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GEMMA2 @ Sapienza, Roma

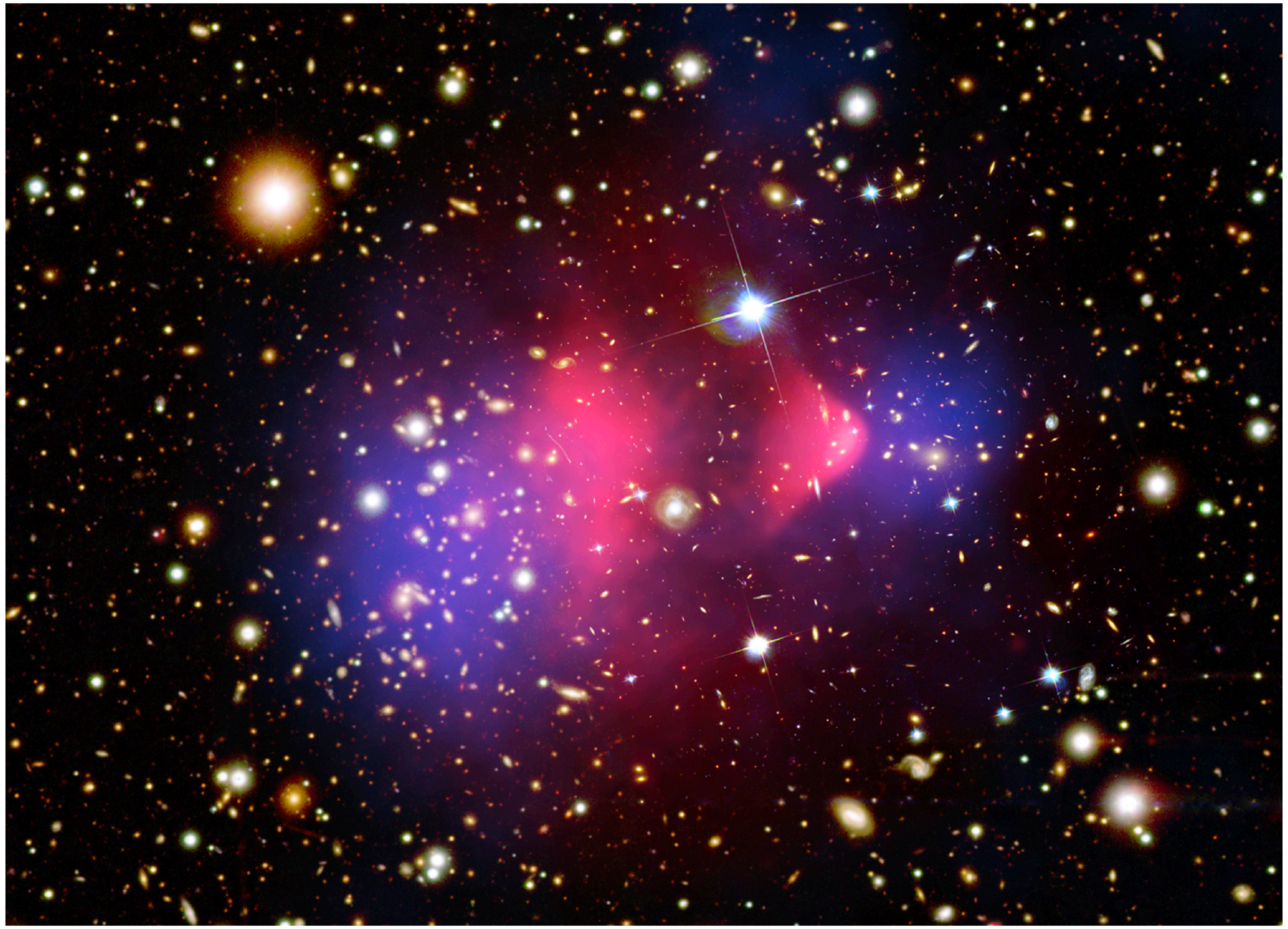
Gravitational-wave event rates as a new probe of dark matter microphysics

Based on arXiv:2207.14126 (published in PRD)

with Markus Mosbech, Sownak Bose, Celine Boehm, Mairi Sakellariadou, & Yvonne Wong

Dark matter

- We have strong evidence that *dark matter* makes up $\sim 85\,\%$ of all the matter in the Universe ...
- ...but, embarrassingly, we still don't know what it's made of
- Is there a dark matter *particle*? If so, what are its *properties*?



