Using SKAO to understand the clustering of gravitational wave sources

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Based on: M.B., S. Libanore, N. Bellomo, C. Scarpel, F. Semenzato, A. Raccanelli and M. Liguori, 2025
(chapter submitted to *Advancing Astrophysics with the SKA – II*)

SKA - Mid

Deep redshift sensitivity

$z \in [0,3]$

Wide sky coverage

$f_{\rm sky} \sim 0.5$

SKA - Mid surveys

Wide Band 1 Survey (Bacon+2020):

- sky coverage of 20,000 deg^2
- integration time of 10,000 hrs

Radio continuum galaxies

Star forming galaxies and AGNs

`T-RECS` (Bonaldi+2018, 2023)

Large angular resolution

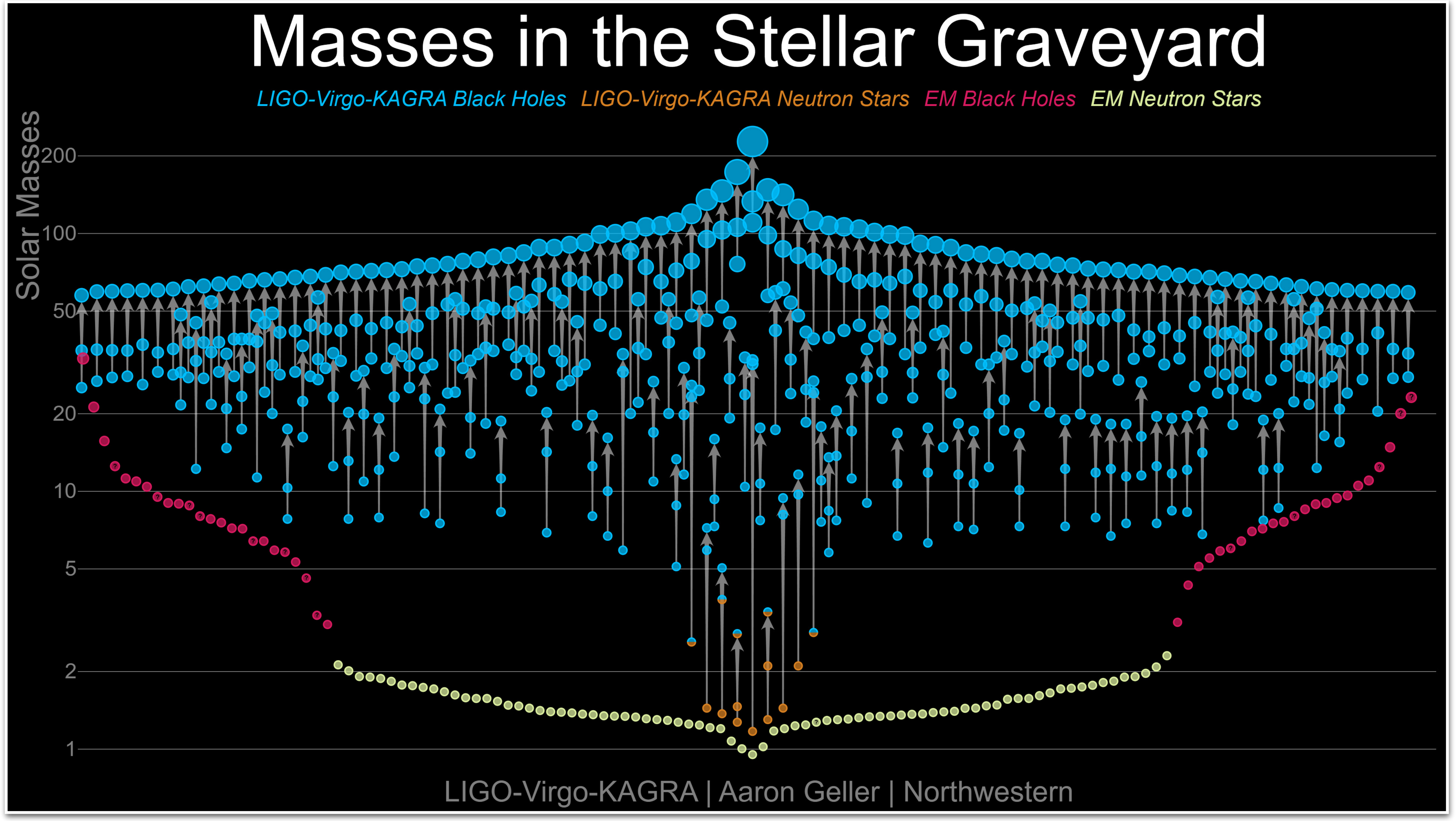
HI Intensity Mapping
(Scelfo+2022)

Integrated emission of the 21-cm HI line

Semi-analytical model
(Crighton+2015, Spinelli+2020)

Great redshift resolution

Gravitational waves



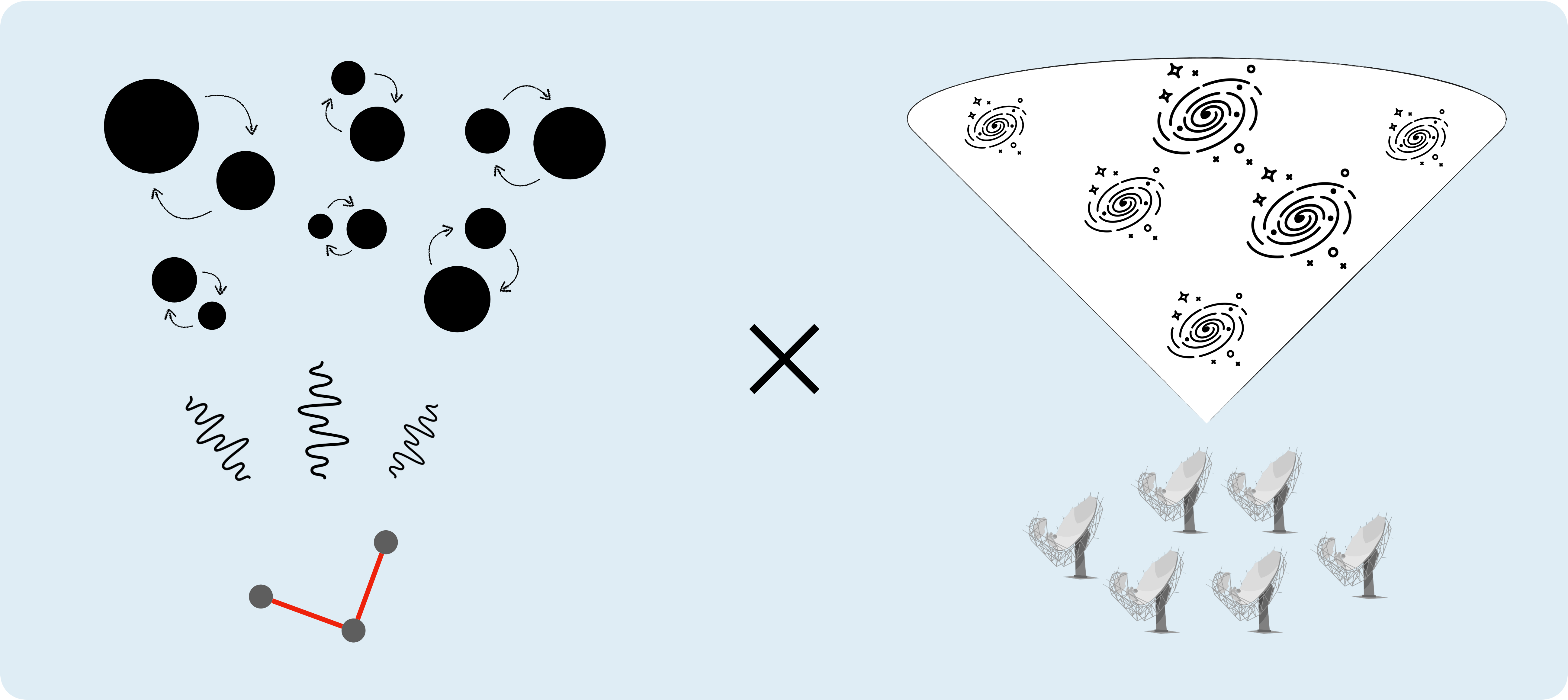
LIGO-Virgo-KAGRA Collaboration:

$$\sim \mathcal{O}(10^2) \quad \text{GW events}$$

Third-Generation GW detectors:

$$\sim \mathcal{O}(10^5) \quad \text{GW events}$$

SKA - Mid × GW



Gravitational waves opened a new observational window on the Universe but:

