SMBH meets HEP phenomenology

Forces	Classical	Quantum	
Electromagnetism	Charges, Electromagnetic field, Light	Charged fermions and photons	
Weak Force		W,Z bosons, neutrinos	SM, Higgs boson
Strong force		Quarks, gluons and family of hadrons	
Gravity	Spacetime, BHs and GWS	Gravitons, ?	

Explored at particle detectors, i.e. CERN

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Previously explored with astrophysics, since 2015 explored with GW observatories!

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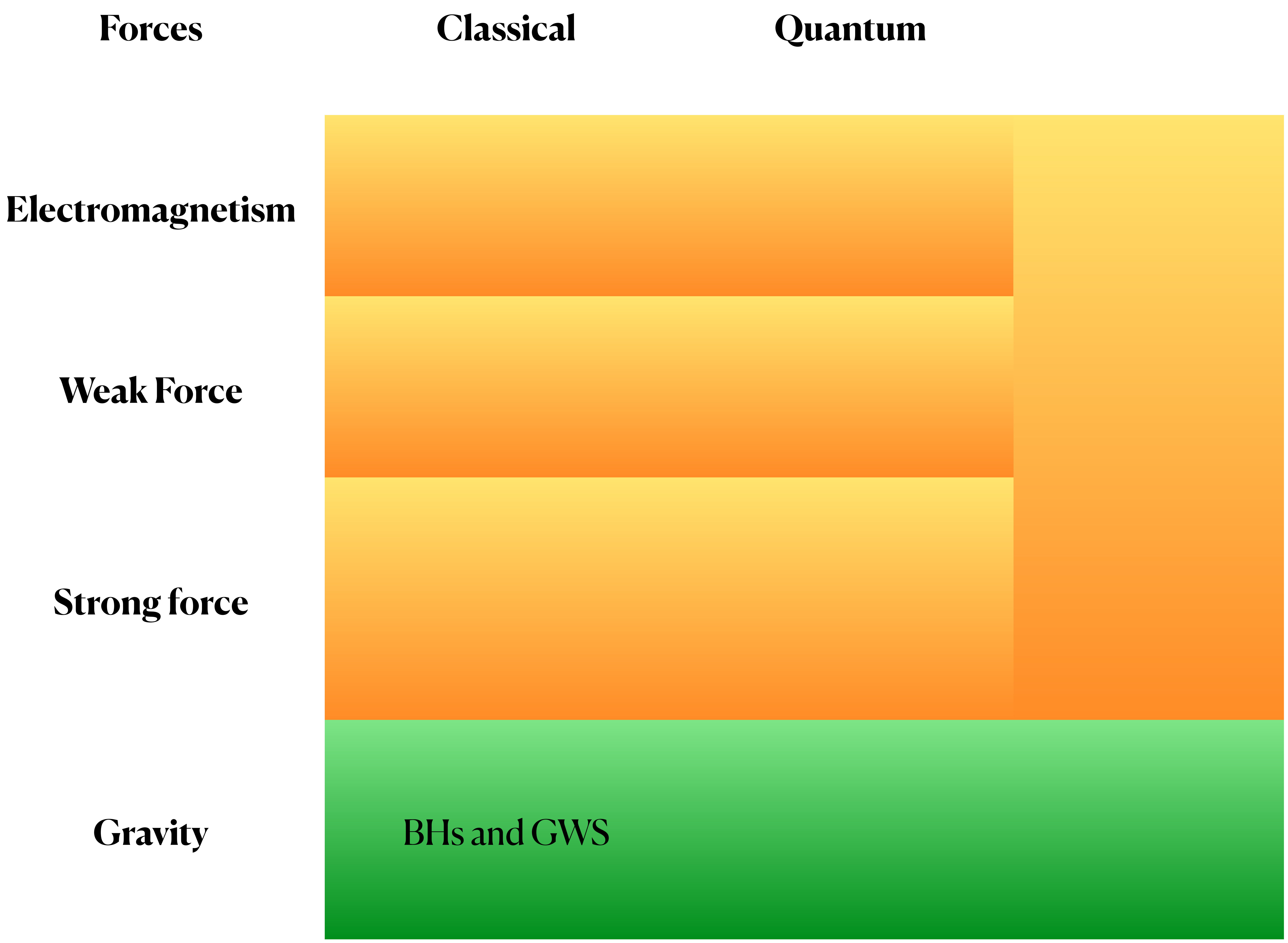
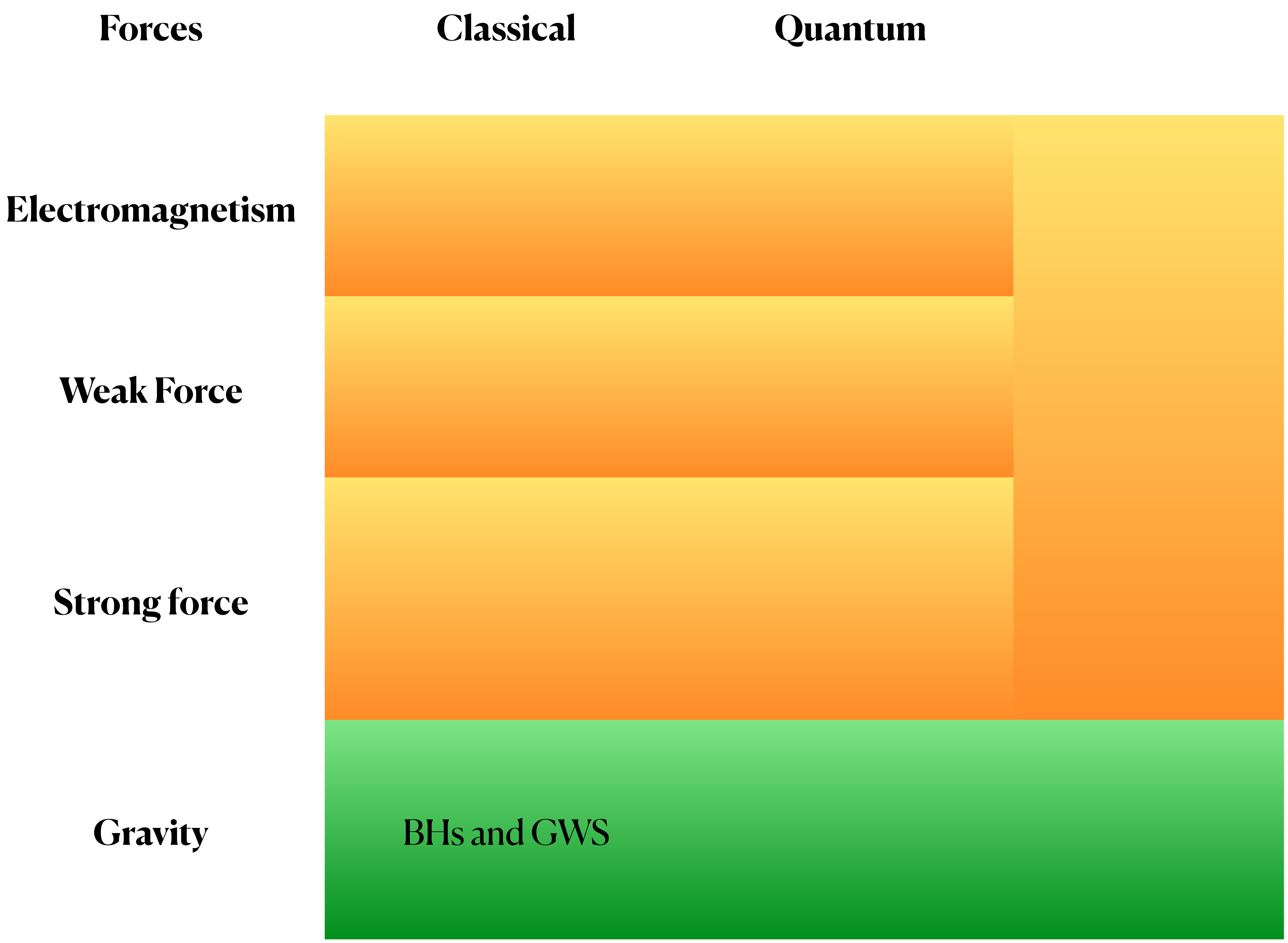
What makes high energy physics ?

- Quantum mechanics
- Relativity
- High Energy, ($E >$ eV)



What makes high energy physics ?

- Quantum mechanics ❌
- Fundamental physics ✅
- Relativity ✅
- High Energy, ($E >$ eV) ✅



Conclusion

- GWs are like “classical light”, but with high occupation number of gravitons
- BHs are fundamental objects predicted by GR
- A new landscape of phenomenology has open to us!

Landmark in GW astronomy and Cosmology

One of the 3 ways ever to detect GWs

- The first indirect detection of GWs with binary pulsars (1975) / Nobel Prize (1993) 
- The first direct observation of BH binaries by the LIGO collaboration (2016) / Nobel Prize (2017) 
- Detection of stochastic GW background by NANOgrav, European PTA, Parkes PTA and the Chinese PTA (2023), ?

What are PTAs?

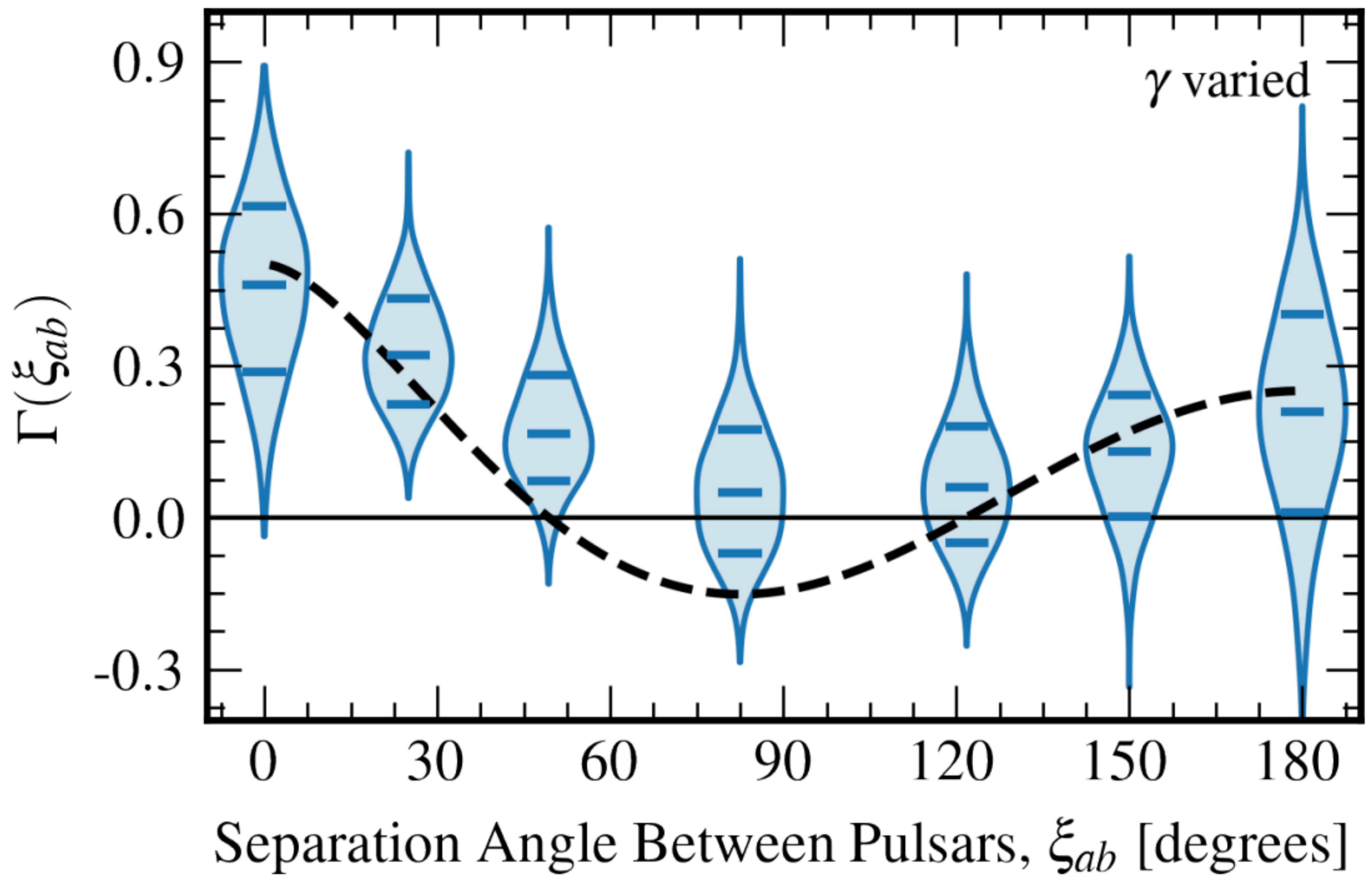
- The use of milisencond pulsars as clocks positioned around the galaxy to measure GW $\mathcal{O}\left(\text{kpc}\right)$