ESA

Dark matter substructure

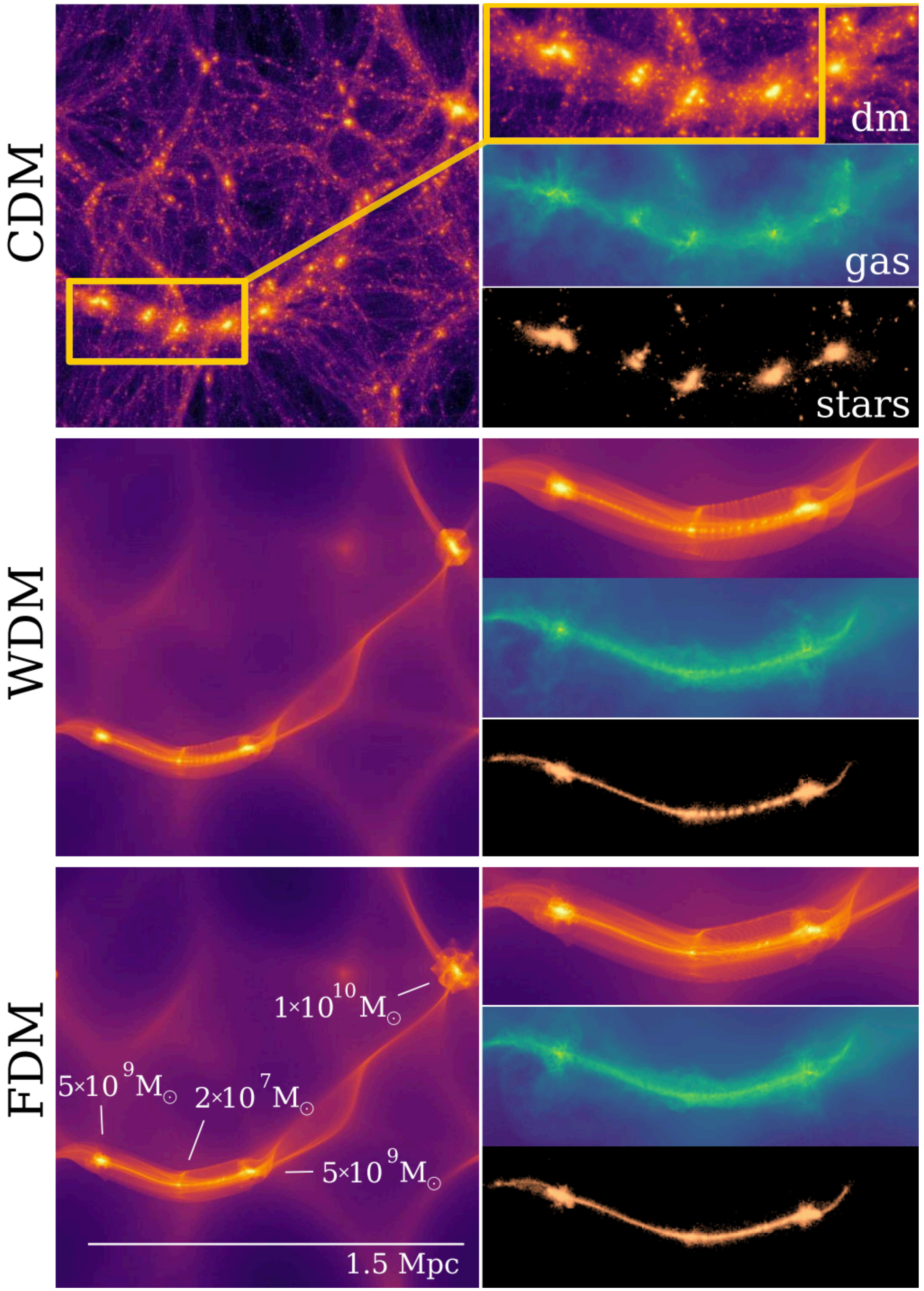
- The standard cosmological model says DM is *cold* (i.e., collisionless, noninteracting, nonrelativistic)

- If so, gravitational collapse forms structures even on very small scales (Jeans wavelength is zero)

- Many alternatives, e.g.
  - Scatters off other particles (*Interacting* DM)
  - Mildly relativistic velocities (*Warm* DM)
  - Wavelike "quantum pressure" (*Fuzzy* DM)

- These all prevent collapse on small scales and *suppress substructure*, so fewer light haloes/galaxies

Mocz+, arXiv:1910.01653



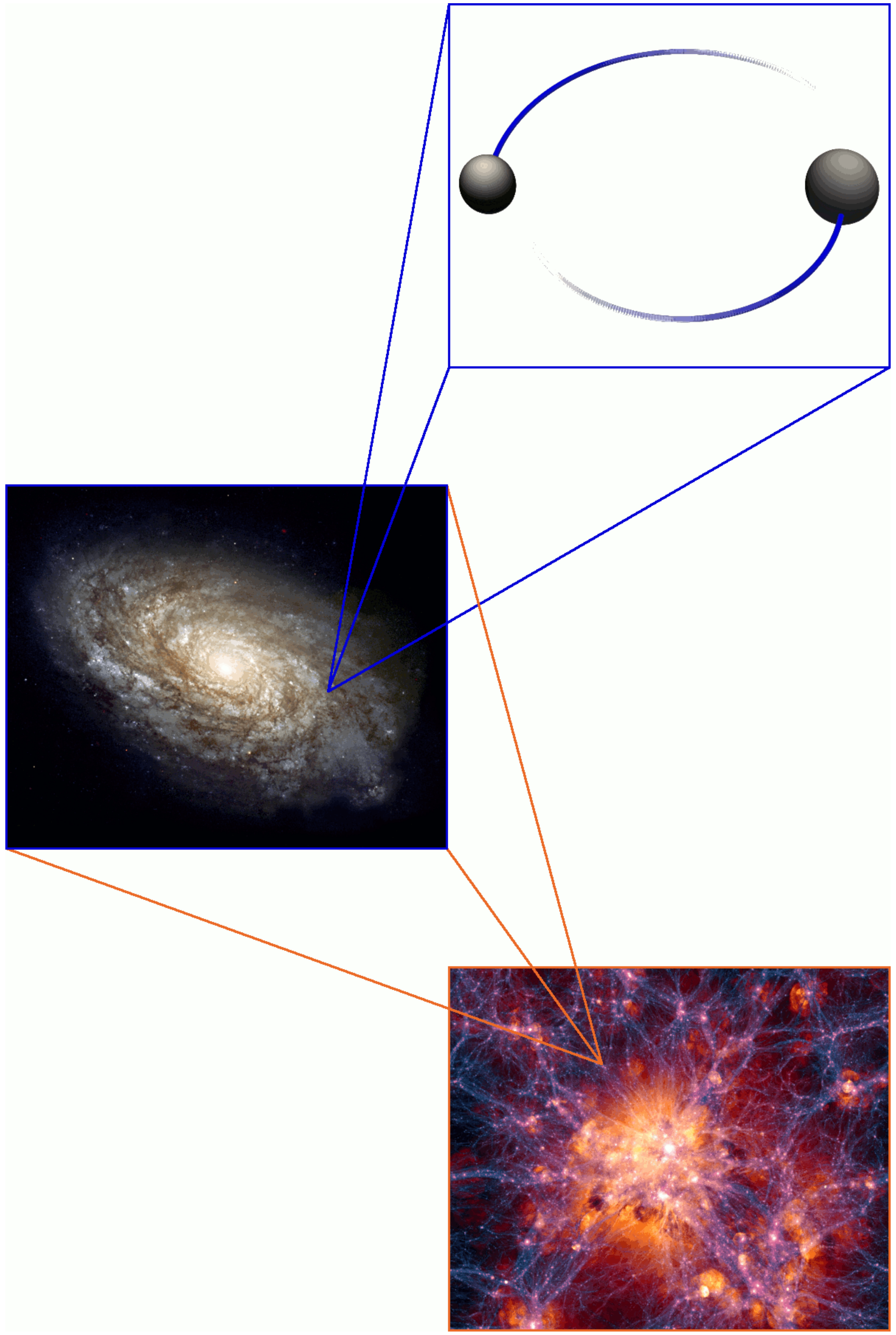
Gravitational-wave signals are an excellent probe of this effect