few GW sources compared to galaxy surveys

poor angular and redshift resolution

Analysis

$$C_\ell^{XY}(z_i, z_j) \propto b_X(z_i)\frac{dN_X}{dz}b_Y(z_j)\frac{dN_Y}{dz}$$

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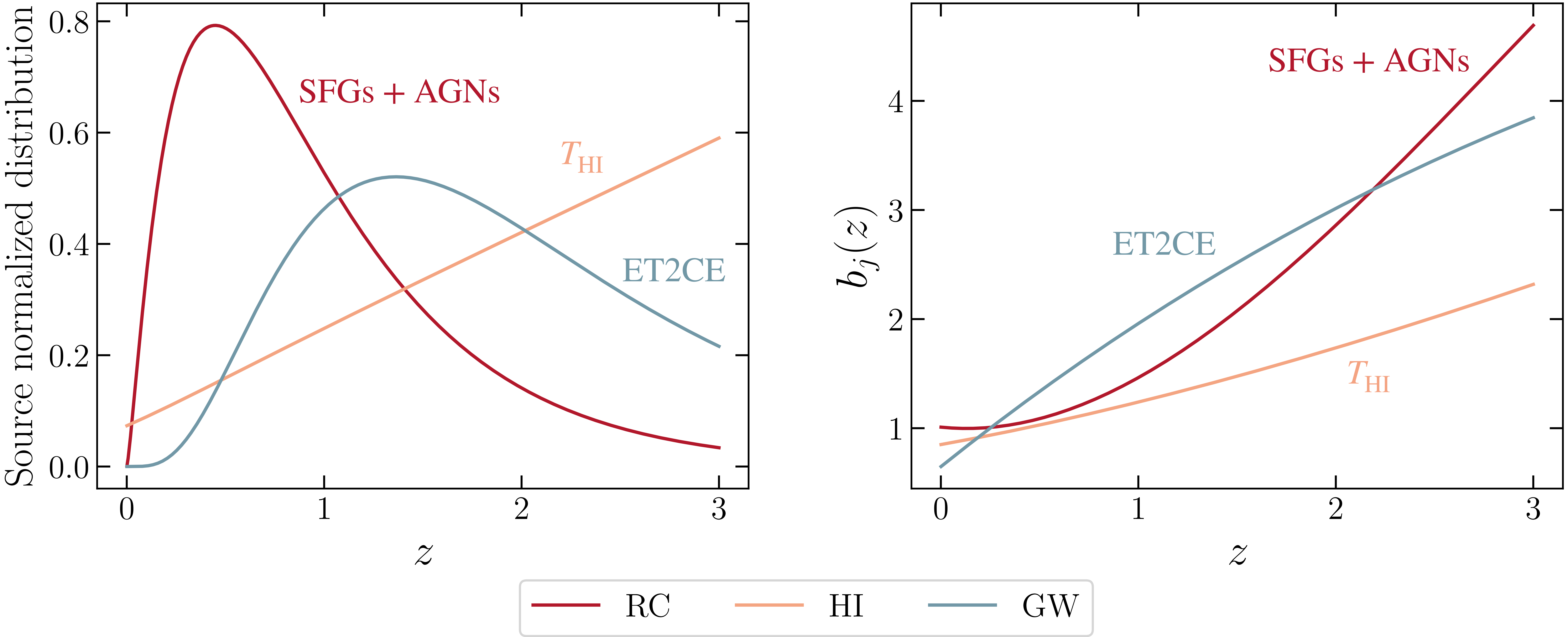
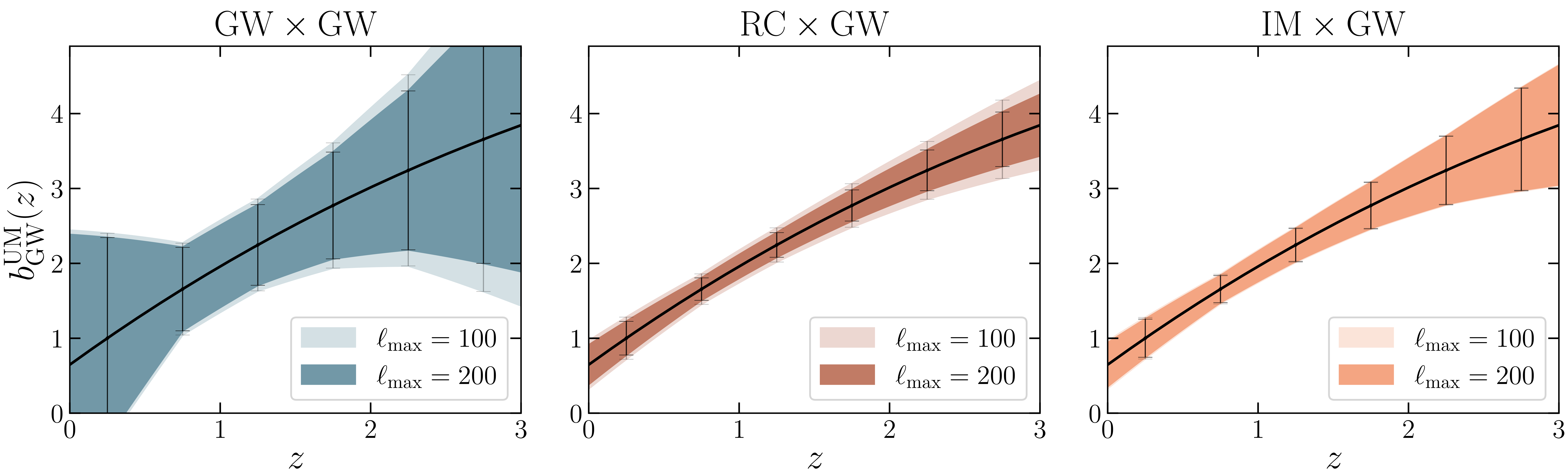
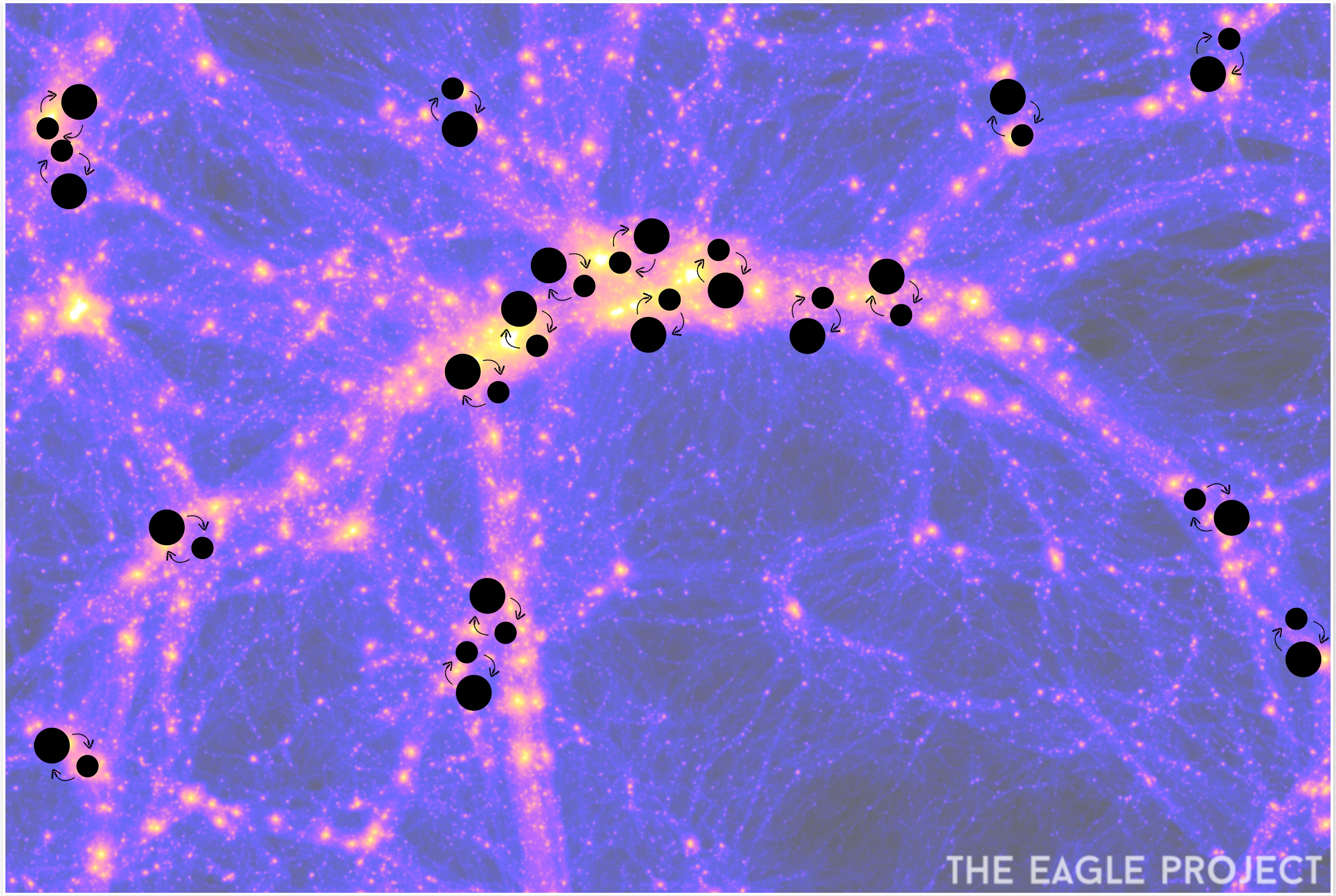


