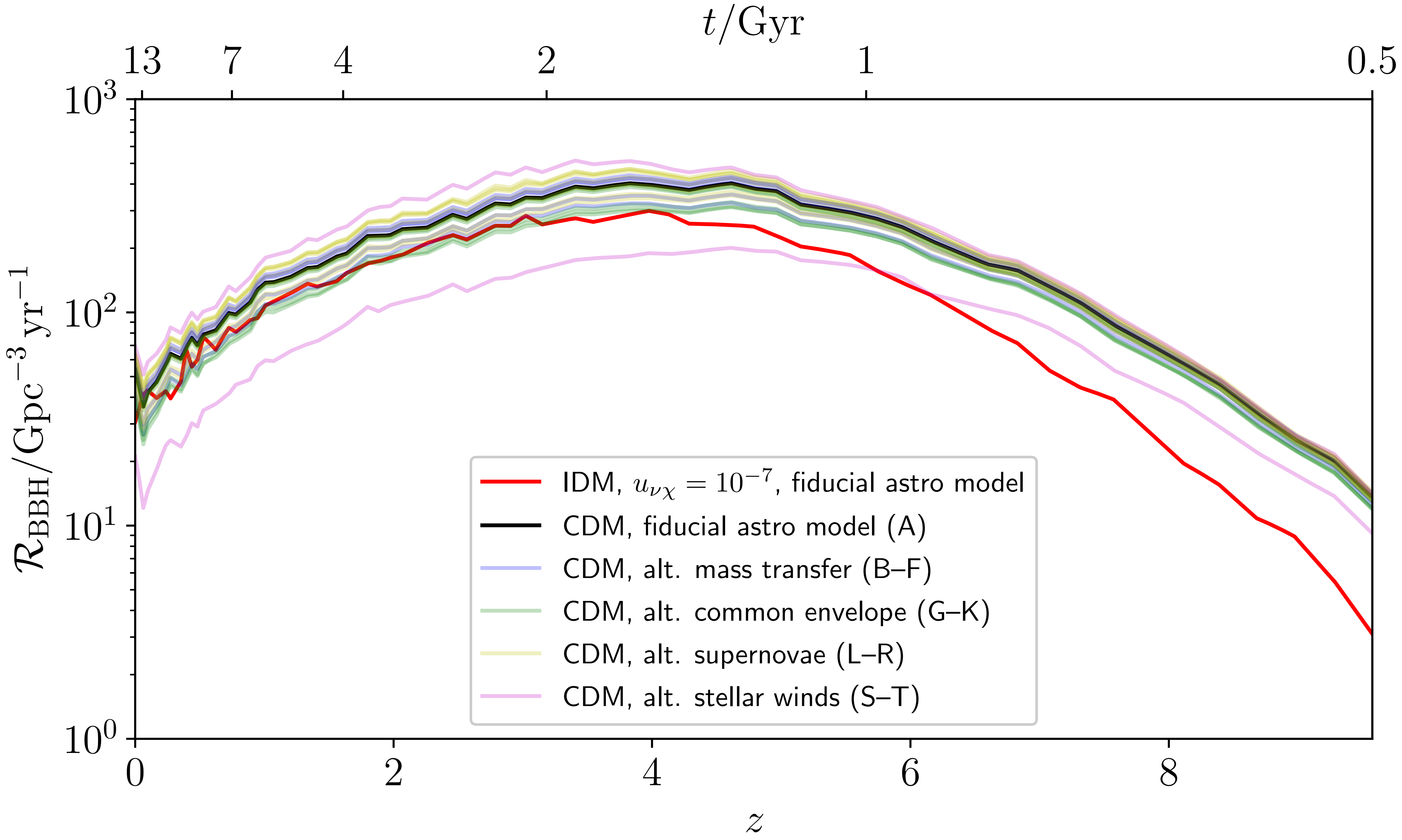
Linear power spectra

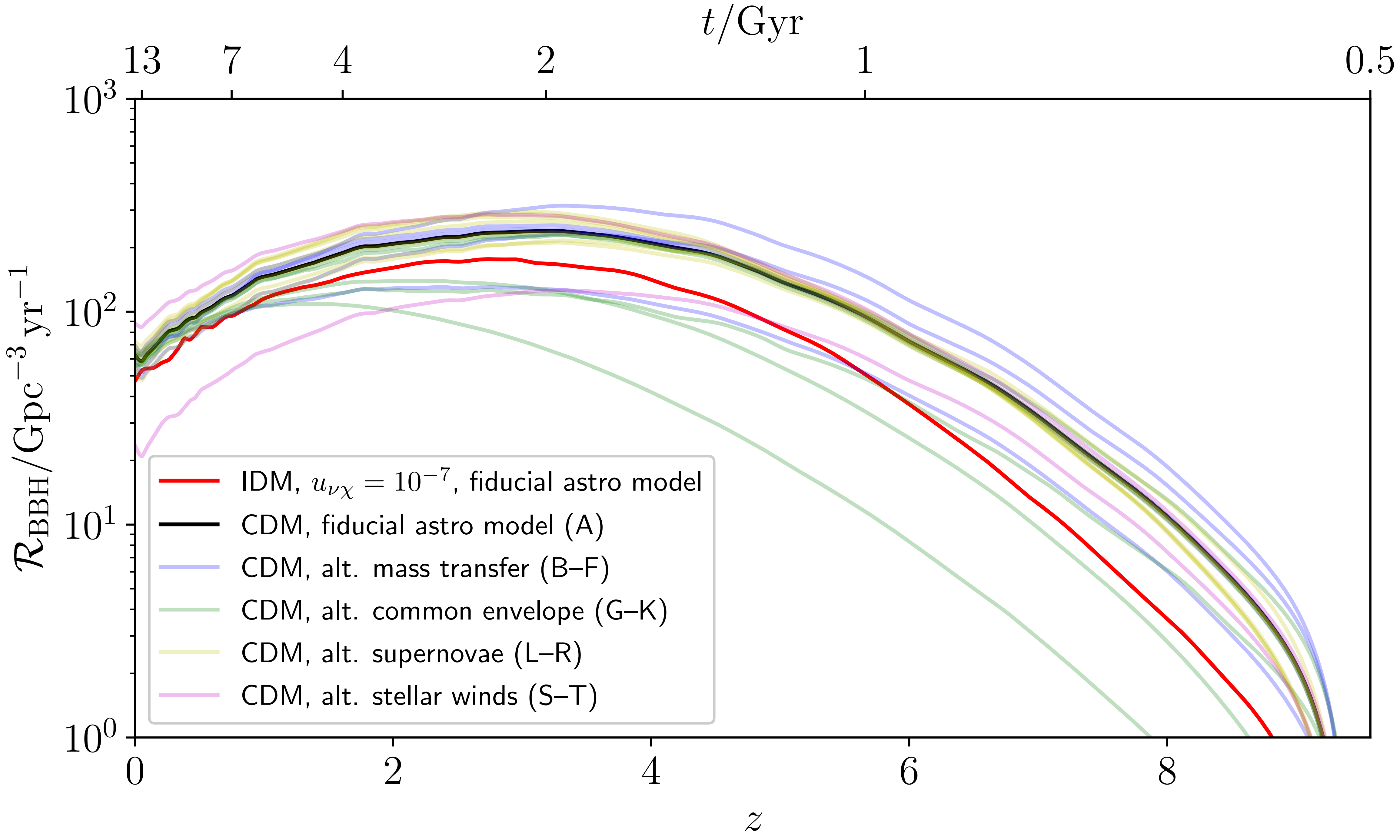
- IDM, WDM, FDM all give small-scale suppression
- Details differ, but are washed out by nonlinear evolution