- which correspond to frequencies at around $\mathcal{O}\,(\text{nHz})$, $\sim\,30\,\text{yr}$

https://nanograv.org/news/nanograv-finds-possible-first-hints-low-frequency-gravitational-wave-background-0

Evidence for the Hellings-Down in the 15-yr Data

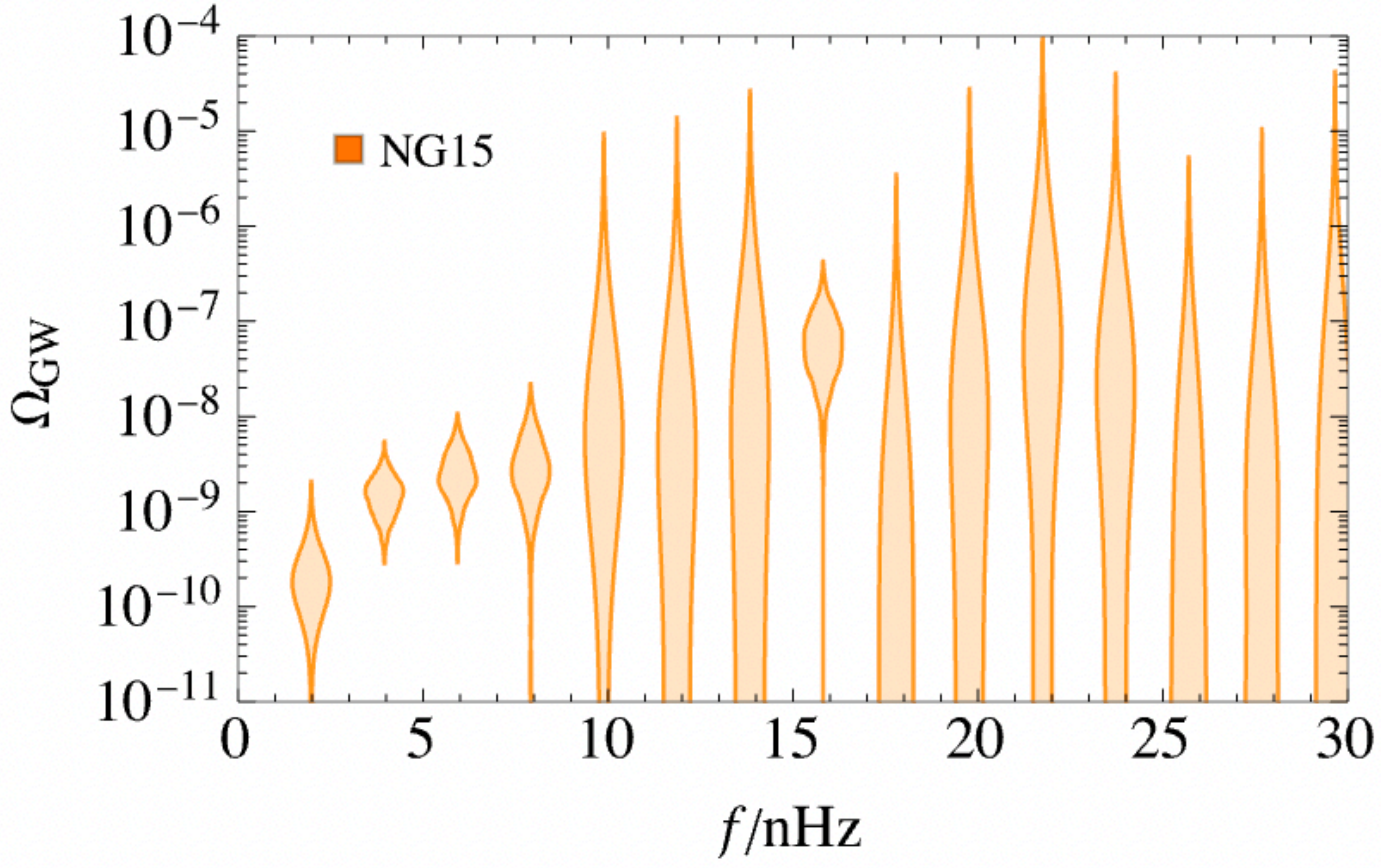
- Angular Correlation smoking gun for GW
  - assumes unpolarised background
  - massless graviton