Results: GW bias



- The constraining power of SKA-Mid × ET2CE largely overcomes forecasts for ET2CE alone
- Our results for Radio Continuum galaxies and HI Intensity Mapping are comparable

Results: exotic GW sources

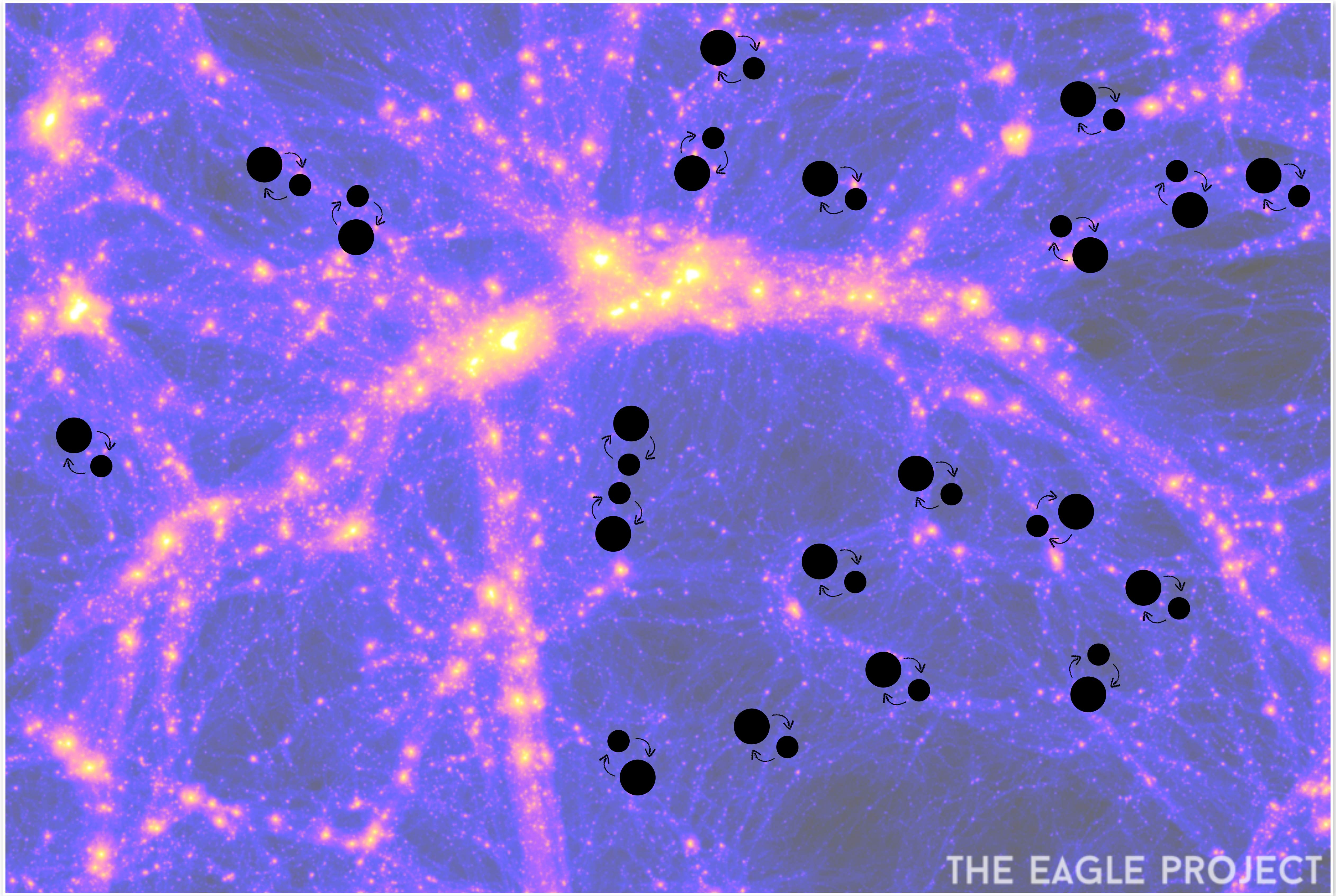


Stellar black hole binaries:

$$b_{\rm GW} > 1$$

(massive halos)

Results: exotic GW sources

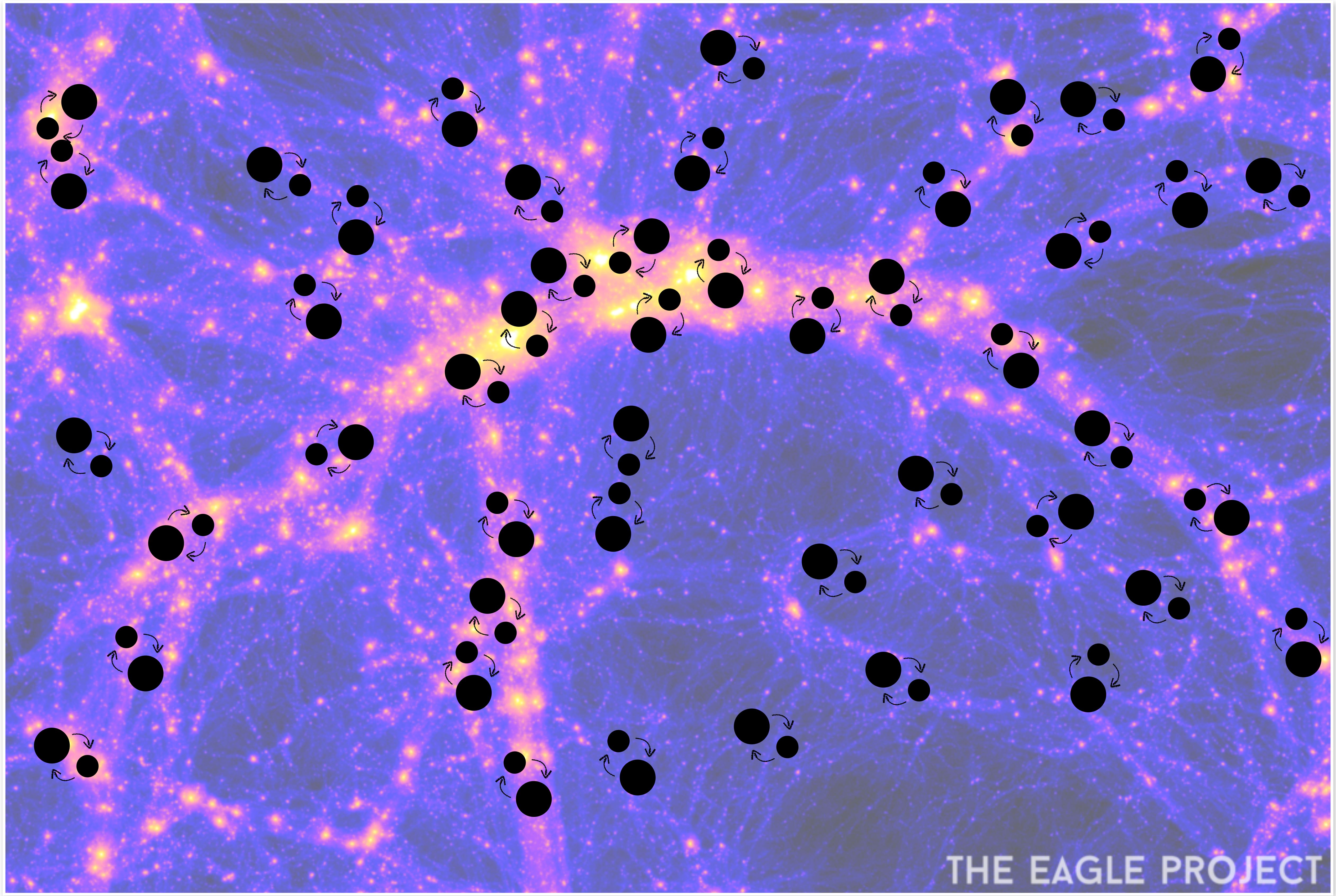


Late primordial black hole binaries:

$$b_{\mathrm{GW}} \sim 0.5$$

(low-mass halos)