- Suppression strongest on small scales and at high redshift (structure formation is "bottom-up")

- These correspond to very faint galaxies that are challenging to access with traditional observations (even with facilities like JWST)

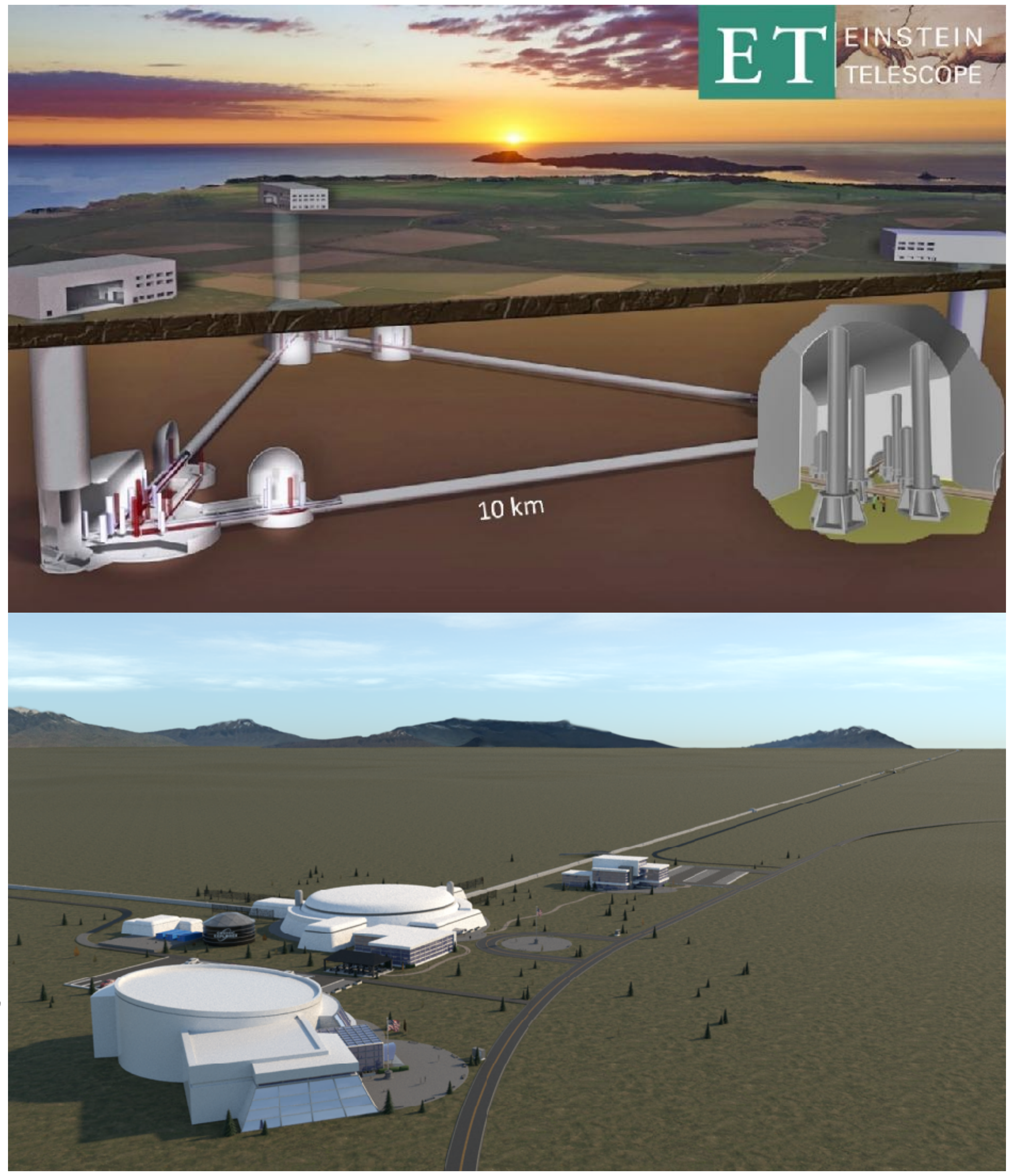
- **Key idea:** use *binary black holes* as tracers of these "missing" haloes