https://arxiv.org/pdf/2306.16213.pdf

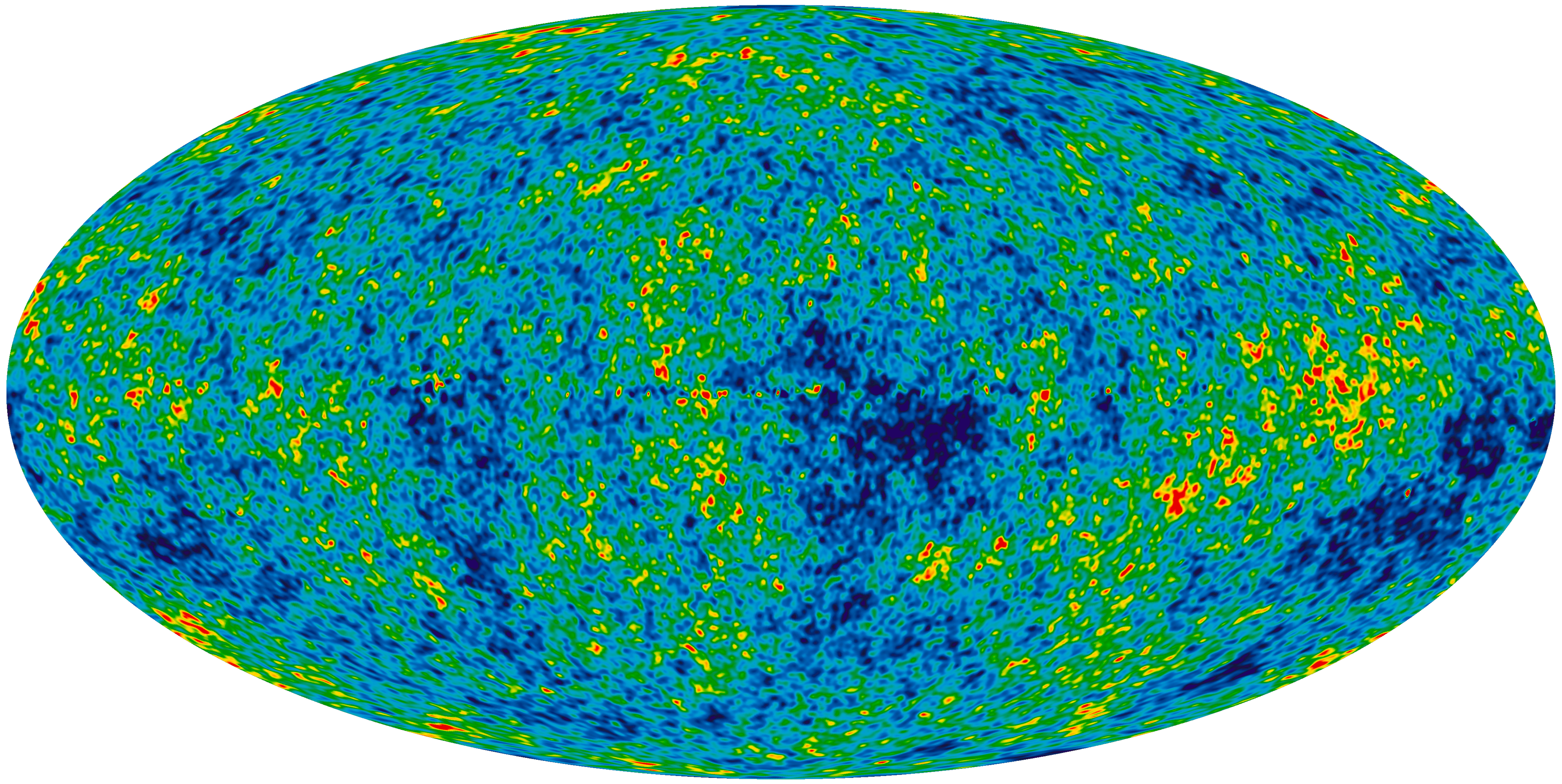
Frequency dependence

Previously (12.5 yr data release) was just a constant amplitude band

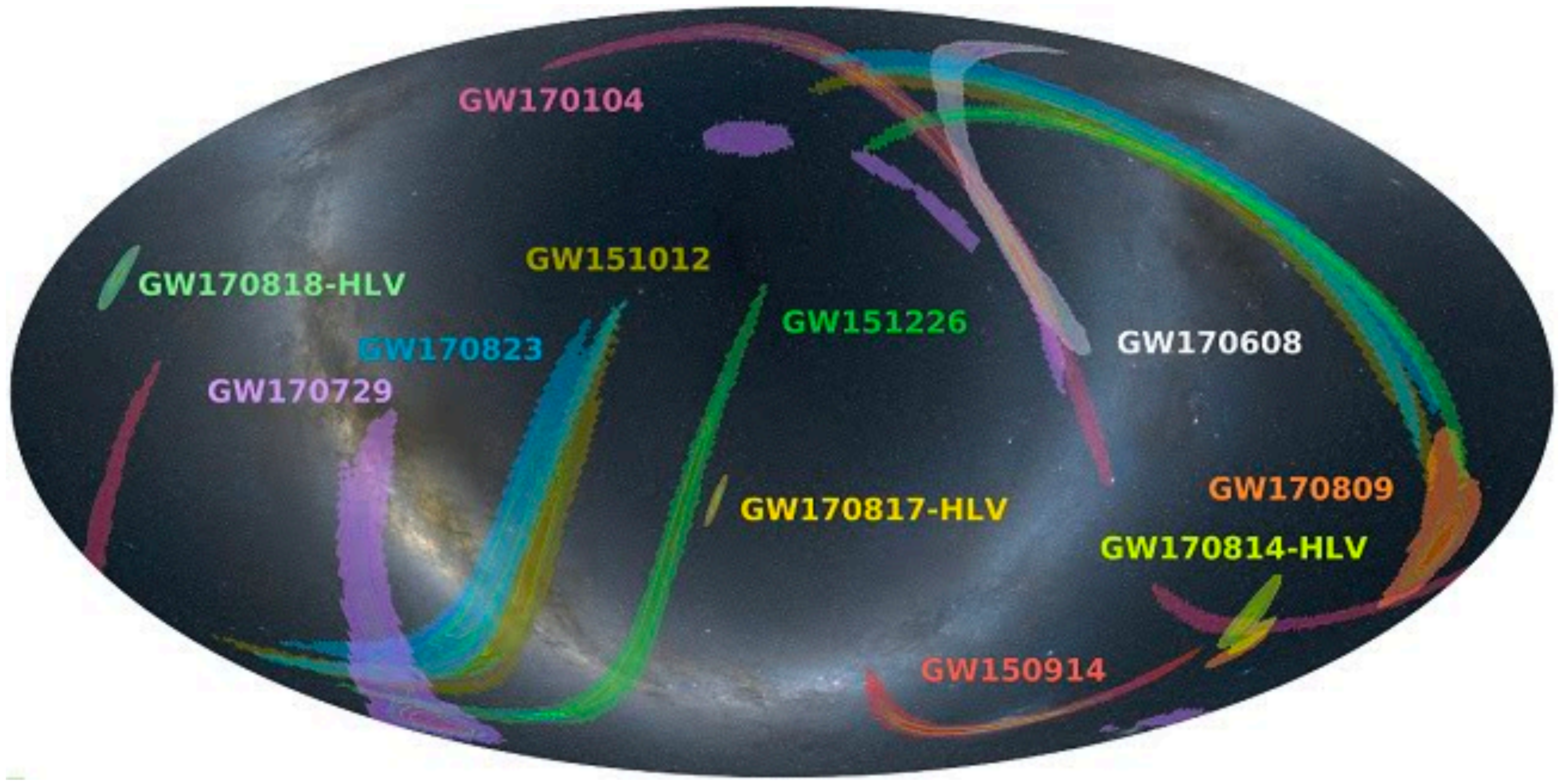


About the PTA signal

- Is it an homogeneous background?



- Is it made of individual sources?



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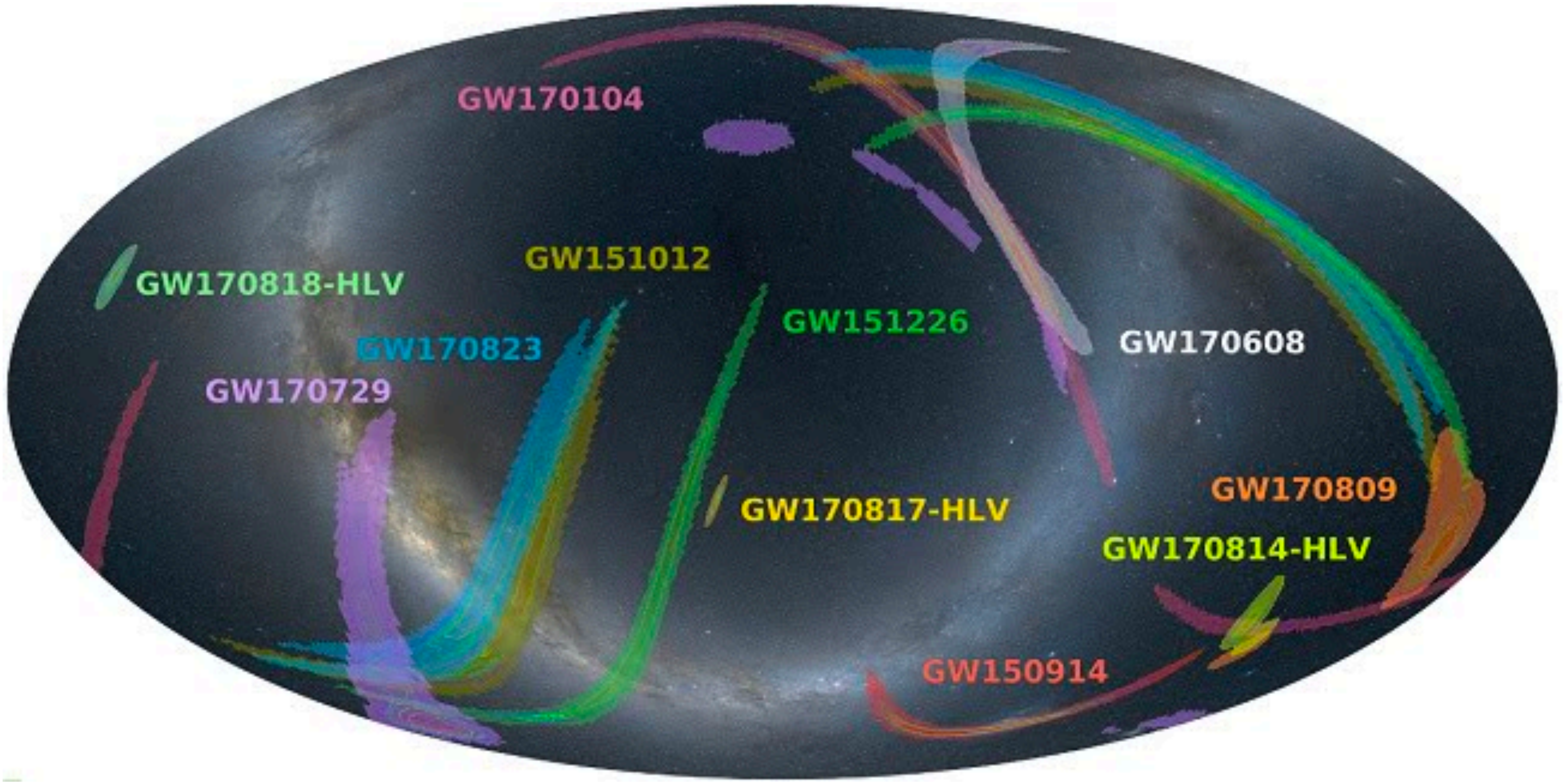
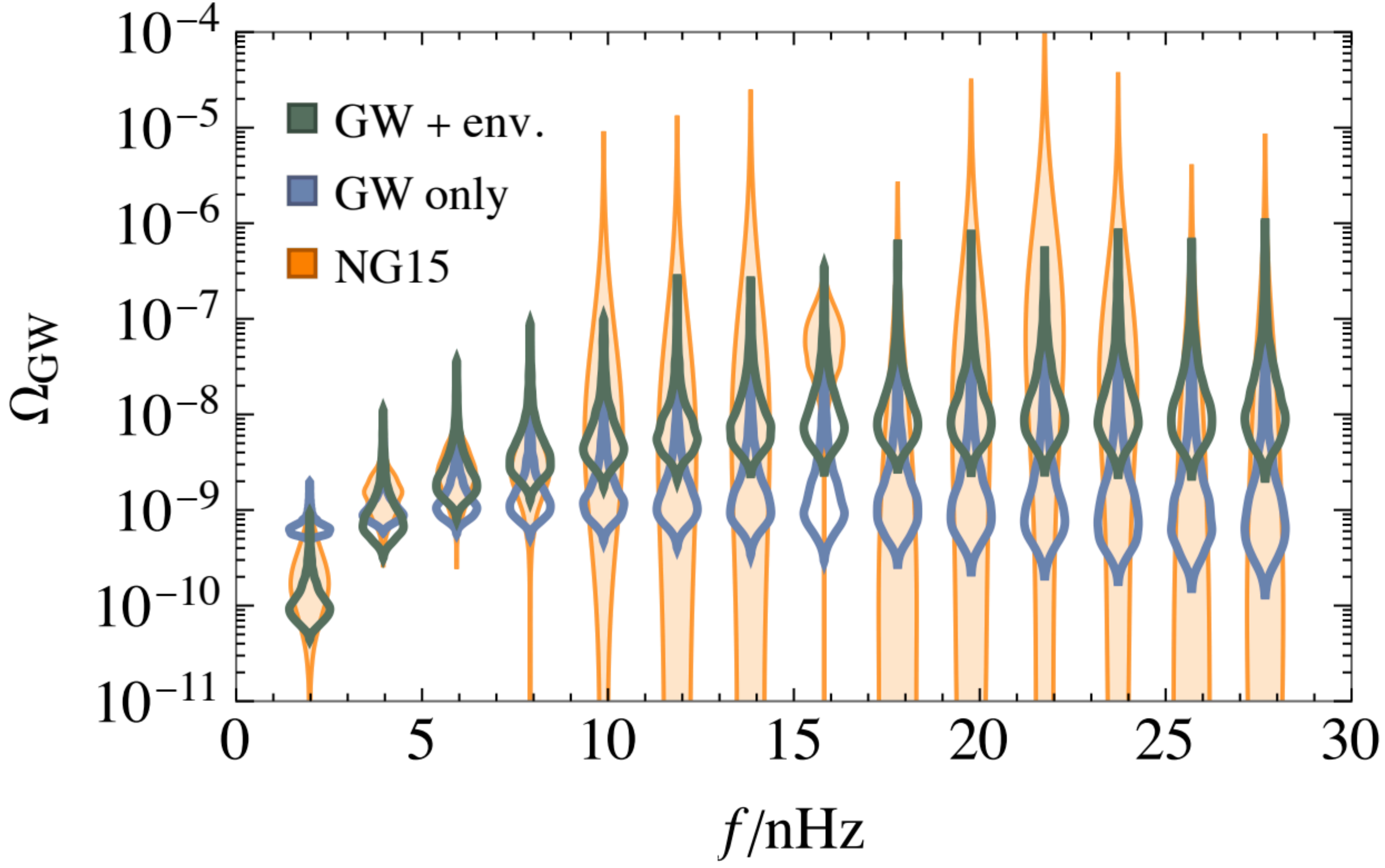