Results: exotic GW sources



Early primordial black hole binaries:

$$b_{\mathrm{GW}} \sim 1$$

(stochastic sample of the dark matter field)

Results: exotic GW sources

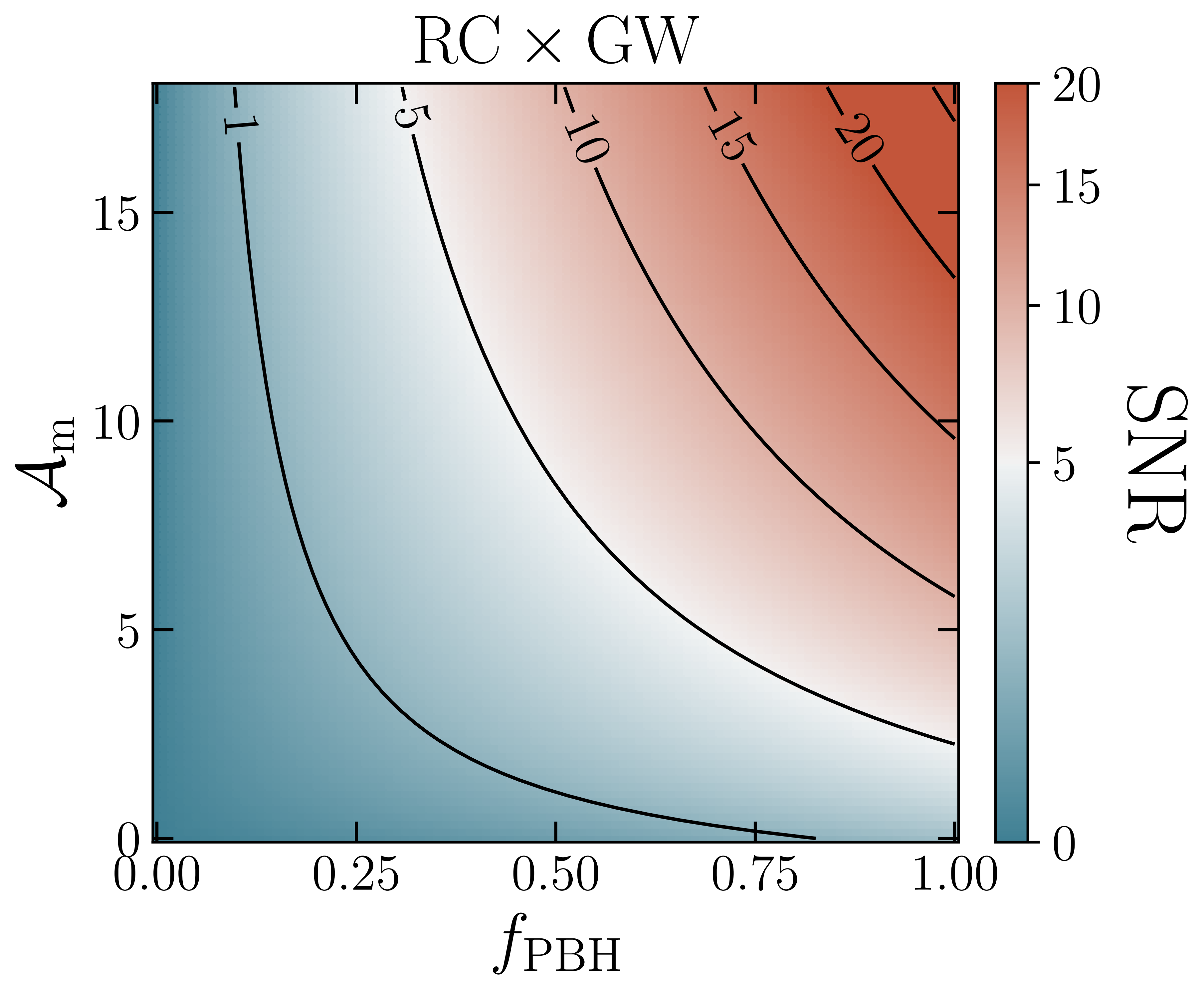
$$\mathrm{SNR}^2 = \sum_j \frac{\left(b^{\mathrm{alt}}_{\mathrm{GW}}(f_{\mathrm{PBH}}, \mathscr{A}_m, z_j) - b^{\mathrm{fid}}_{\mathrm{GW}}(z_j)\right)^2}{\sigma^2_{b^{\mathrm{fid}}_{\mathrm{GW}}}(z_j)}$$

stellar+primordial stellar

Results: exotic GW sources

$$\mathrm{SNR}^2 = \sum_j \frac{\left(b^{\mathrm{alt}}_{\mathrm{GW}}(f_{\mathrm{PBH}}, \mathscr{A}_m, z_j) - b^{\mathrm{fid}}_{\mathrm{GW}}(z_j)\right)^2}{\sigma^2_{b^{\mathrm{fid}}_{\mathrm{GW}}}(z_j)}$$

stellar+primordial   stellar



- For $\mathscr{A}_m \sim \mathcal{O}(10)\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, $f_{\mathrm{PBH}} \in [0.5,1.0]$ could be constrained by SKA-Mid×ET2CE at $> 5\sigma$ level
- Results compatible with current constraints on f_{PBH} for $M_{\mathrm{PBH}} \in [1M_\odot,100M_\odot]$

Results: time delay distribution

PRELIMINARY

$$R(z) \propto \int dt_d \; p(t_d) \; R_f\left(t(z) - t_d\right)$$

Results: time delay distribution

PRELIMINARY

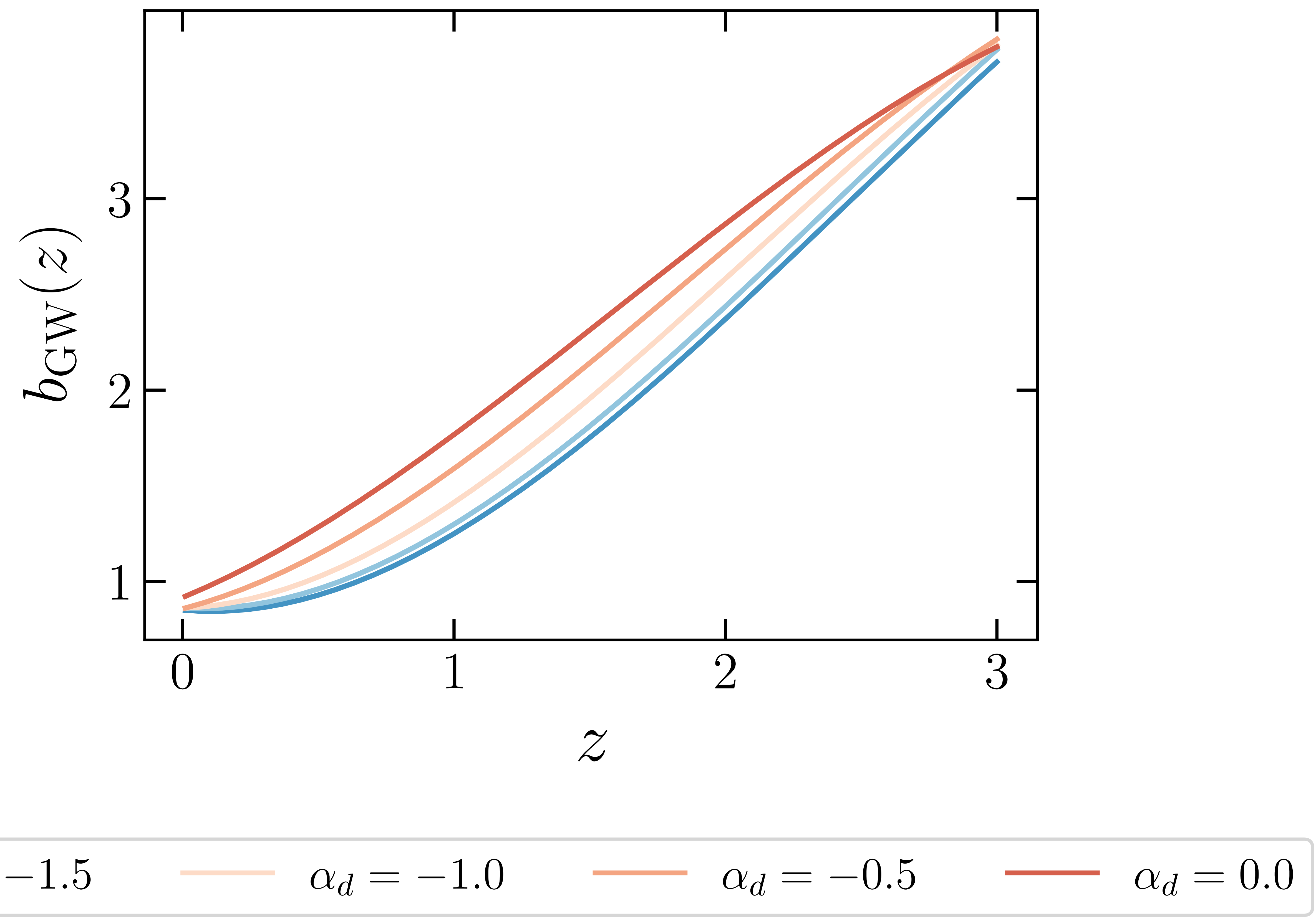
$$R(z) \propto \int dt_d \, \boxed{p(t_d)} \, R_f\left(t(z) - t_d\right)$$