- Break CDM → fewer light, early haloes
  → fewer high-redshift BBHs



Next-gen GW interferometers

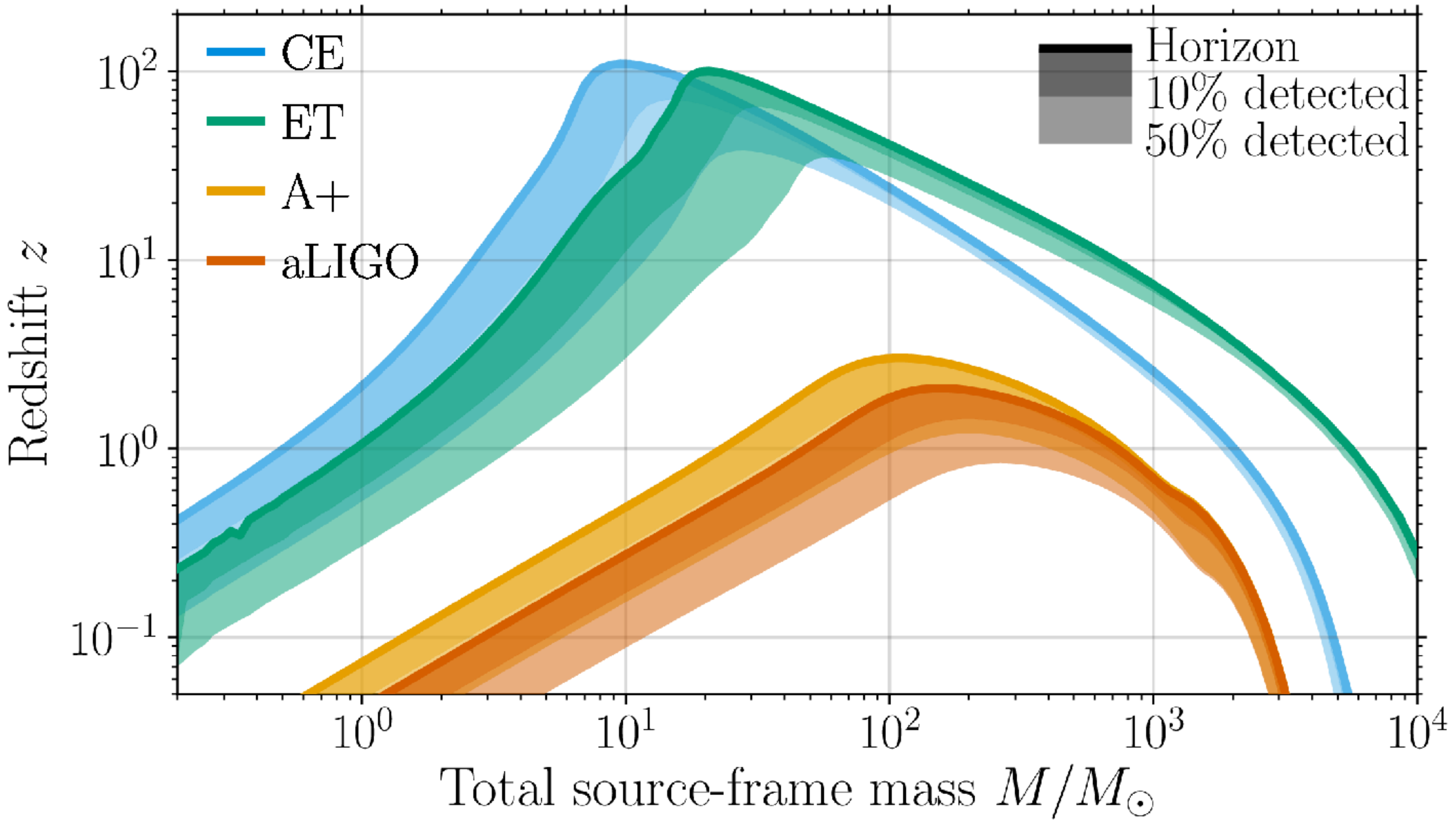
- Einstein Telescope (EU) and Cosmic Explorer (US) will detect essentially *all* BBHs in the observable Universe (*thousands per year* at $z > 7$)