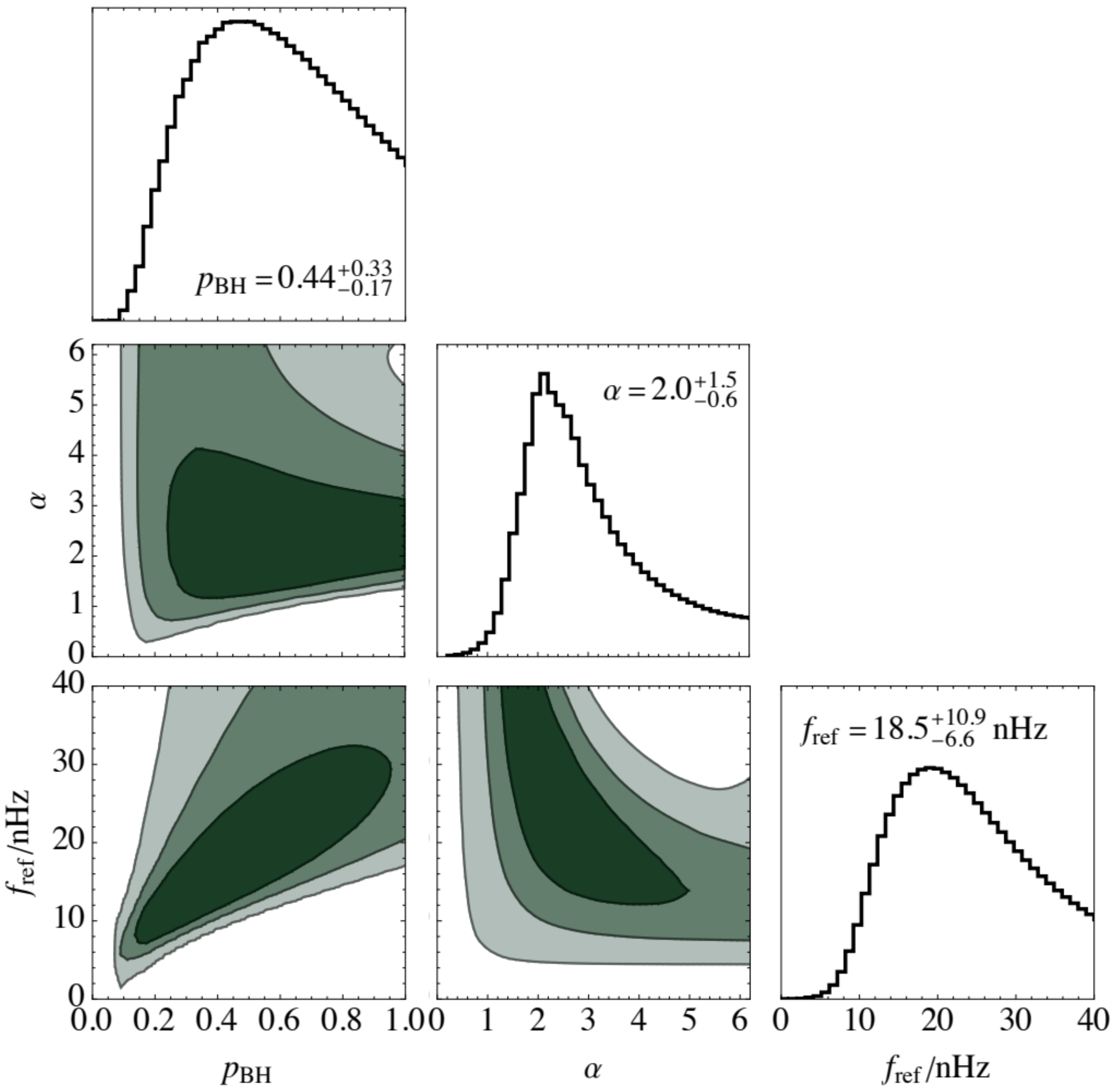
Assuming signal comes from SMBH

- We use the merger-rate of Dark Matter halos
- populate the halos with SMBH
- get merger-rate for SMBH

$$\frac{\mathrm{d}R_{\mathrm{BH}}}{\mathrm{d}m_1\mathrm{d}m_2} = p_{\mathrm{BH}}(m_1, m_2, z) \int \mathrm{d}M_1\mathrm{d}M_2 \, \frac{\mathrm{d}R_h}{\mathrm{d}M_1\mathrm{d}M_2} \times p_{\mathrm{occ}}(m_1|M_1, z) p_{\mathrm{occ}}(m_2|M_2, z) \, ,$$



10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ω_{GW}
GW + env.
GW only
NG15
0
5
10
15
20
25
30
f/nHz



Likelihood and confidence levels for the parameters of the fit

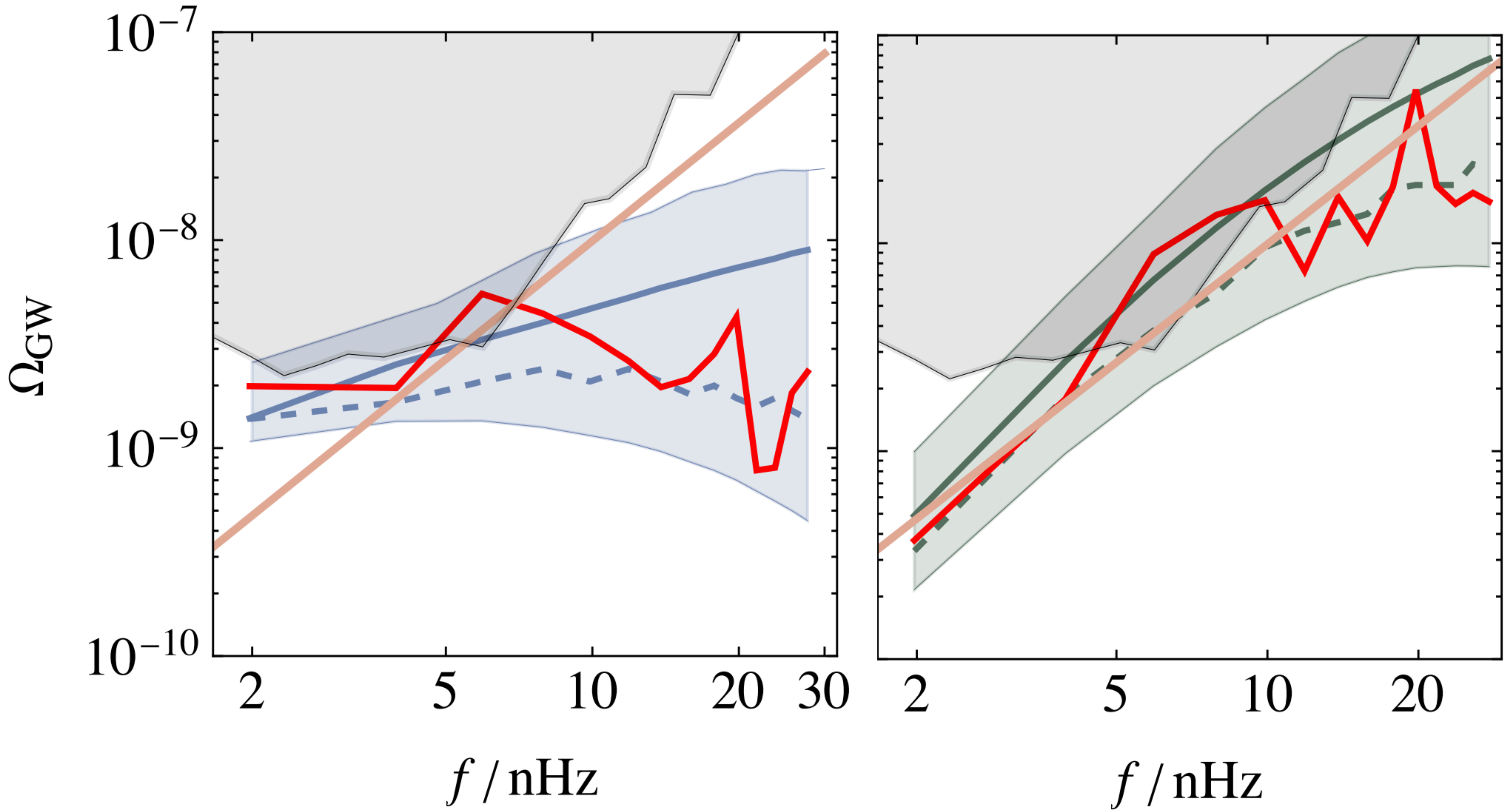
The GW+Env model is favoured $> 2\sigma$

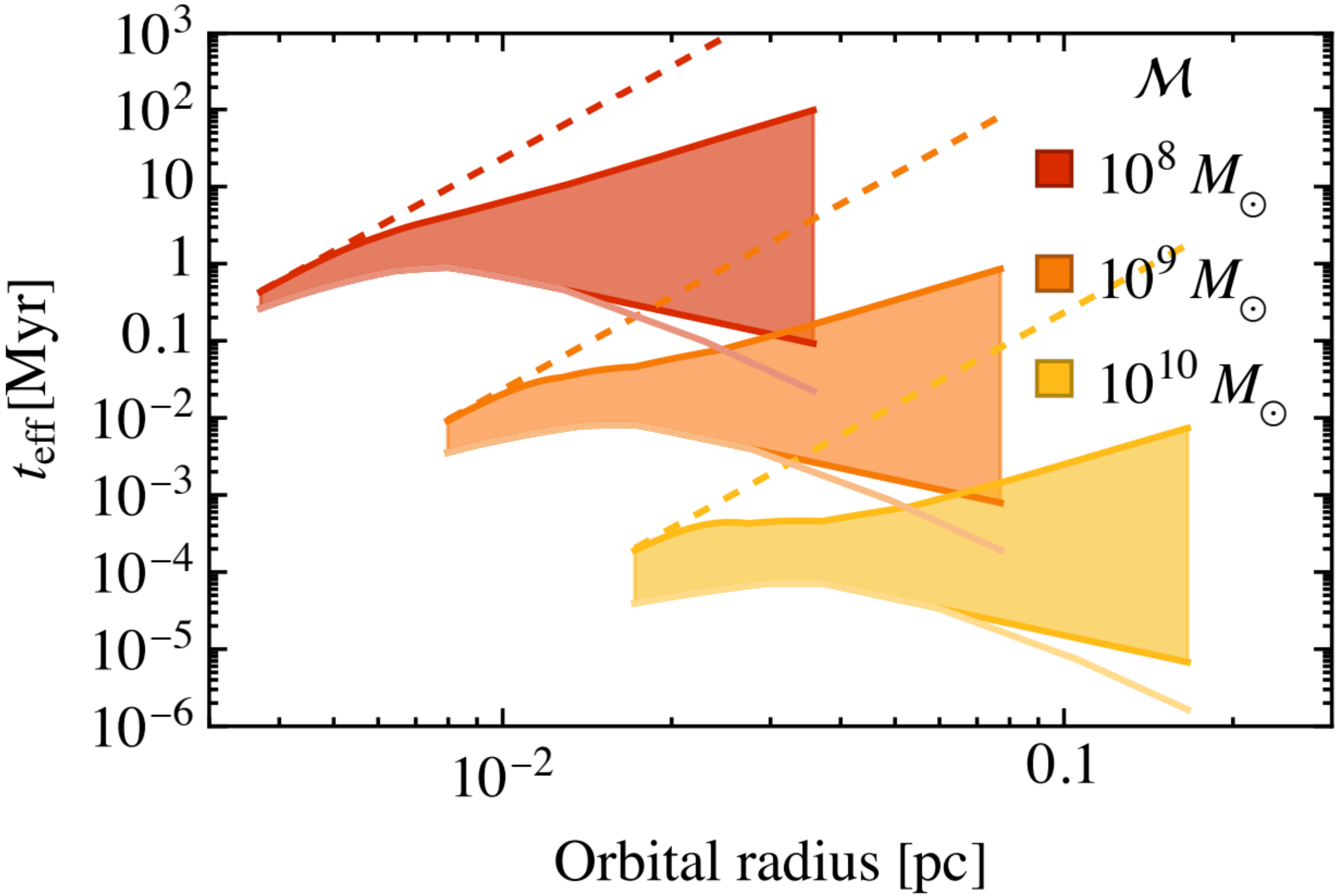
- p_{BH} is the probability of the binary to emit GW efficiently