Can **GW clustering**, cross-correlated with **SKAO surveys**, provide information on the **time delay distribution**?

Results: time delay distribution

PRELIMINARY

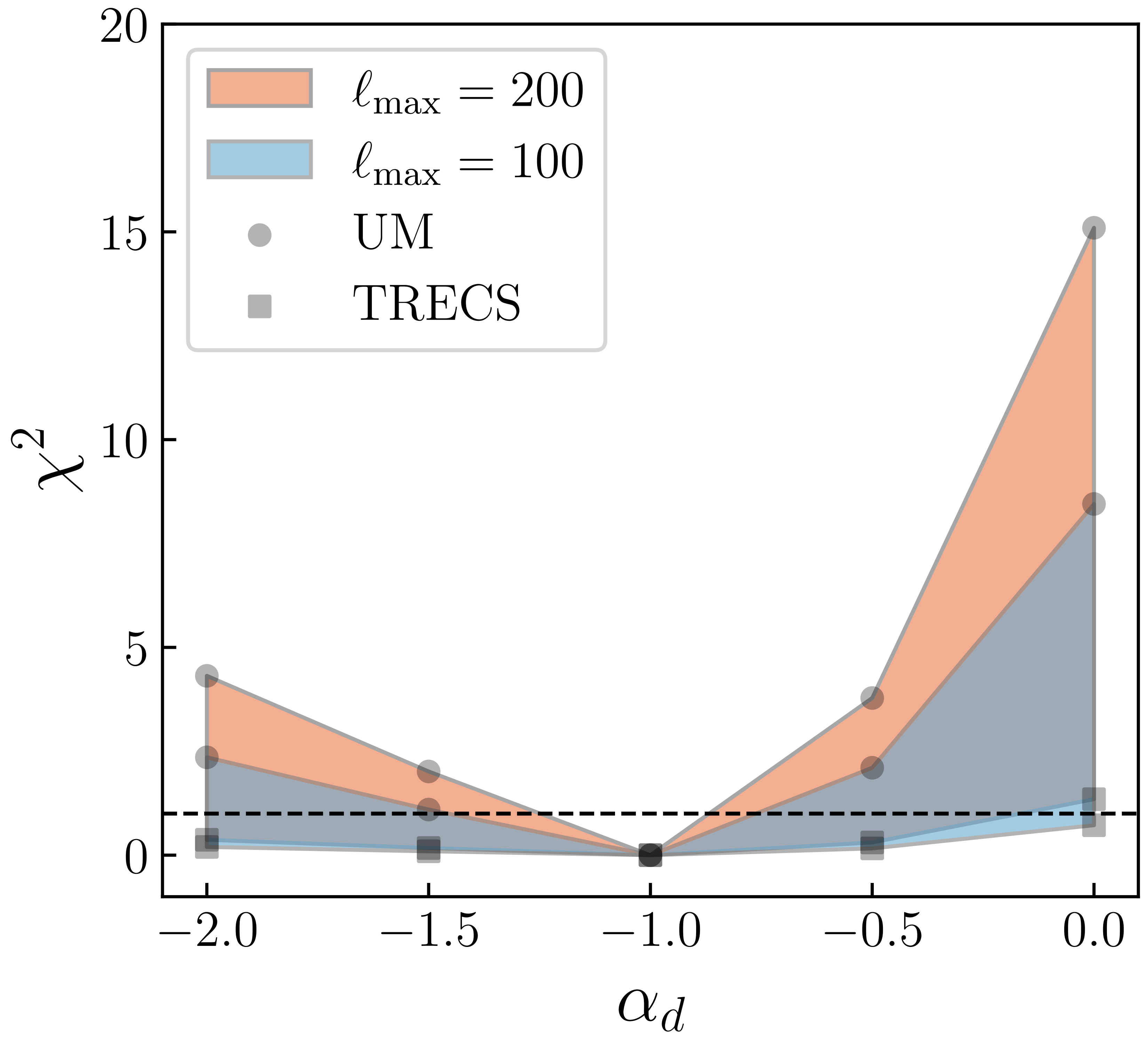
$$p(t_d) \propto t_d^{\alpha_d}$$



Results: time delay distribution

PRELIMINARY

$$\chi^2 \propto \frac{C_\ell^{\text{RCGW, alt}} - C_\ell^{\text{RCGW, fid}}}{C_\ell^{\text{RCGW, fid}}}$$



- The physical effect is present irrespective of the assumed star formation prescription
- Cross-correlation with SKAO provides a **novel observable** to probe the BBH formation physics

Take-home messages

$b_{\rm gw}$

- The constraining power of SKA-Mid $\times$ ET2CE overcomes forecasts for ET2CE alone
- Our results for Radio Continuum galaxies and HI Intensity Mapping are comparable

$f_{\rm PBH}$

- $f_{\rm PBH} \in [0.5, 1.0]$ could be constrained by SKA-Mid$\times$ET2CE at $> 5\sigma$ level
- Result compatible with current constraints for $M_{\rm PBH} \in [1 M_\odot, 100 M_\odot]$

$p(t_d)$

PRELIMINARY

- different time-delay models leave imprints on the clustering bias of the GW sources
- GW $\times$ SKAO provides a novel observable to probe the BBH formation mechanisms

Useful references

(1) D. J. Bacon et al., 2020, “Cosmology with Phase 1 of the Square Kilometre Array”, arXiv:1811.02743

(2) G. Scelfo et al., 2022 , “Gravitational waves ×HI intensity mapping: cosmological and astrophysical applications”, arXiv:2106.09786

(3) A. Bonaldi et al., 2023, “The Tiered Radio Extragalactic Continuum (T-RECS) simulation II: HI emission and continuum-HI cross-correlation.”, arXiv:2305.10175

(4) R. Aversa et al., 2015, “Black Hole and Galaxy Coevolution from Continuity Equation and Abundance Matching”,arXiv:1507.07318

(5) C. M. Baugh et al., 2019, “Galaxy formation in the Planck Millennium: the atomic hydrogen content of dark matter halos”, arXiv:1808.08276

(6) R. A. Battye et al., 2013, “HI intensity mapping : a single dish approach”, arXiv:1209.0343

(7) N.H.M. Crighton et al., 2015, “The Neutral Hydrogen Cosmological Mass Density at z=5”, arXiv:1506.02037

(8) M. Spinelli et al., 2020, “The atomic Hydrogen content of the post-reionization Universe”,

(9) A. Rodriguez-Puebla et al., 2016, “Halo and subhalo demographics with Planck cosmological parameters: Bolshoi-Planck and MultiDark–Planck simulations”, arXiv:1602.04813

(10) P. Behroozi et al., 2019, “UniverseMachine: The correlation between galaxy growth and dark matter halo assembly from z = 0-10”, arXiv:1806.07893

(11) N. Bellomo et al., 2022, “CLASS GWB: robust modeling of the astrophysical gravitational wave background anisotropies”, arXiv:2110.15059

(12) M. Bosi et al., 2023, “Constraining extended cosmologies with GW×LSS cross-correlations”, arXiv:2306.03031