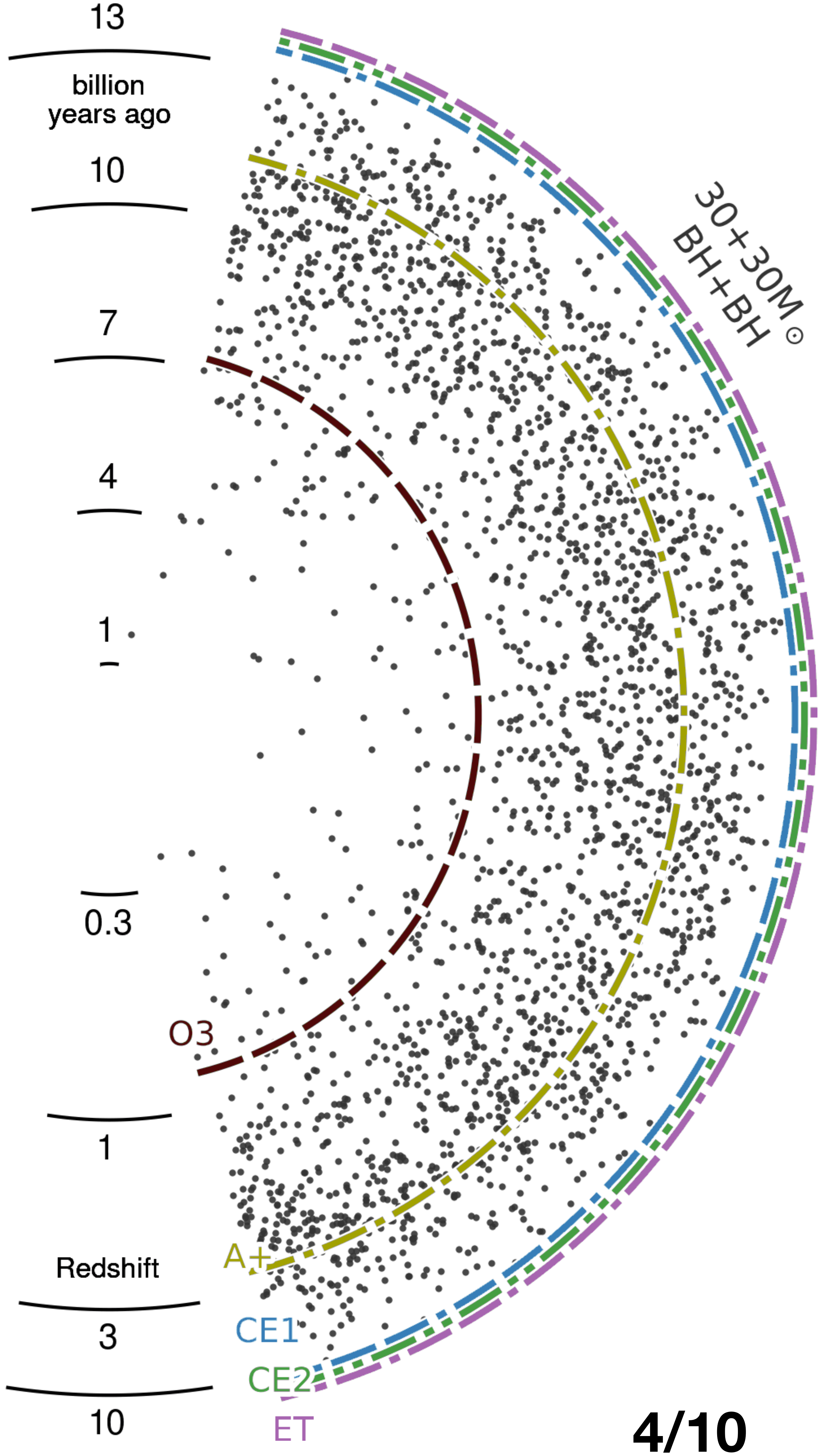
EGO

E. Anaya

Hall & Evans, arXiv:1902.09485



Hall & Vitale

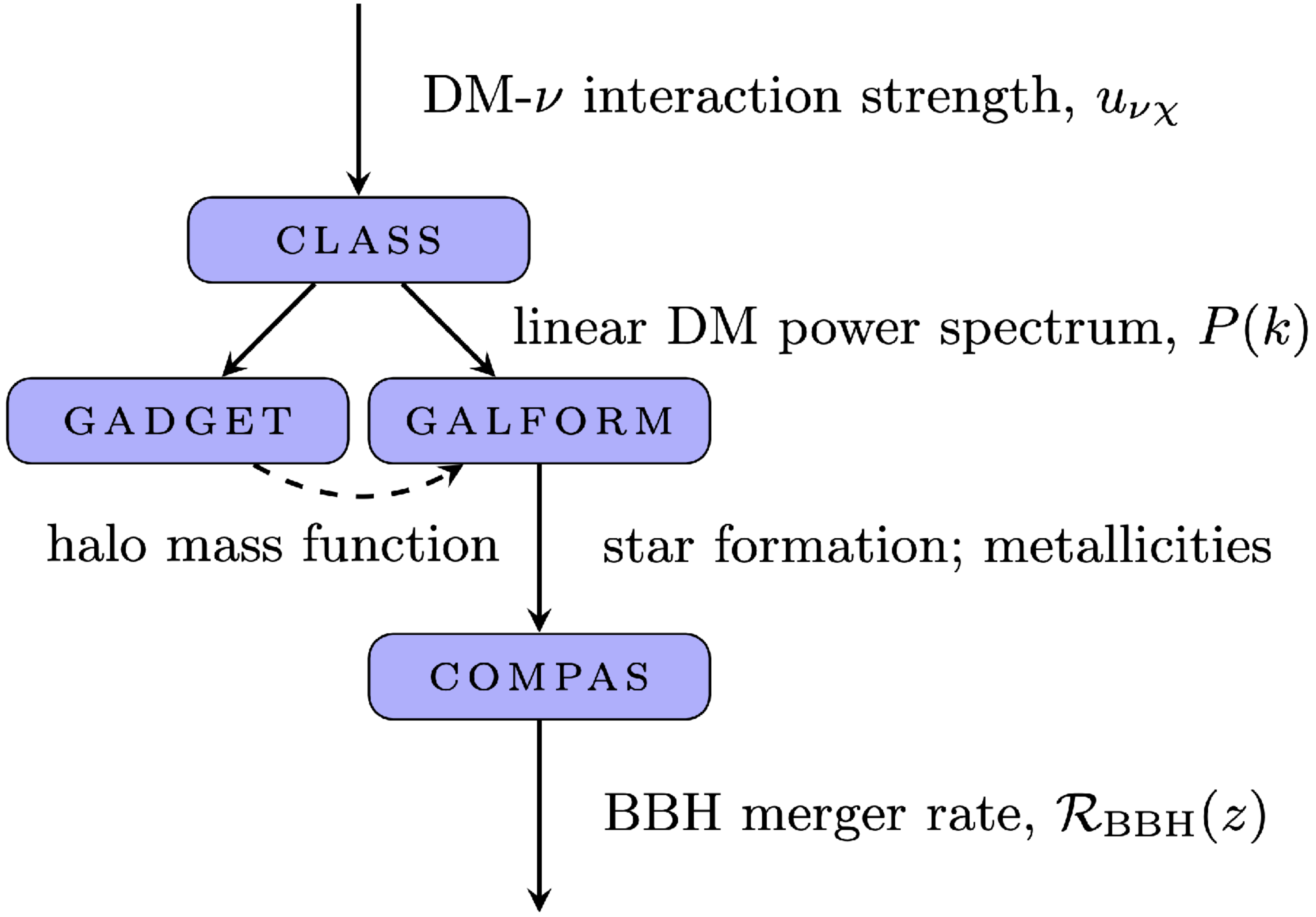


Our simulation pipeline

- Example dark matter model:
  elastic scattering with neutrinos
- Single new parameter ($= 0$ in CDM):

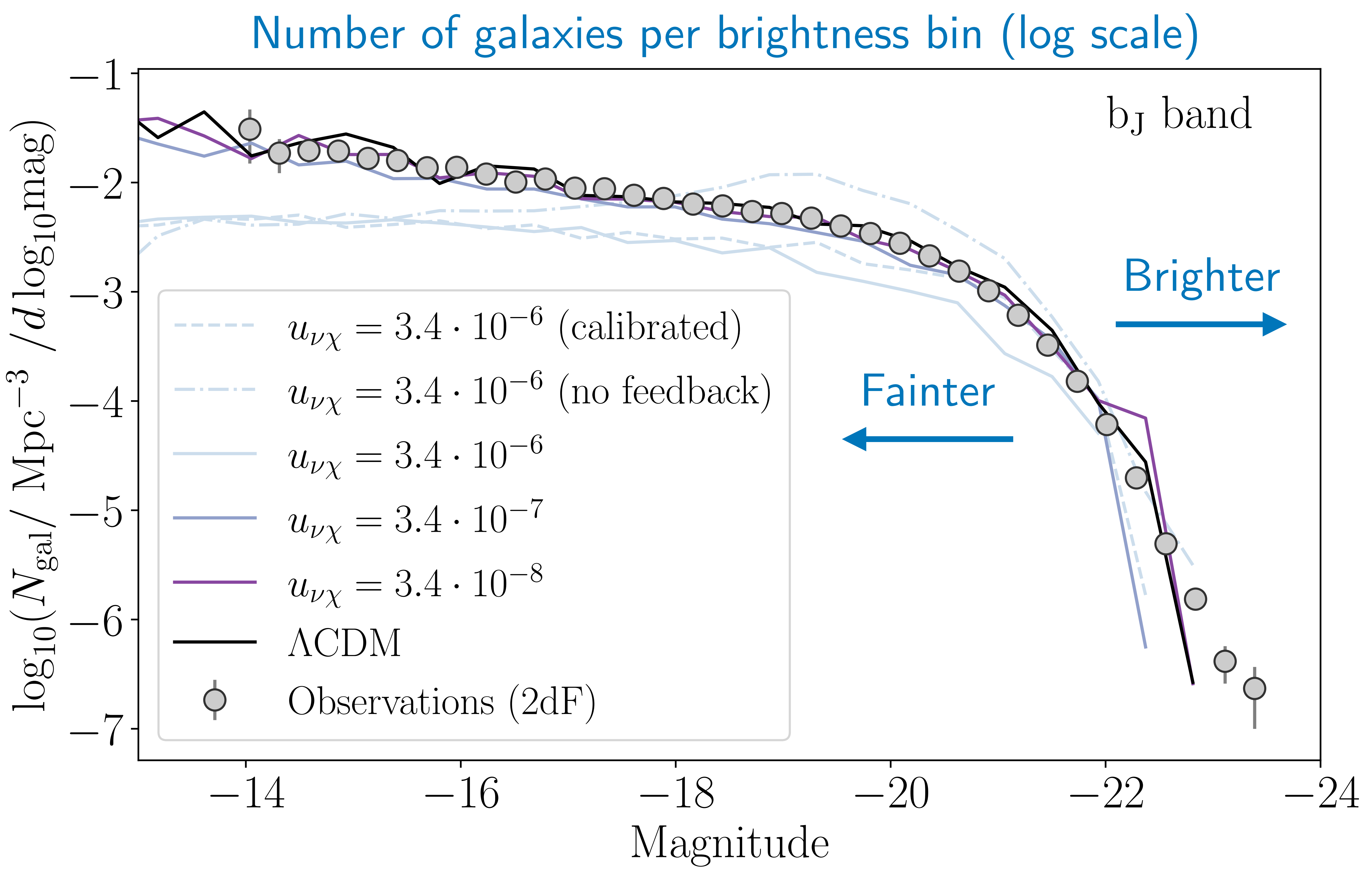
$$u_{\nu\chi} = \frac{\text{DM-}\nu\text{ cross-section}}{\text{Thompson cross-section}} \left(\frac{\text{DM mass}}{100\,\text{GeV/c}^2} \right)^{-1}$$