- f_{ref} is the transition frequency between env. effects and GW dominated

- α is the power-law index of the env. effects

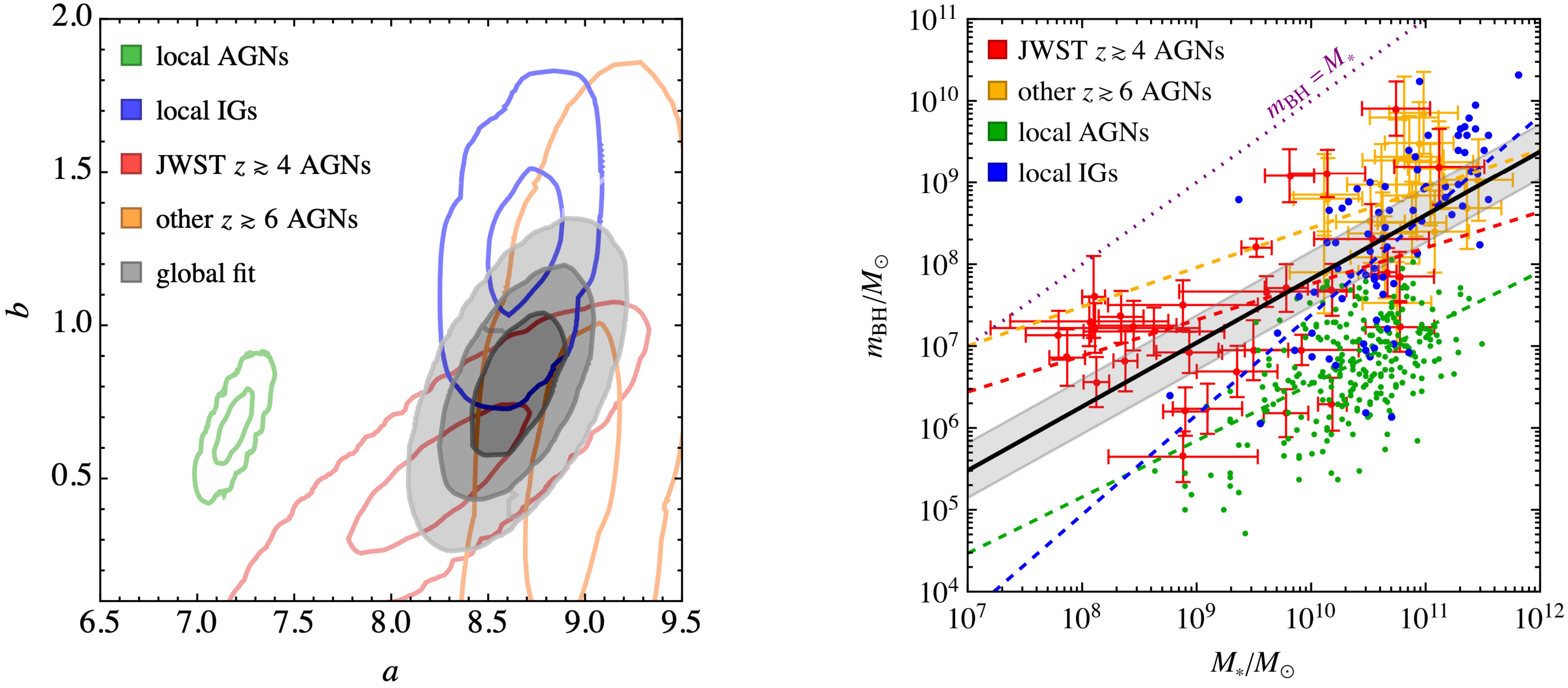
The background is a long tail distribution





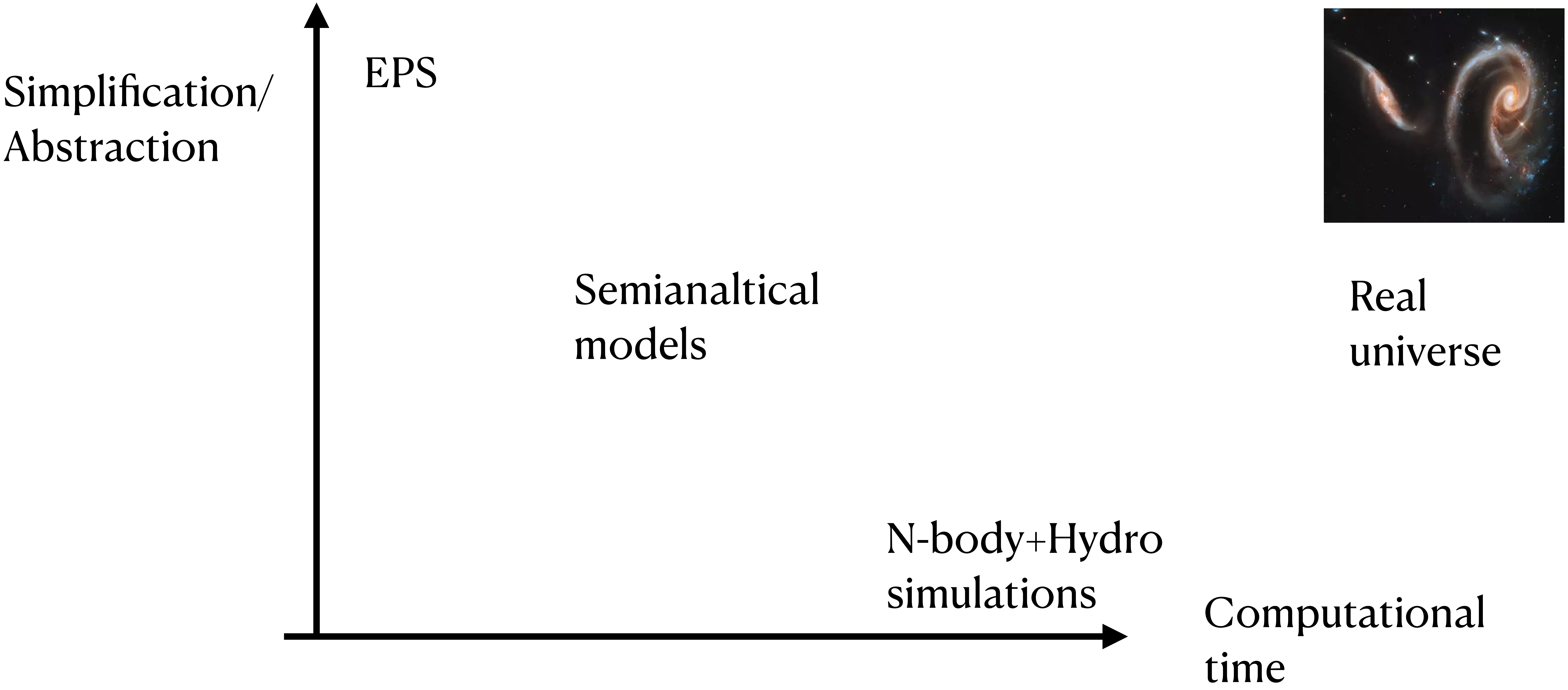
Solves the final parsec problem

What have we recently learned about SMBH?



Juan Urrutia-KBFI 2024, PhD student

The universe growth at different levels of abstraction



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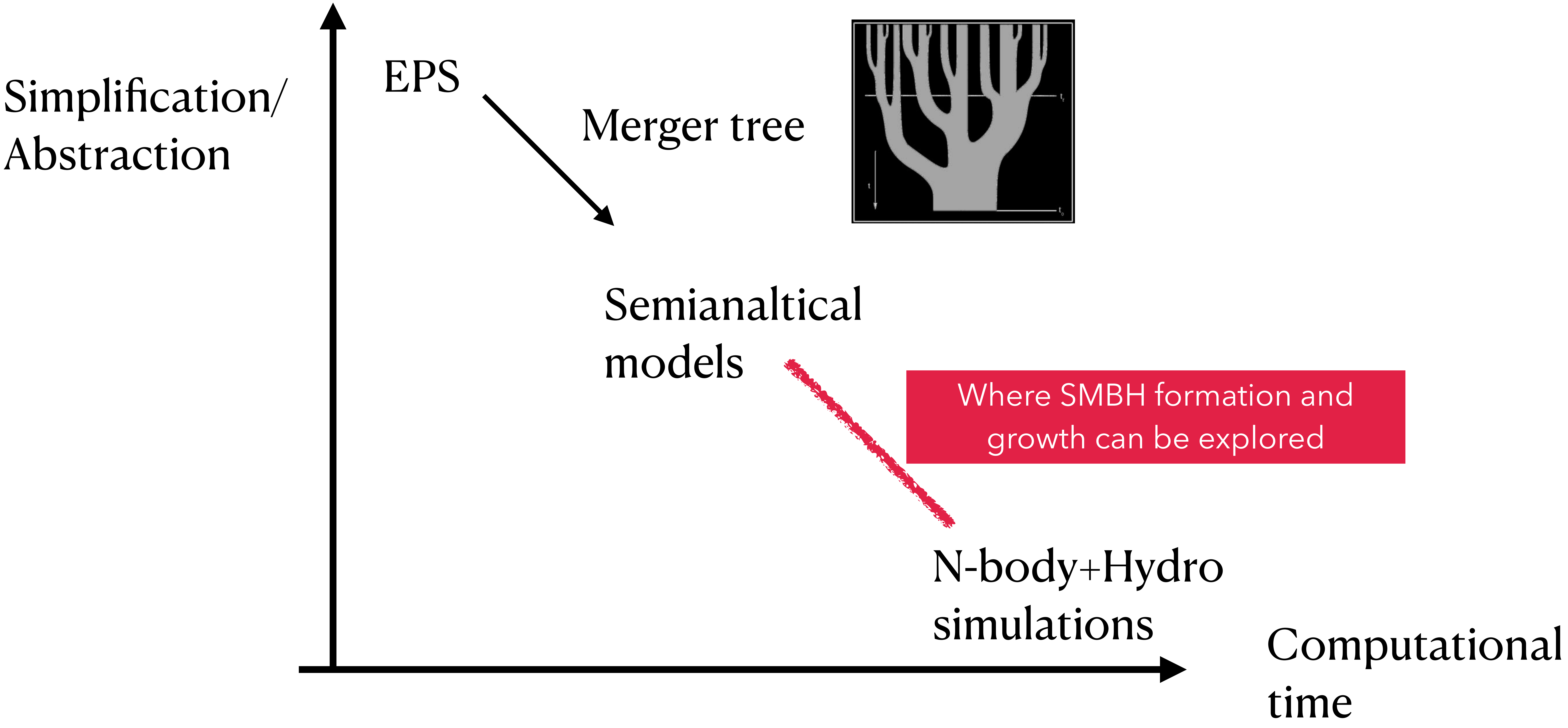