Astrophysical uncertainties

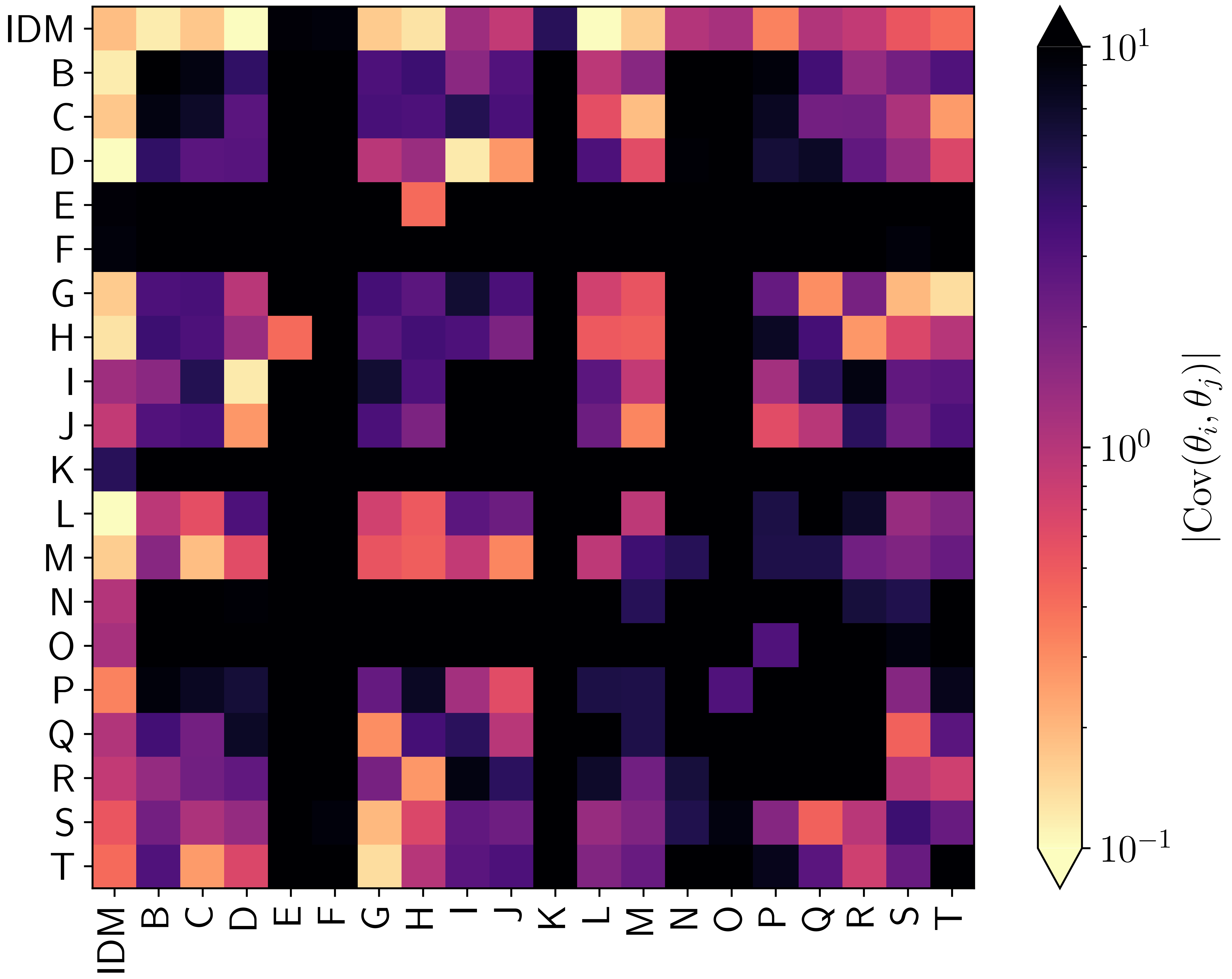
- We ran our pipeline with 20 different astrophysical model choices for COMPAS (data from Broekgaarden+, arXiv:2112.05763)
- BBH *formation* rate (top plot here) clearly distinguishable by eye in IDM scenario
- BBH *merger* rate slightly trickier…





Degeneracy with astro parameters

- Use a Fisher forecast to determine how well IDM suppression can be distinguished from alternative astro modelling
- IDM is *not degenerate* with modelling choices
- Can distinguish $u_{\nu\chi} \sim 10^{-7}$ even with model uncertainties



Constraints from galaxy luminosity function

- Even without GWs, we already beat current constraints *by an order of magnitude*
- Observed abundance of faint galaxies rules out $u_{\nu\chi} \gtrsim 10^{-6}$
- Robust against modelling choices for baryonic feedback