- 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)



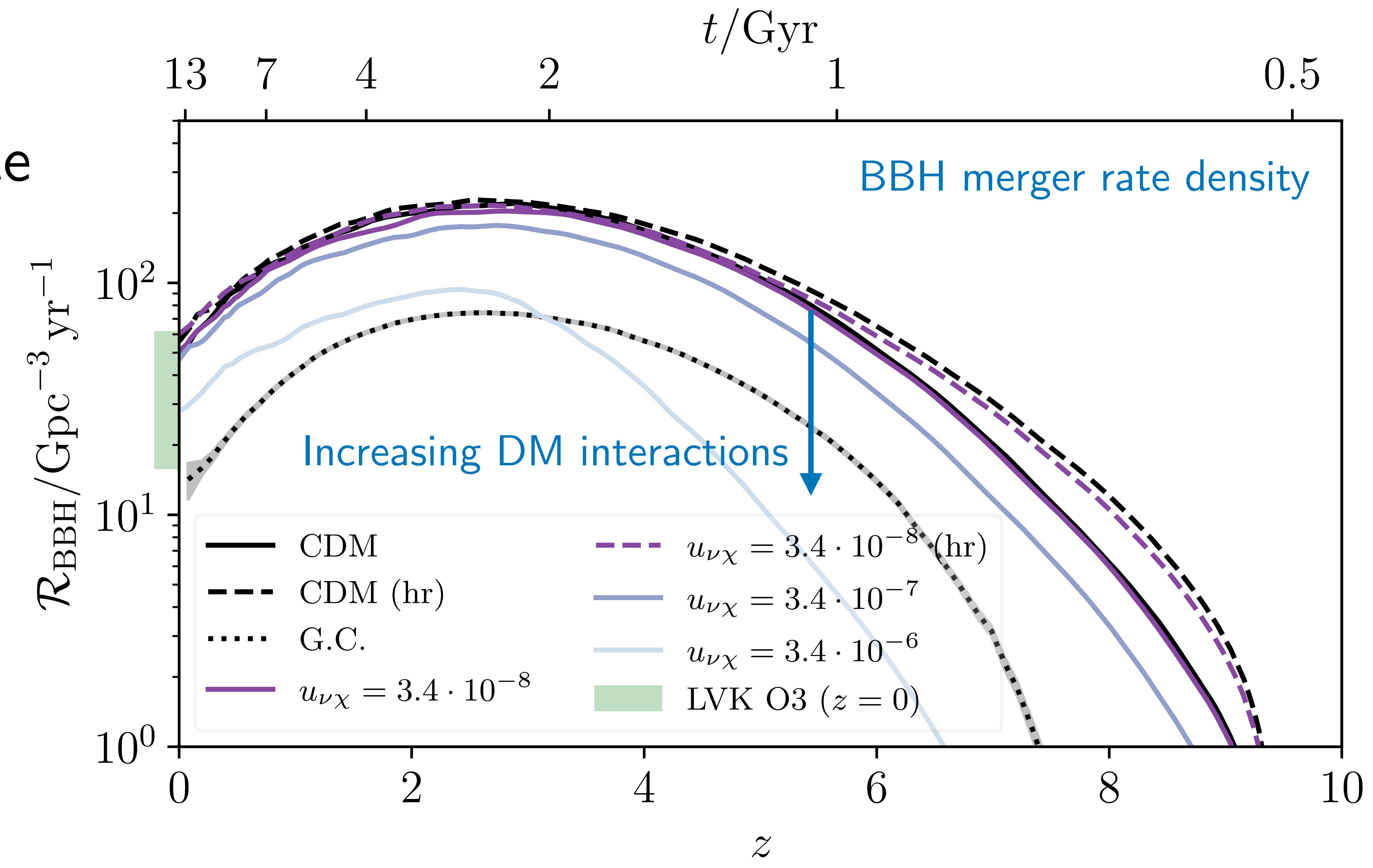
Constraints from galaxy luminosity function

- 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
- These are *low redshift* data — GWs should do even better