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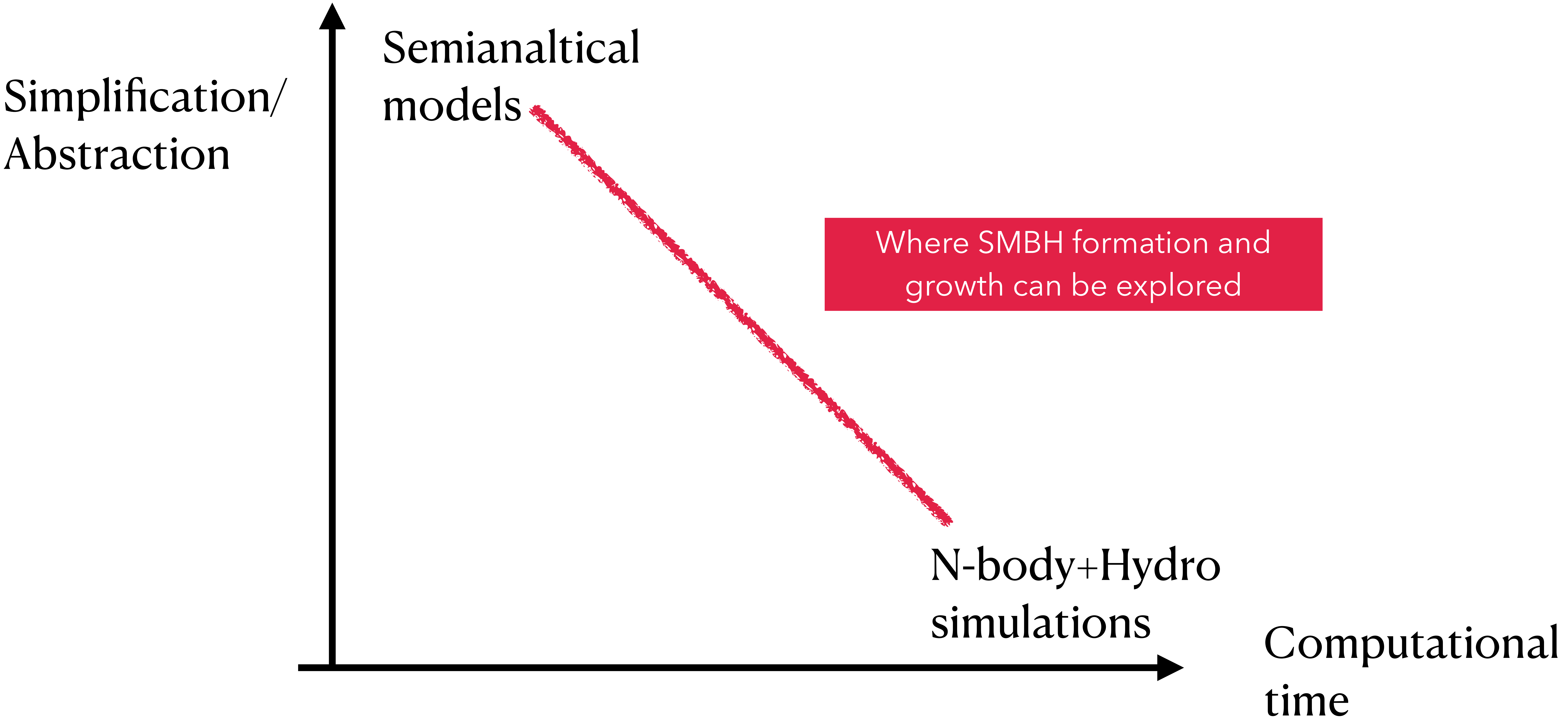

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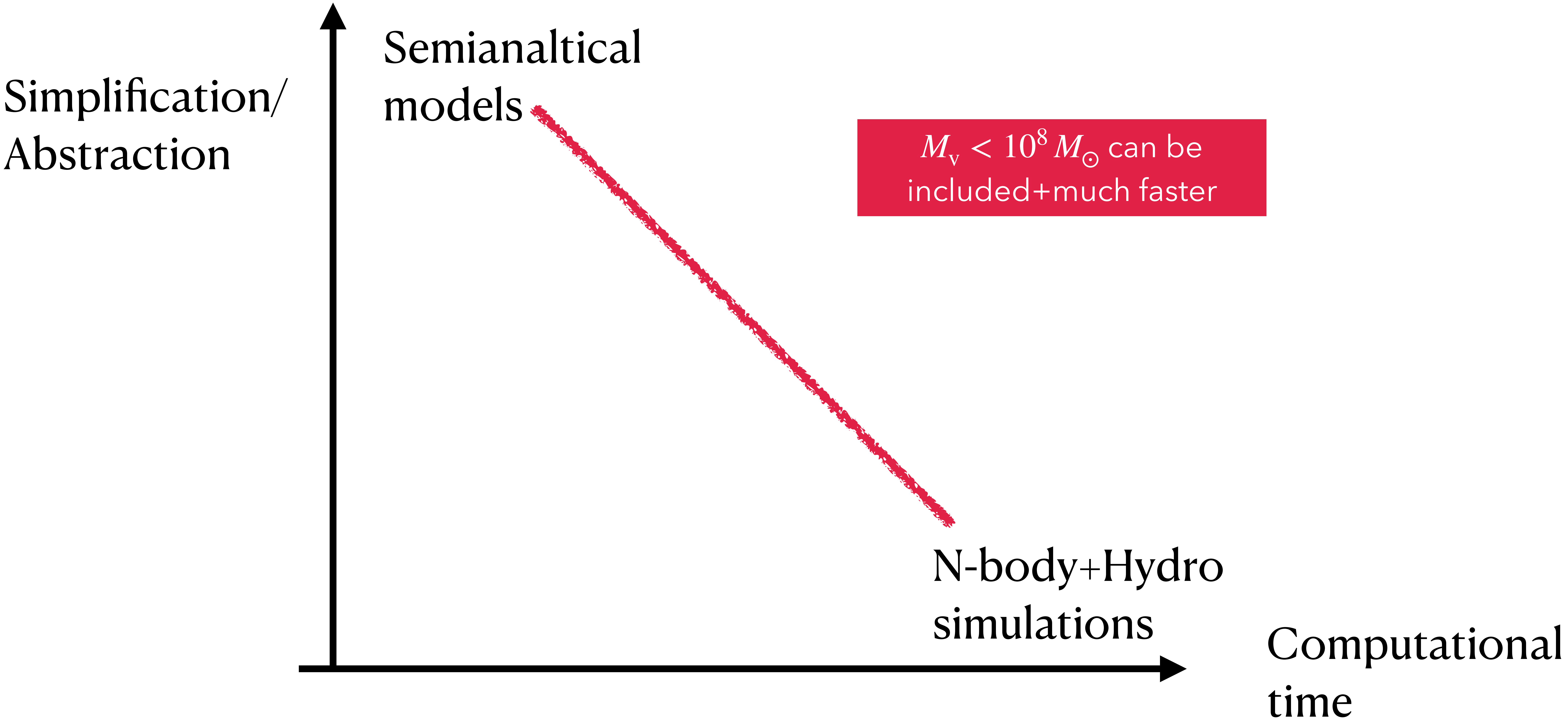

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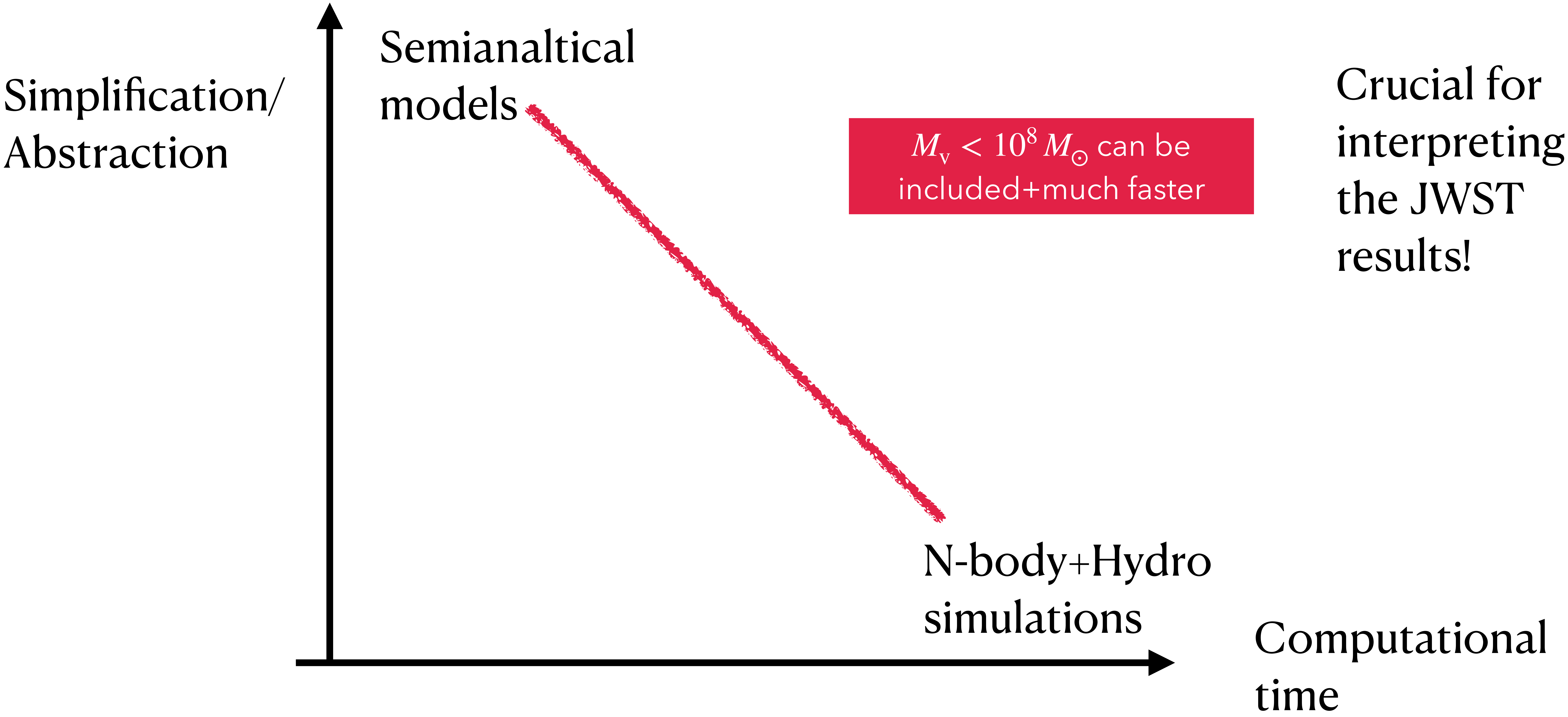

Crucial for interpreting the JWST results!