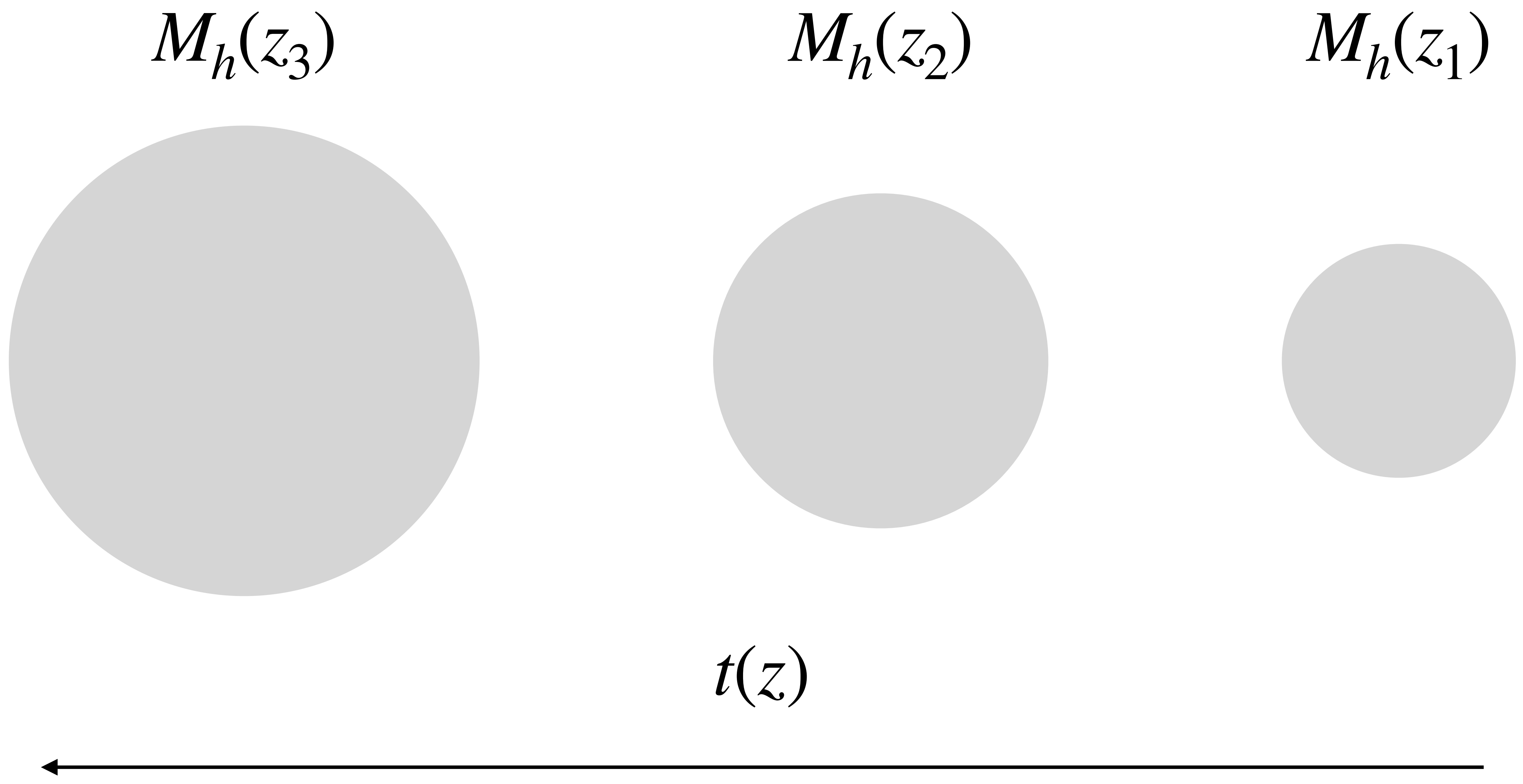
(13) S. Zazzera et al., 2025, “Exploring future synergies for large-scale structure between gravitational waves and radio sources", arXiv:2505.15645

Back-up

PRELIMINARY

Bellomo+2026 (in preparation)

$$p(t_d) \propto t_d^{\alpha_d}$$



Back-up

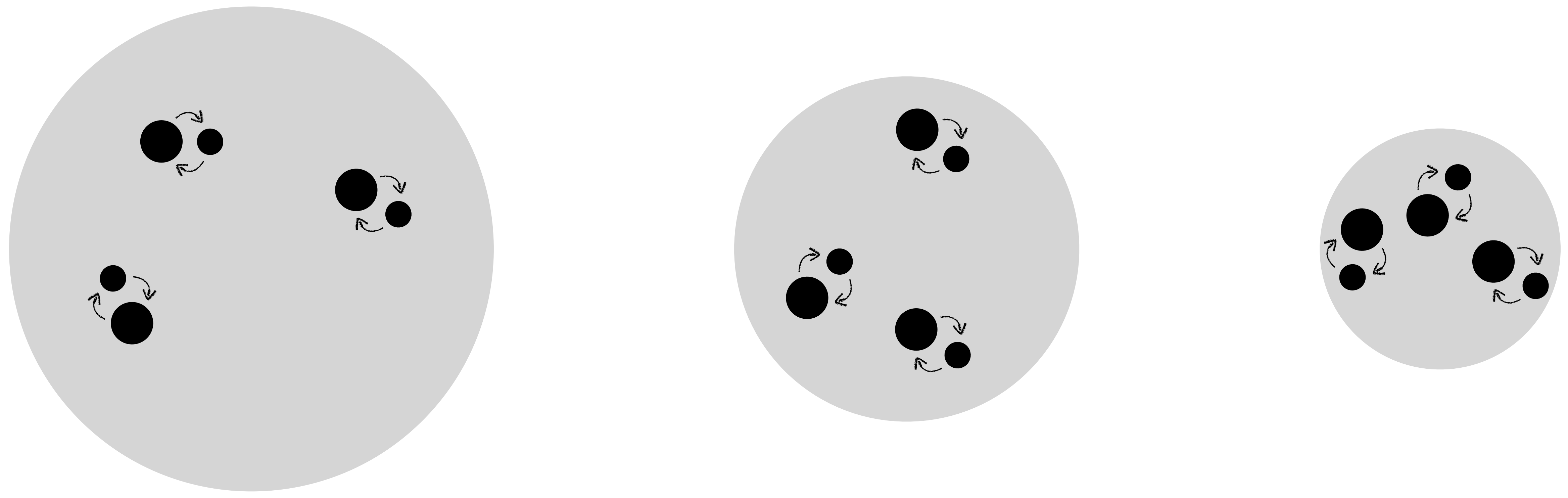
PRELIMINARY

Bellomo+2026 (in preparation)

$$p(t_d) \propto t_d^{\alpha_d}$$

$M_h(z_3)$ $M_h(z_2)$ $M_h(z_1)$

$\alpha_d = 0$:



$t(z)$

Back-up

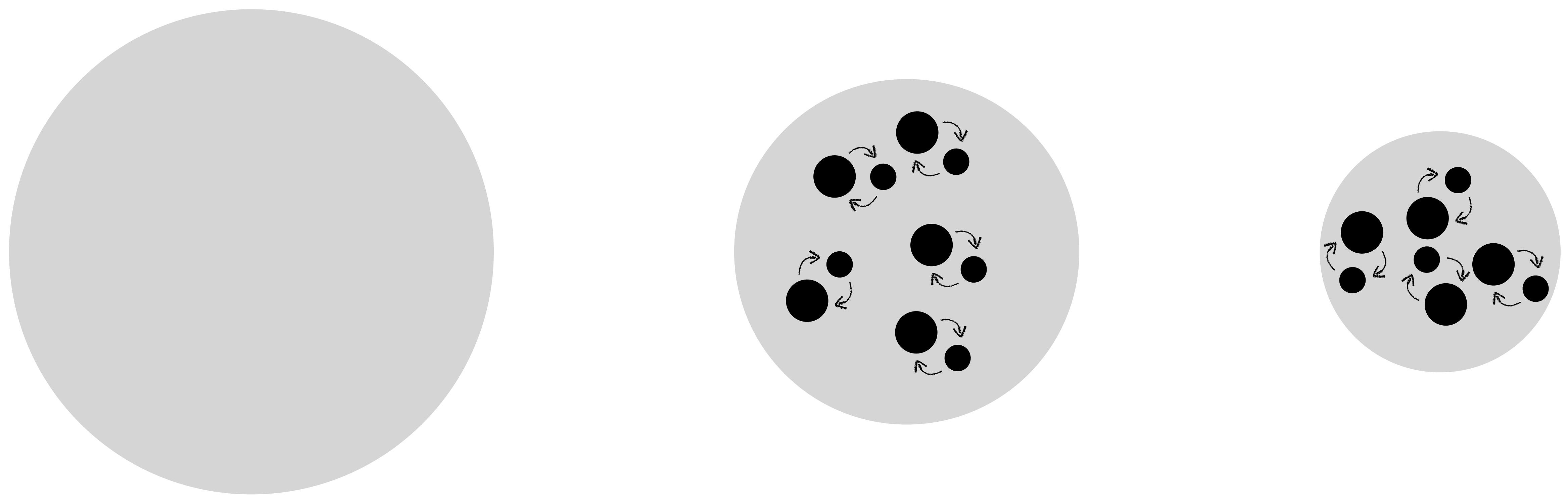
PRELIMINARY

Bellomo+2026 (in preparation)