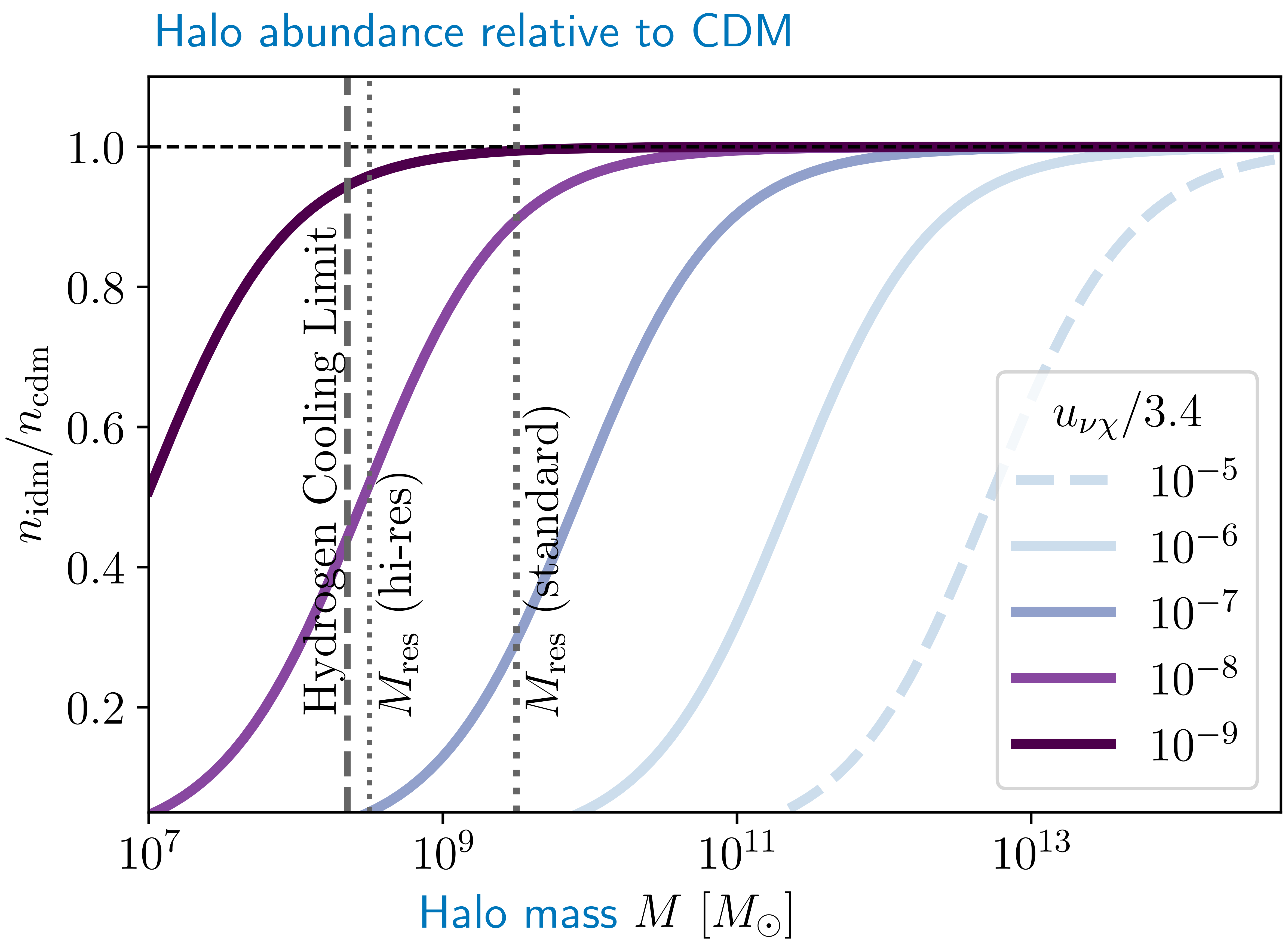
Results for BBH merger rate

- All models consistent with LVK O3 results for the present-day merger rate
- Suppression strongest at high redshift (as expected)
- Significant even for $u_{\nu\chi} \sim 10^{-7}$ (excluded at 95% confidence with just 1yr of data)
- Corresponds to halo masses $M \lesssim 10^{10} M_\odot$