Juan Urrutia-KBFI 2024, PhD student

Growth beyond merger trees

- Applying the EPS formalism more directly to SMBH growth, i.e. *a SMBH inside a halo on average has had the same history as the average mass of the halo.*
- We can track the differential growth by mergers for DM, gas, stars and SMBHs.

$$M_J(M,z') + \Delta M_J^{\mathrm{merg.}}(M,z,z') = \left[\frac{\mathrm{d}n(z)}{\mathrm{d}M}\right]^{-1} \int_0^M \mathrm{d}M' \, \frac{\mathrm{d}n(z')}{\mathrm{d}M'} \frac{\mathrm{d}P(M,z|M',z')}{\mathrm{d}M} M_J(M',z')$$
$$= \int_0^M \mathrm{d}M' \left|\frac{\mathrm{d}S}{\mathrm{d}M'}\right| \frac{M}{M'} M_J(M',z') \frac{\delta_c(z') - \delta_c(z)}{\sqrt{2\pi[S(M') - S(M)]^3}} e^{-\frac{[\delta_c(z') - \delta_c(z)]^2}{2[S(M') - S(M)]}}$$

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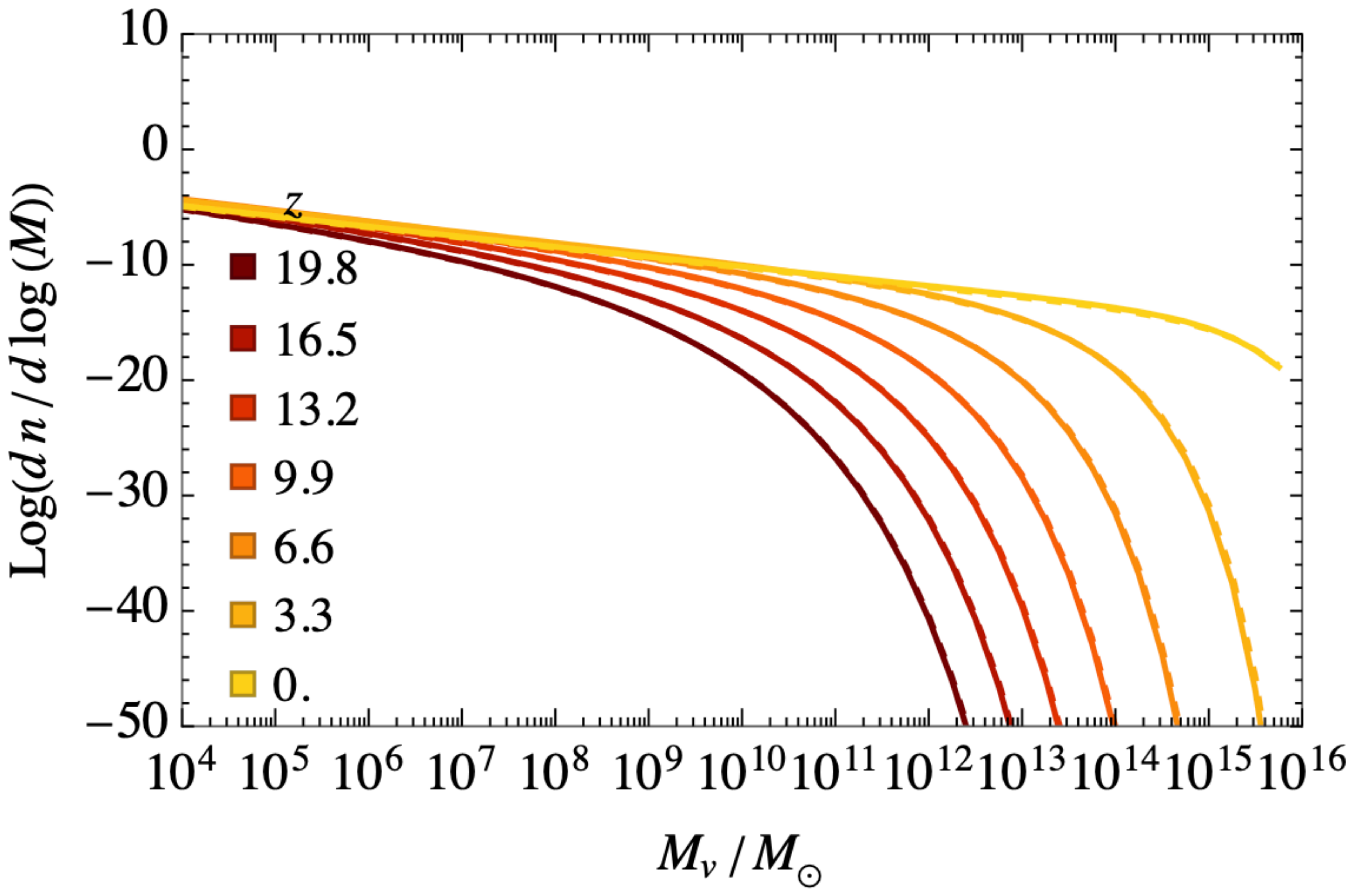
Growth beyond merger trees

- Automatically matches the EPS formalism for DM
- arbitrarily small DM halos can be taken into account



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Growth beyond merger trees

- The SMBH origin becomes the initial conditions to the solution to the coupled differential equations
- We take into account the difference between hot and cold gas

$$
\begin{aligned}
\dot{M}_{\rm BH}(M) &= \dot{M}_{\rm BH}^{\rm merg.}(M) + \dot{M}_{\rm BH}^{\rm acc.,cold}(M_{\rm BH}, M) + \dot{M}_{\rm BH}^{\rm acc.,hot}(M_{\rm BH}, M)\,, \\
\dot{M}_{*}(M) &= \dot{M}_{*}^{\rm merg.}(M) + \dot{M}_{*}^{\rm sf.}(M)\,, \\
\dot{M}_{\rm cold}(M) &= f_{\rm cold}(M) f_B \dot{M} - \dot{M}_{\rm cold}^{\rm ej.}(M) - \dot{M}_{\rm cold}^{\rm heated}(M) - \dot{M}_{*}^{\rm sf.}(M) - \dot{M}_{\rm BH}^{\rm acc.,cold}(M_{\rm BH}, M) \\
\dot{M}_{\rm hot}(M) &= f_{\rm hot}(M) f_B \dot{M} + \dot{M}_{\rm cold}^{\rm heated}(M) - \dot{M}_{\rm BH}^{\rm acc.,hot}(M_{\rm BH}, M)
\end{aligned}
$$

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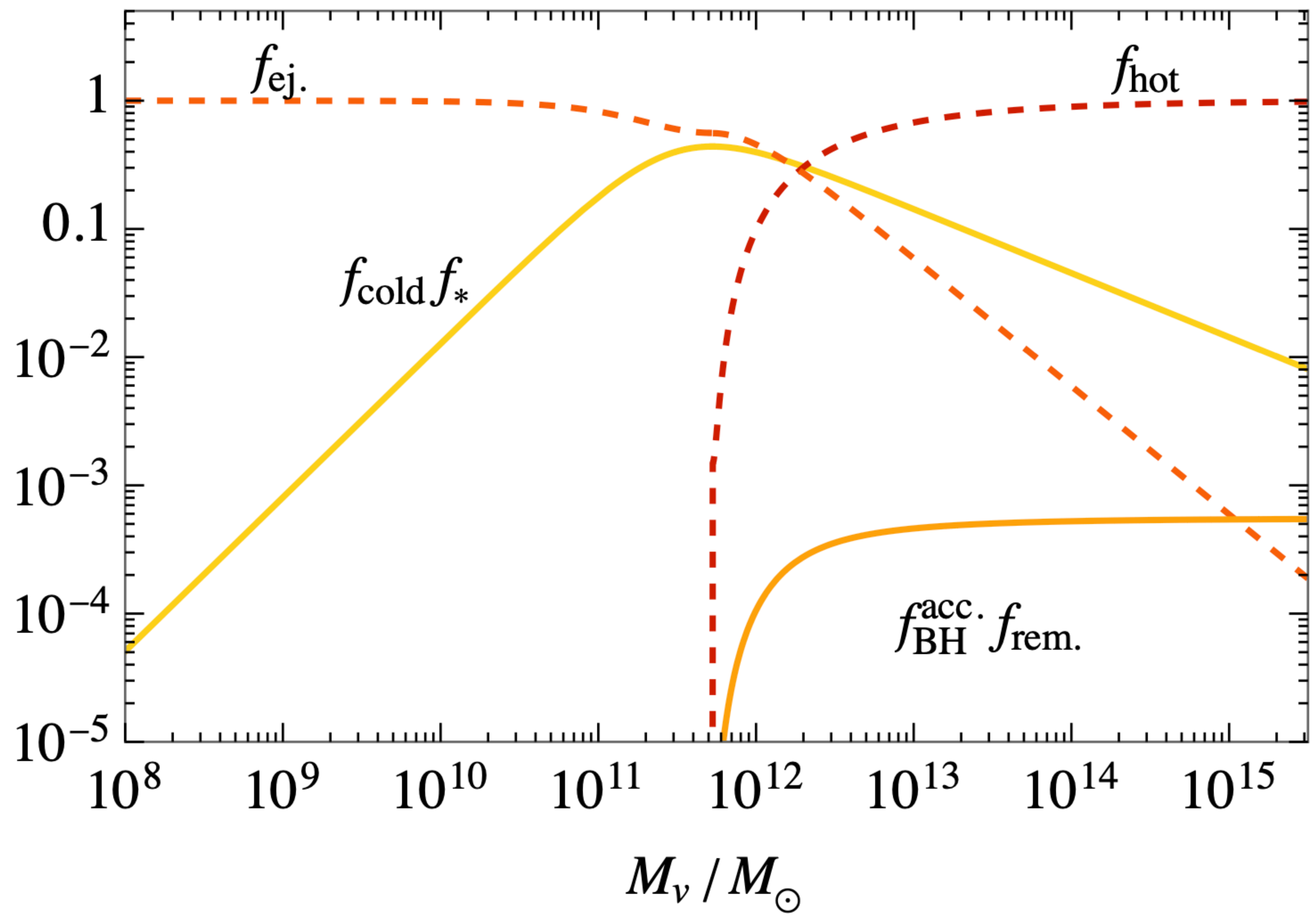
Star formation

- Ejected gas by SN feedback
- heated gas by AGN activity
- Fits high-z UV luminosity function by construction
- the AGN activity also matches UV luminosity functions

$$\dot{M}_*^{\mathrm{sf.}}(M,z) = \frac{6.4\times10^{-2}[0.53\tanh(0.54(2.9-z))+1.53]}{(M/M_{\mathrm{crit}})^{-1.2}+(M/M_{\mathrm{crit}})^{0.5}}\dot{M}$$



