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Formation of early galaxies and supermassive black holes

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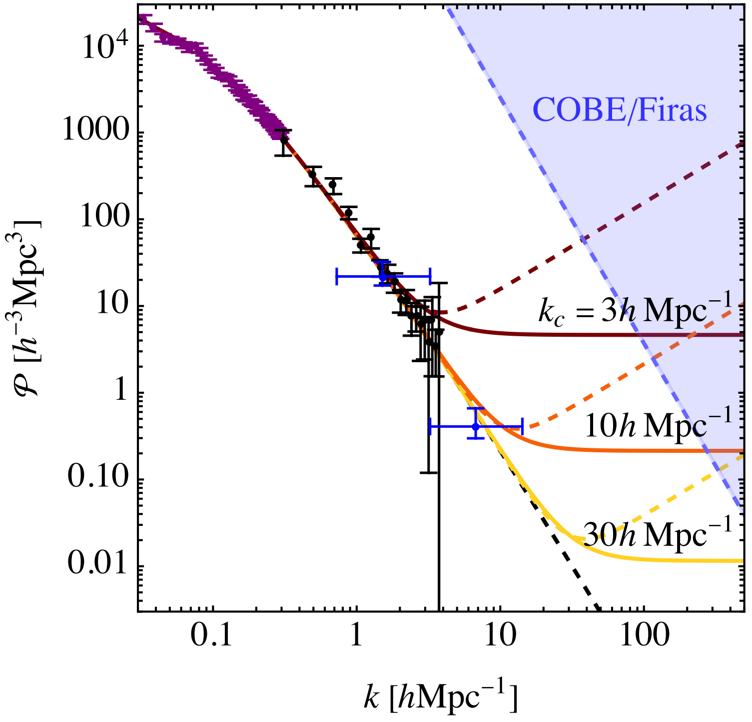
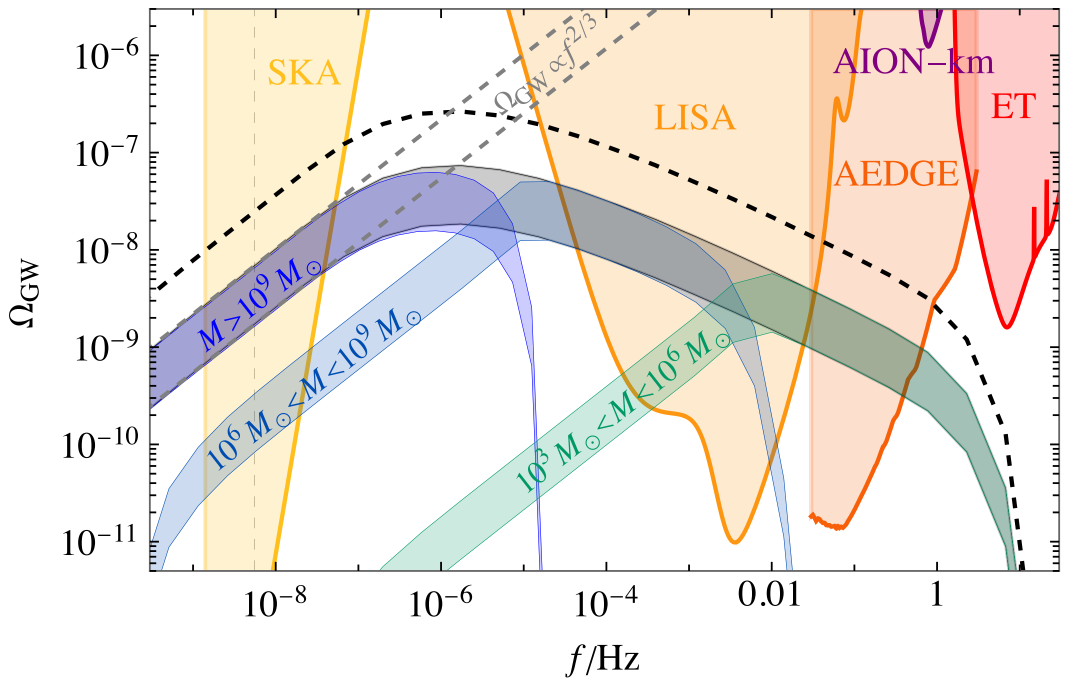
Warsaw, January 24, 2022.