$$p(t_d) \propto t_d^{\alpha_d}$$

$M_h(z_3)$ $M_h(z_2)$ $M_h(z_1)$

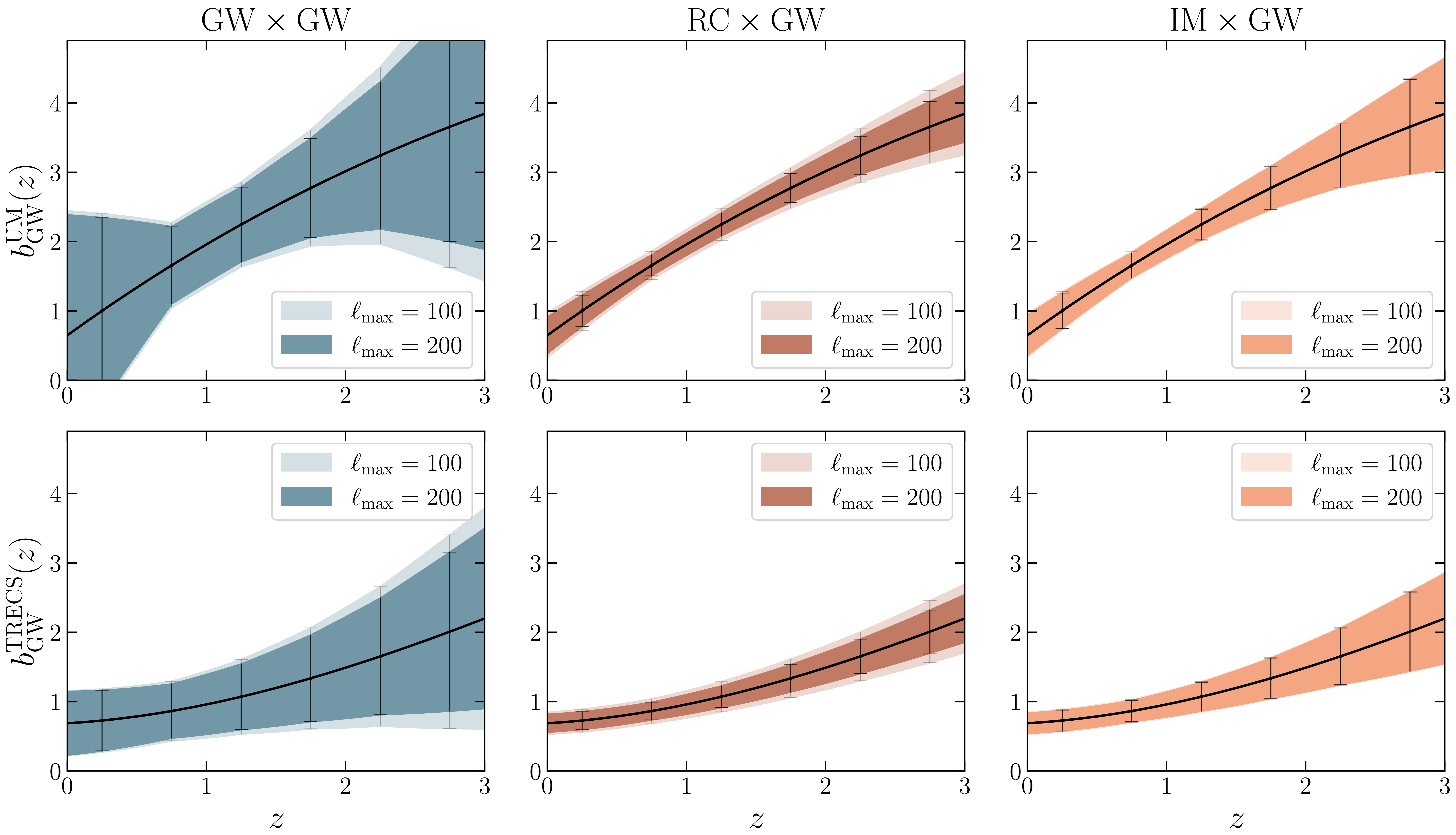
$\alpha_d = -2:$



$b_{\rm GW} \downarrow$

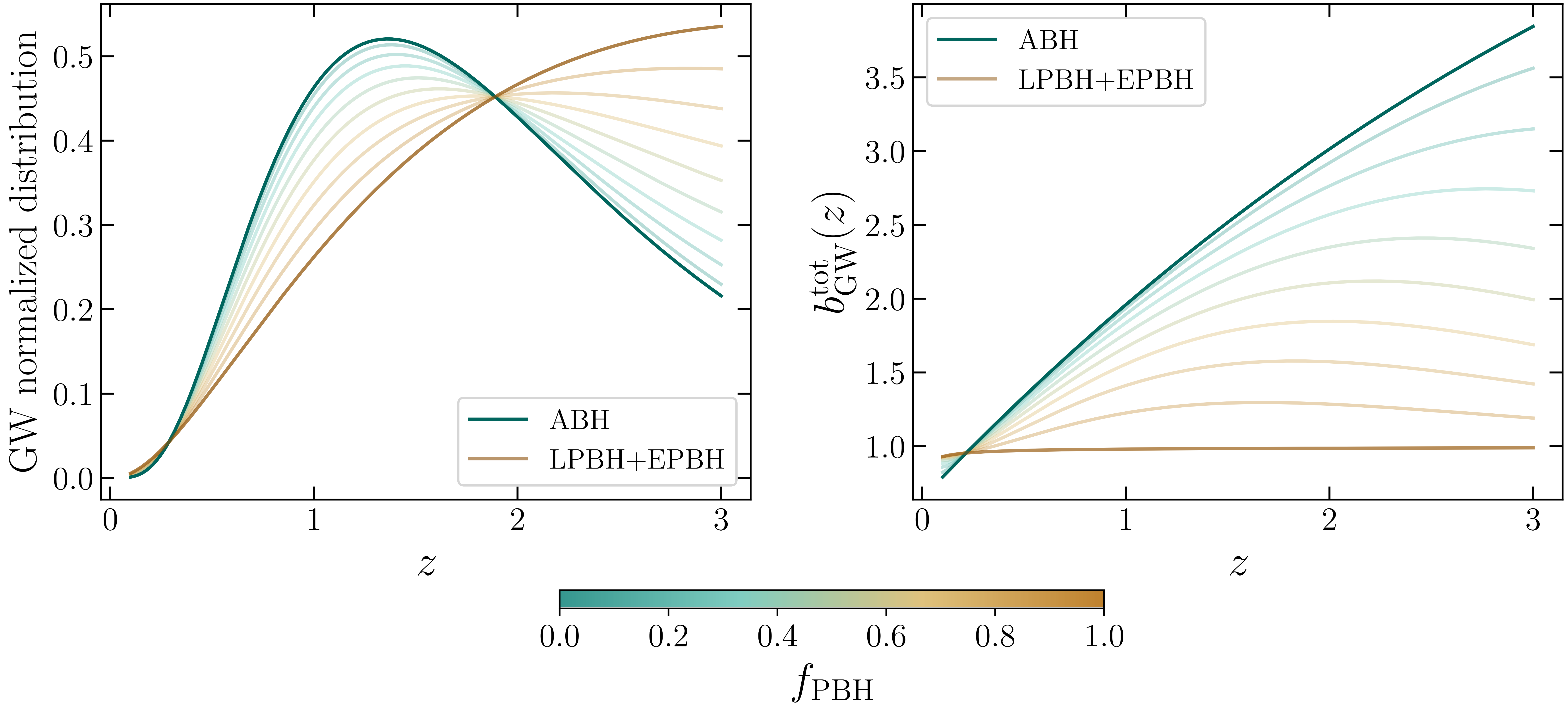
$t(z)$

Back-up



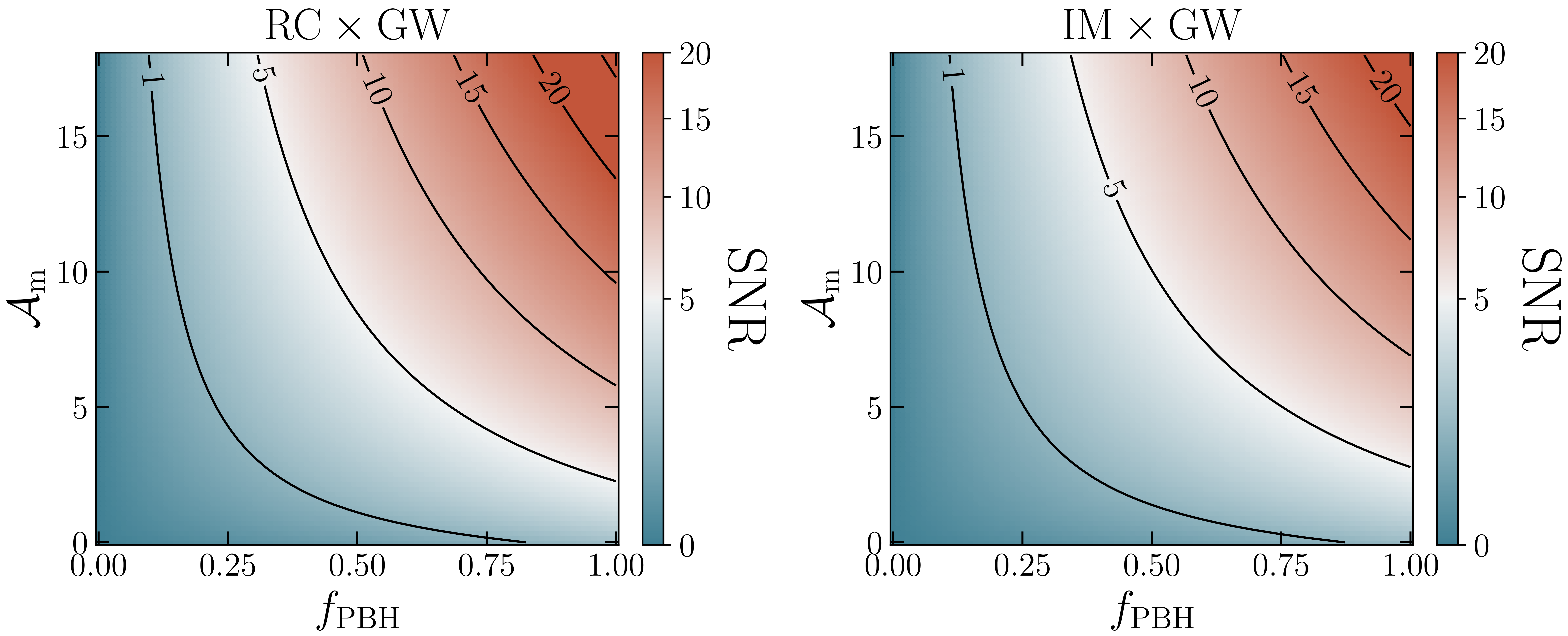
GW × GW
RC × GW
IM × GW
$b_{\mathrm{GW}}^{\mathrm{UM}}(z)$
$b_{\mathrm{GW}}^{\mathrm{TRECS}}(z)$
$\ell_{\max} = 100$
$\ell_{\max} = 200$
z

Back-up



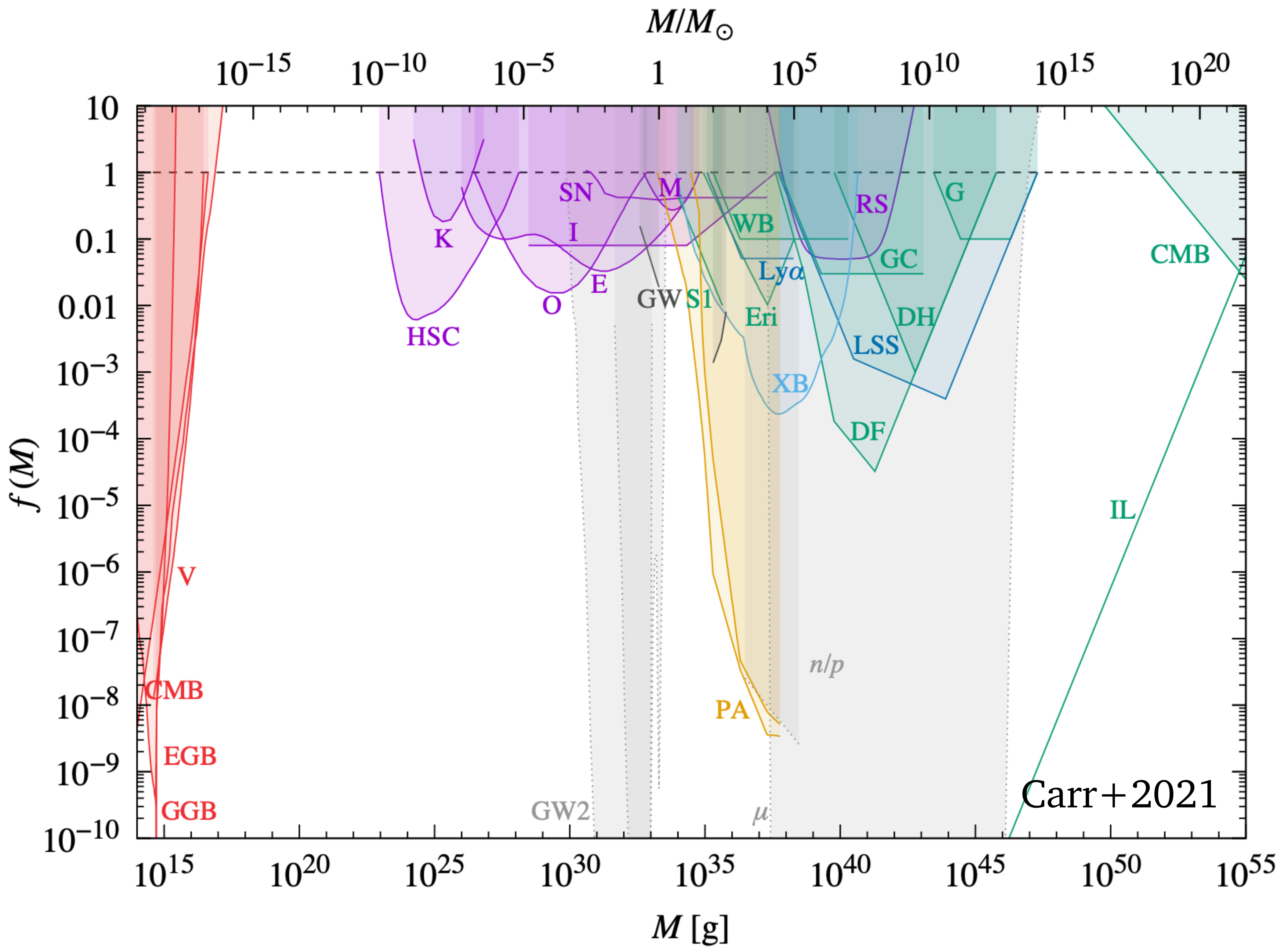
GW normalized distribution
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
z
ABH
LPBH+EPBH
$b^{\mathrm{tot}}_{\mathrm{GW}}(z)$
1.0
1.5
2.0
2.5
3.0
3.5
0
1
2
3
z
ABH
LPBH+EPBH
0.0
0.2
0.4
0.6
0.8
1.0
f_{PBH}

Back-up



RC × GW
IM × GW
$\mathcal{A}_{\rm m}$
$f_{\rm PBH}$
SNR
0
5
10
15
20
0.00
0.25
0.50
0.75
1.00

Back-up



$M/M_\odot$
10^{-15}
10^{-10}
10^{-5}
1
10^{5}
10^{10}
10^{15}
10^{20}
$f(M)$
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{15}
10^{20}
10^{25}
10^{30}
10^{35}
10^{40}
10^{45}
10^{50}
10^{55}
M [g]
V
CMB
EGB
GGB
HSC
K
O
E
I
SN
M
GW
S1
GW2
WB
Lyα
Eri
RS
GC
G
DH
LSS
XB
DF
PA
n/p
μ
CMB
IL
Carr+2021