https://arxiv.org/pdf/2108.01090

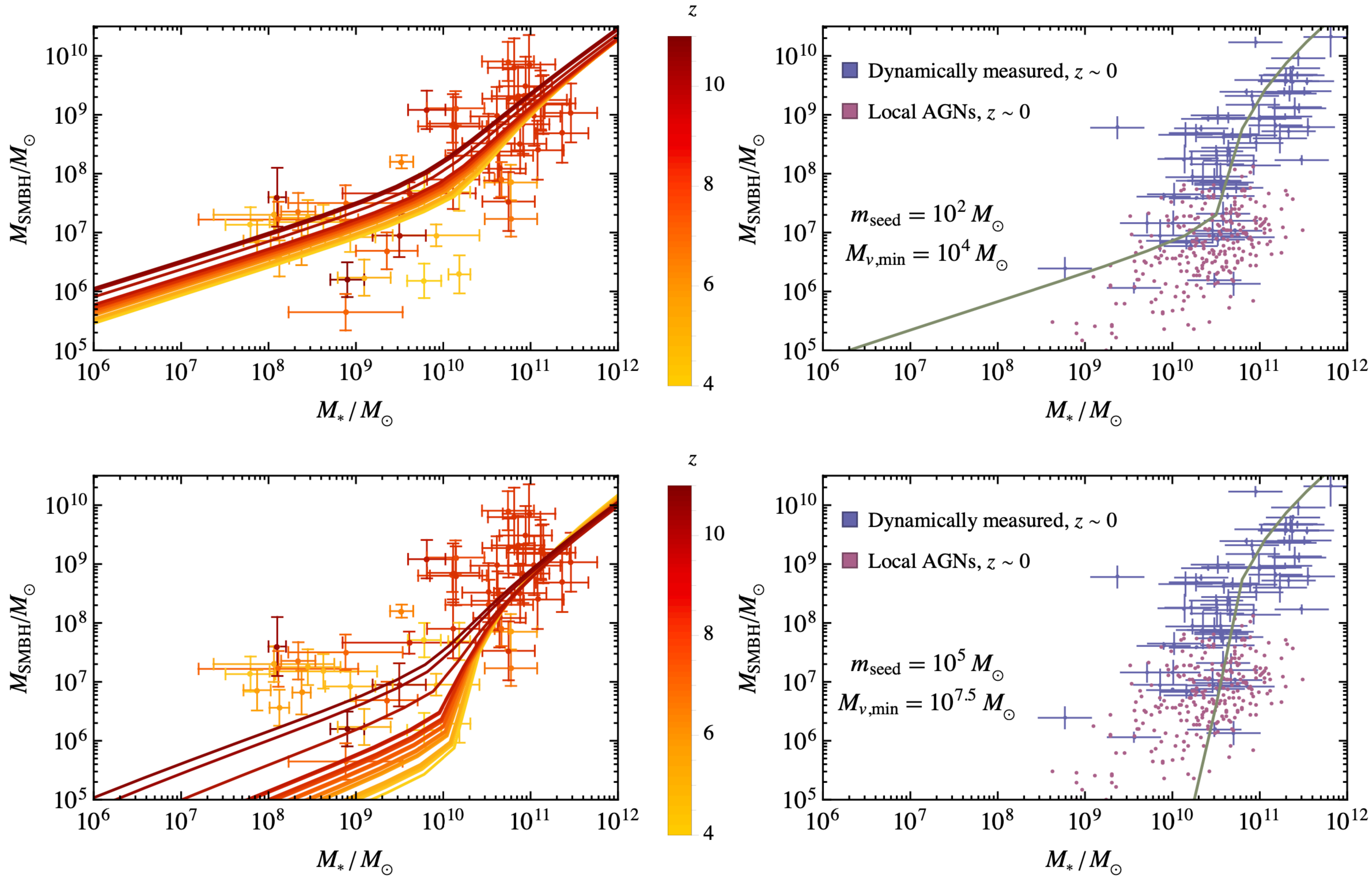
SMBH accretion

$$\dot{M}_{\rm BH}^{\rm acc.}(M_{\rm BH}, M) = \min\left\{ f_{\rm rem.}(M,z) f_B (f_1^{\rm acc.}\dot{M} + f_2^{\rm acc.}M),\ f_{\rm Edd.}\dot{M}_{\rm Edd.}(M_{\rm BH}) \right\}$$

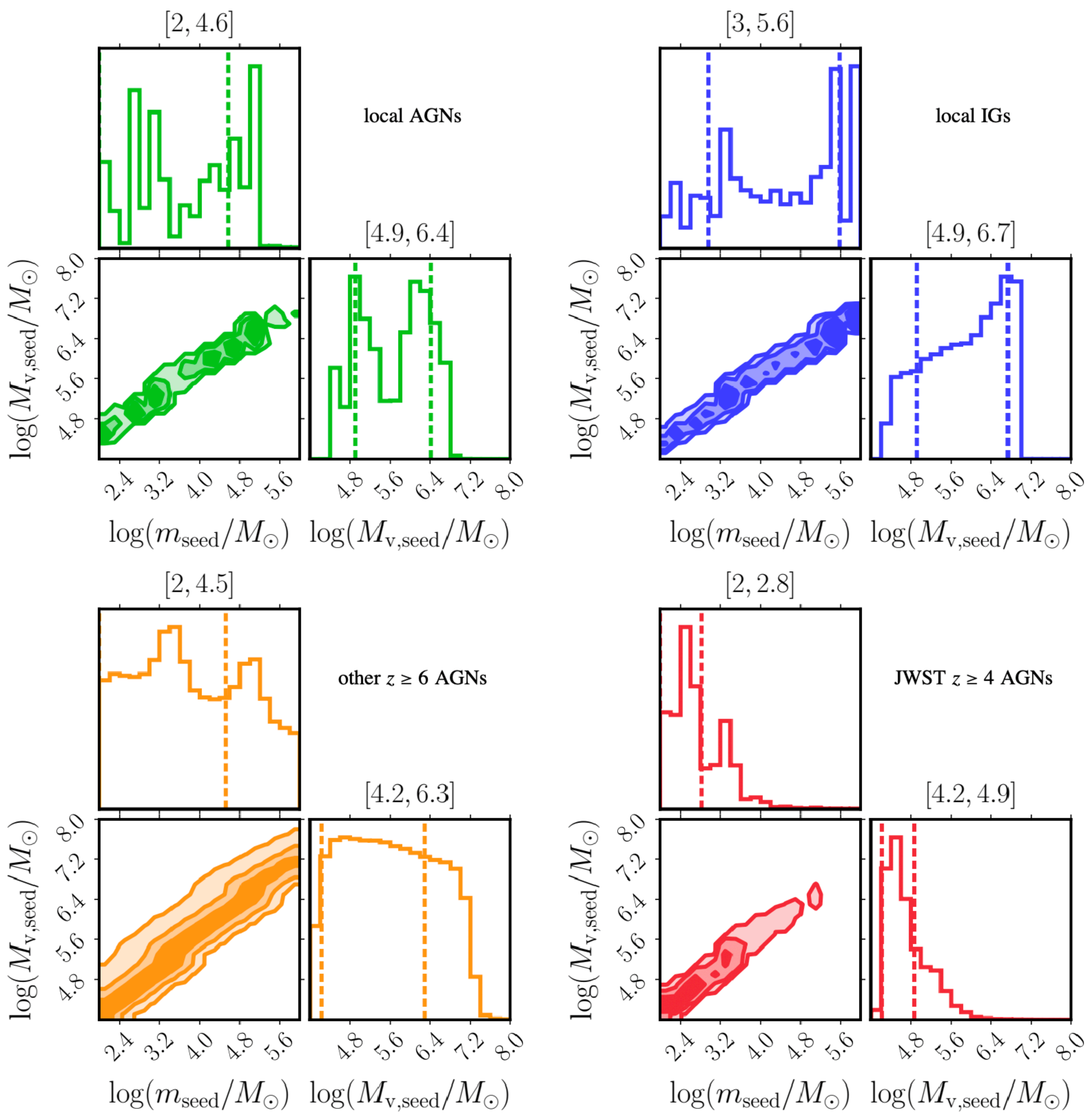
$$\dot{M}_{\rm Edd.}(M_{\rm BH}) = \frac{4\pi G M_{\rm BH} m_p}{\epsilon_r \sigma_T} \approx 2.2\times 10^{-3} m_{\rm BH}(M_{\rm BH})/{\rm Myr}$$

- Sub-Eddington accretion of both hot and cold gas
- a term proportional to the baryon accretion rate and another one proportional to the gas content
- standard practice in SAMs

Results and fits



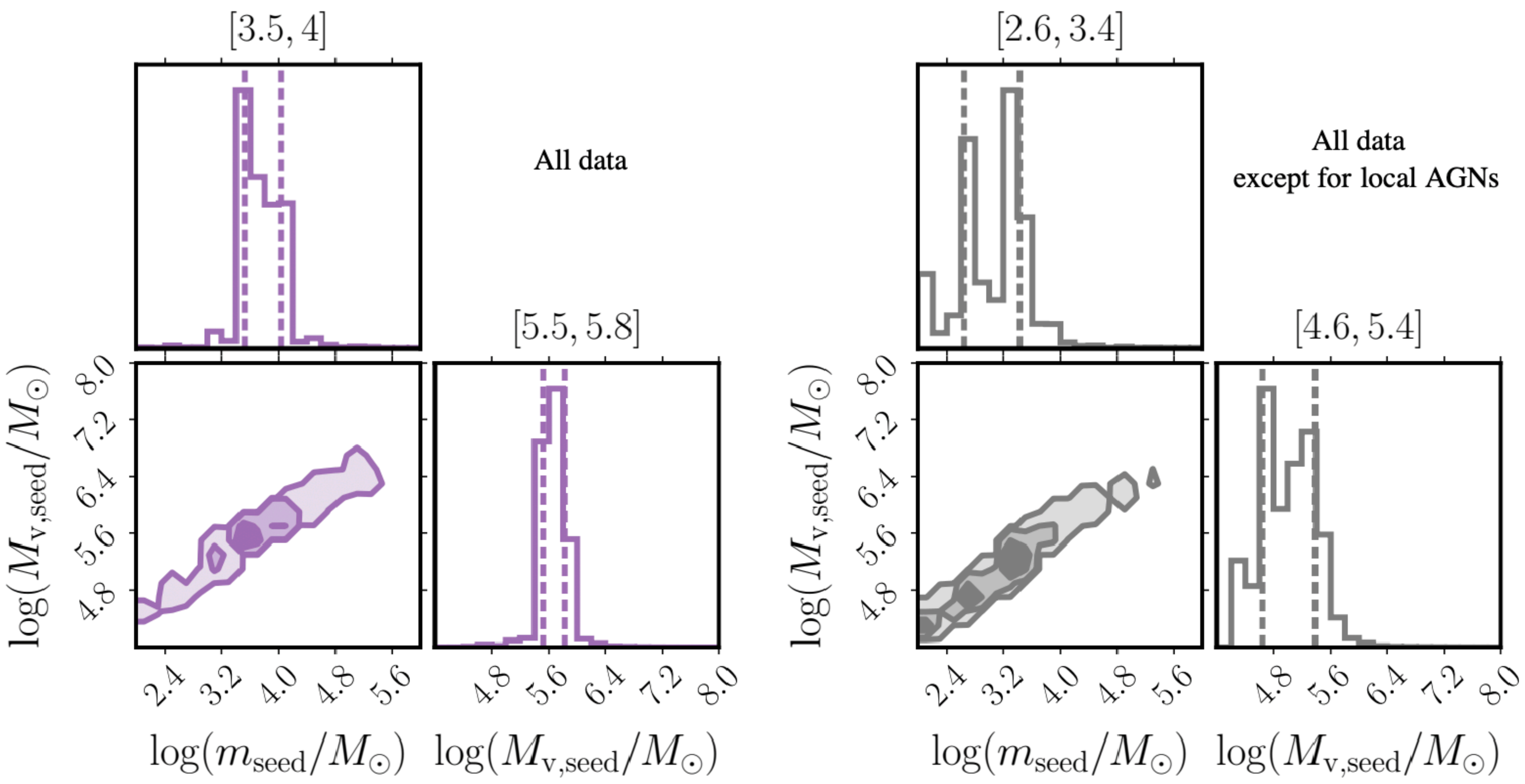
$$\boldsymbol{\theta} = (m_{\rm seed}\,, M_{\rm seed}\,, z_{\rm seed})$$



Results and fits

- All data points to a scaling relation between the BH mass and the halo mass at which these seeds are planted,
- the heaviest SMBH do not constraining seeding
- Local AGNs, (all pre JWST data), points to a heavy seed scenario
- But JWST data strongly prefers light-seed scenario.

Results and fits



- All the data except the local AGNs (gray) is compatible with the light-seed scenario
- To fit to all the data an intermediate scenario is favored (purple)

Shortcoming

- All galactic mergers do not have to induce instantaneous mergers, especially for light halos and SMBH
  - nuclear star clusters around the SMBH can do the work
  - DM only induced can also lead to short timescales although is more uncertain, only $\mathcal{O}(0.1)$ of configurations lead to thigh binaries
- It has been suggested that JWST observations, which are x-ray opaque, might be because they are accreting at super-Eddington rate, which implies lighter SMBH
- The implications of this will be explored in the arXiv version!