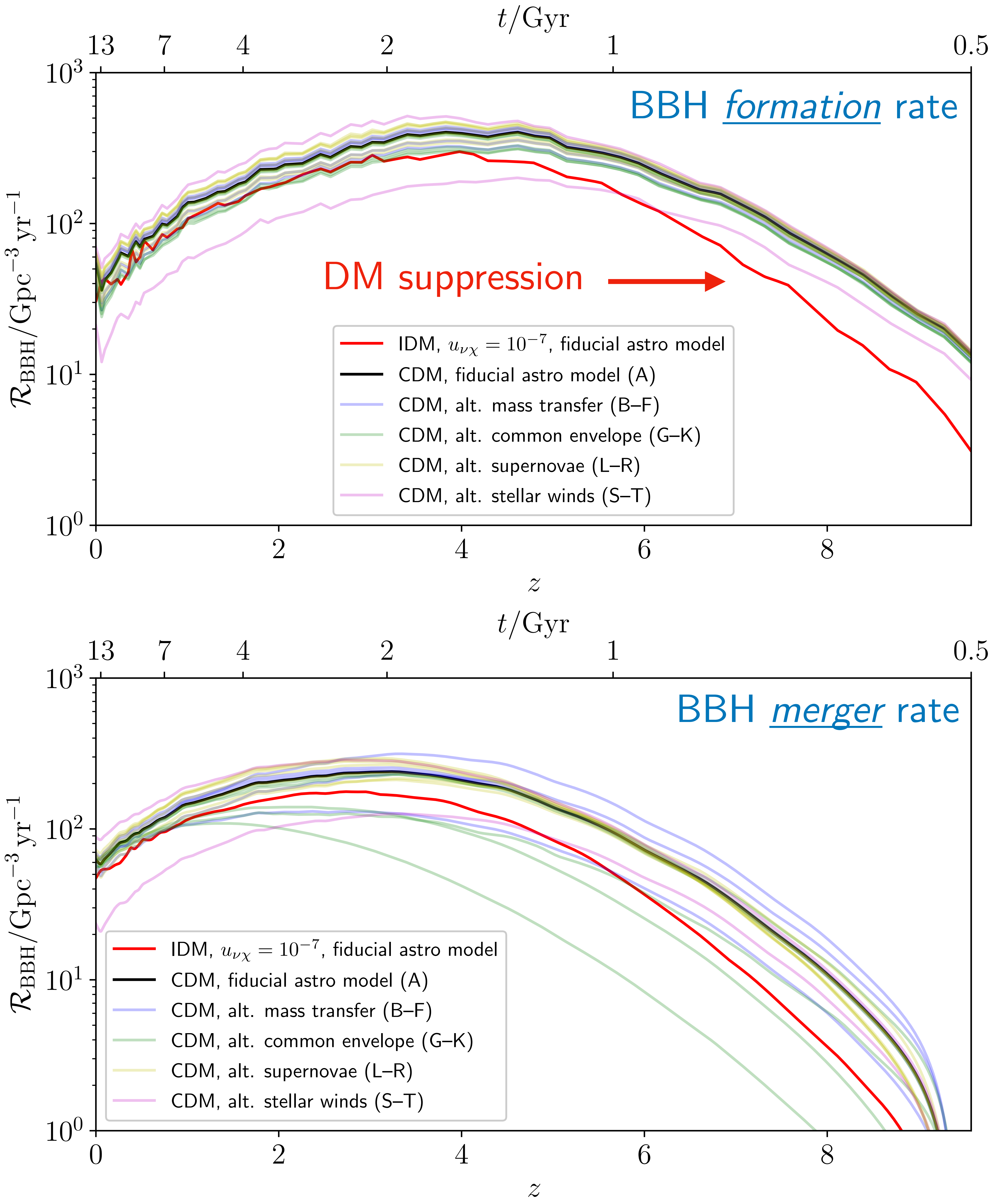
Halo mass resolution

- Smaller DM-neutrino cross-section pushes the suppression of structure to smaller scales / lighter haloes
- Our "high resolution" runs capture essentially all haloes massive enough to host star formation (and therefore binary black holes)
- This shows that one cannot do better than $u_{\nu\chi} \sim 10^{-8}$ with any method that relies on star formation



Astrophysical uncertainties

- We ran our pipeline with 20 different astrophysical model choices for COMPAS, labelled "A"—"T" (data from Broekgaarden+, arXiv:2112.05763)
- DM suppression of BBH *formation* rate (top plot here) clearly distinguishable from astrophysical effects, even by eye
- BBH *merger* rate slightly trickier, due to convolution with delay times

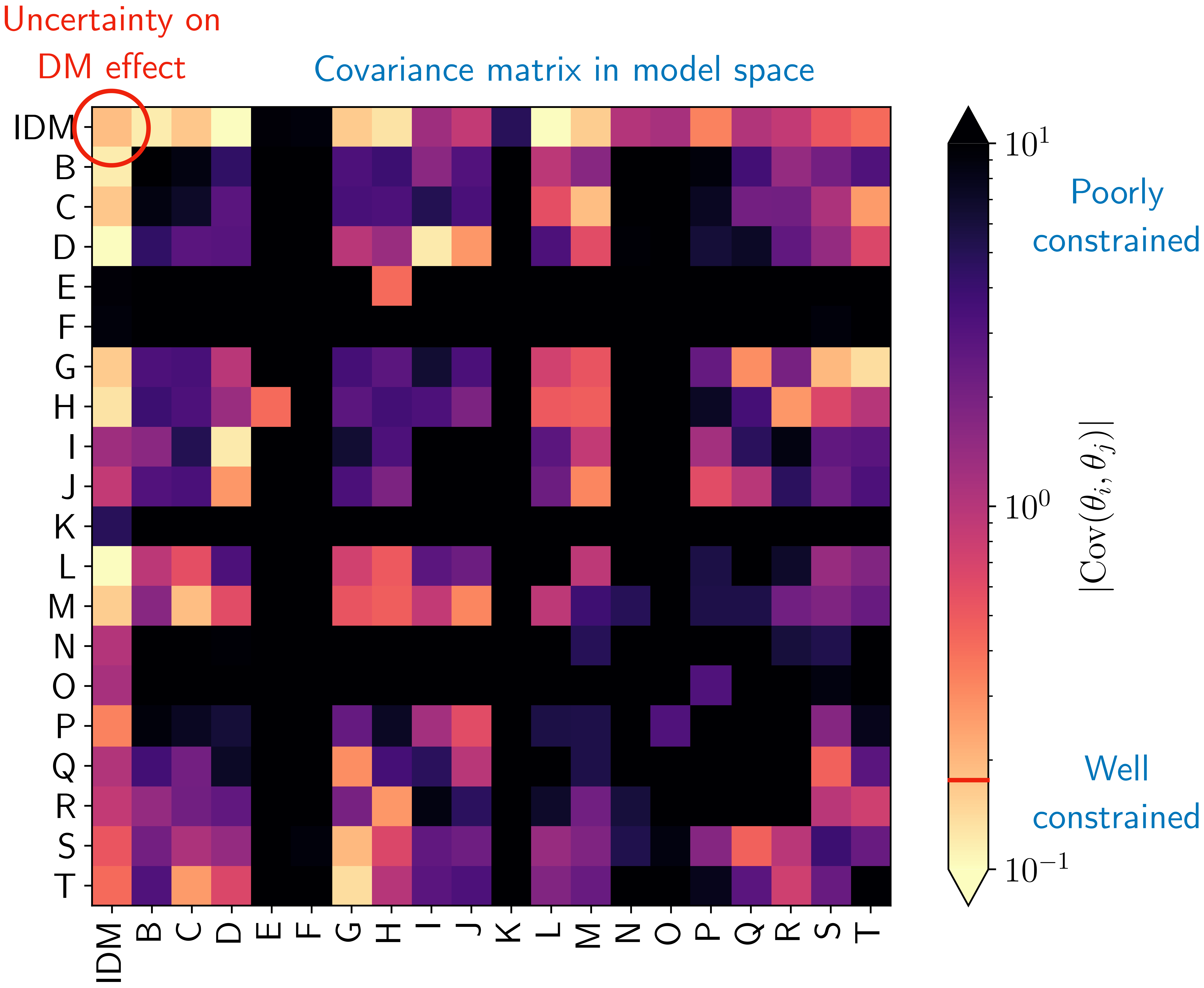


Non-degeneracy with astrophysics

- We use a Fisher forecast to determine how well DM suppression can be untangled from astrophysical effects

- DM effect is *not degenerate* with these modelling choices

- Can exclude $u_{\nu\chi} \sim 10^{-7}$ even with astrophysical uncertainties



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

Thanks for listening!