1. James Webb Space Telescope



2. Pulsar timing arrays



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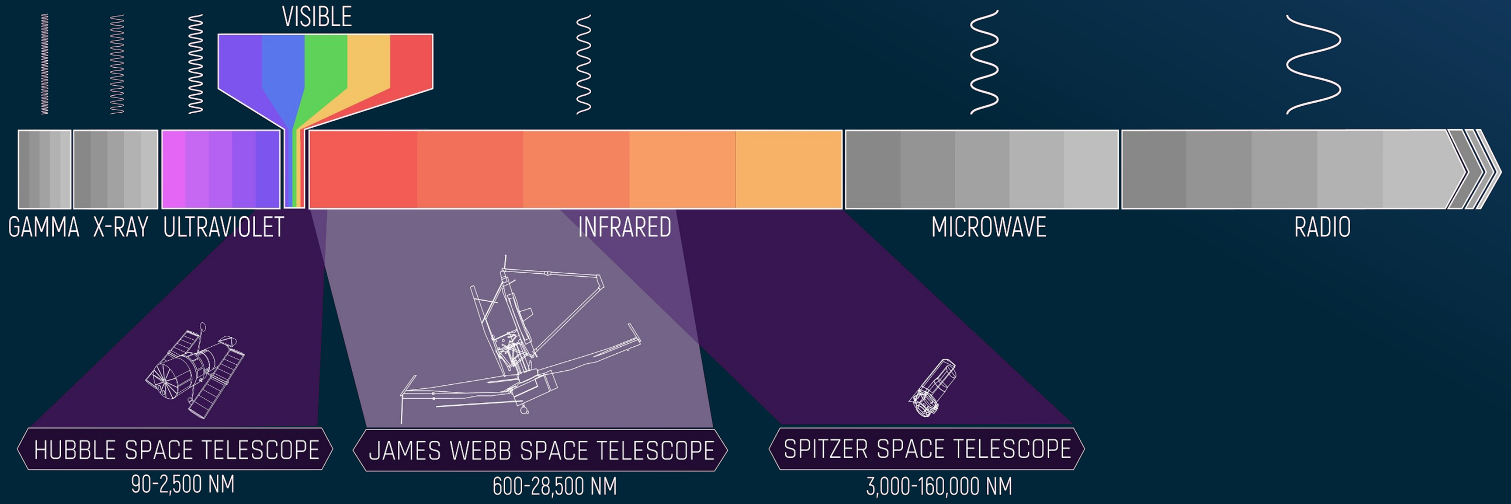
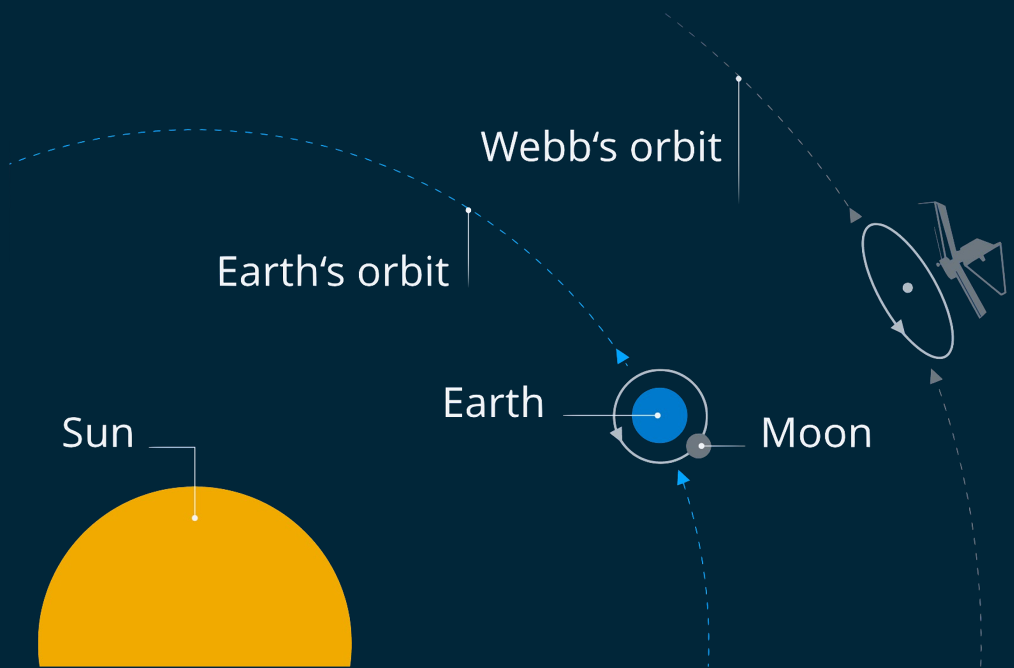
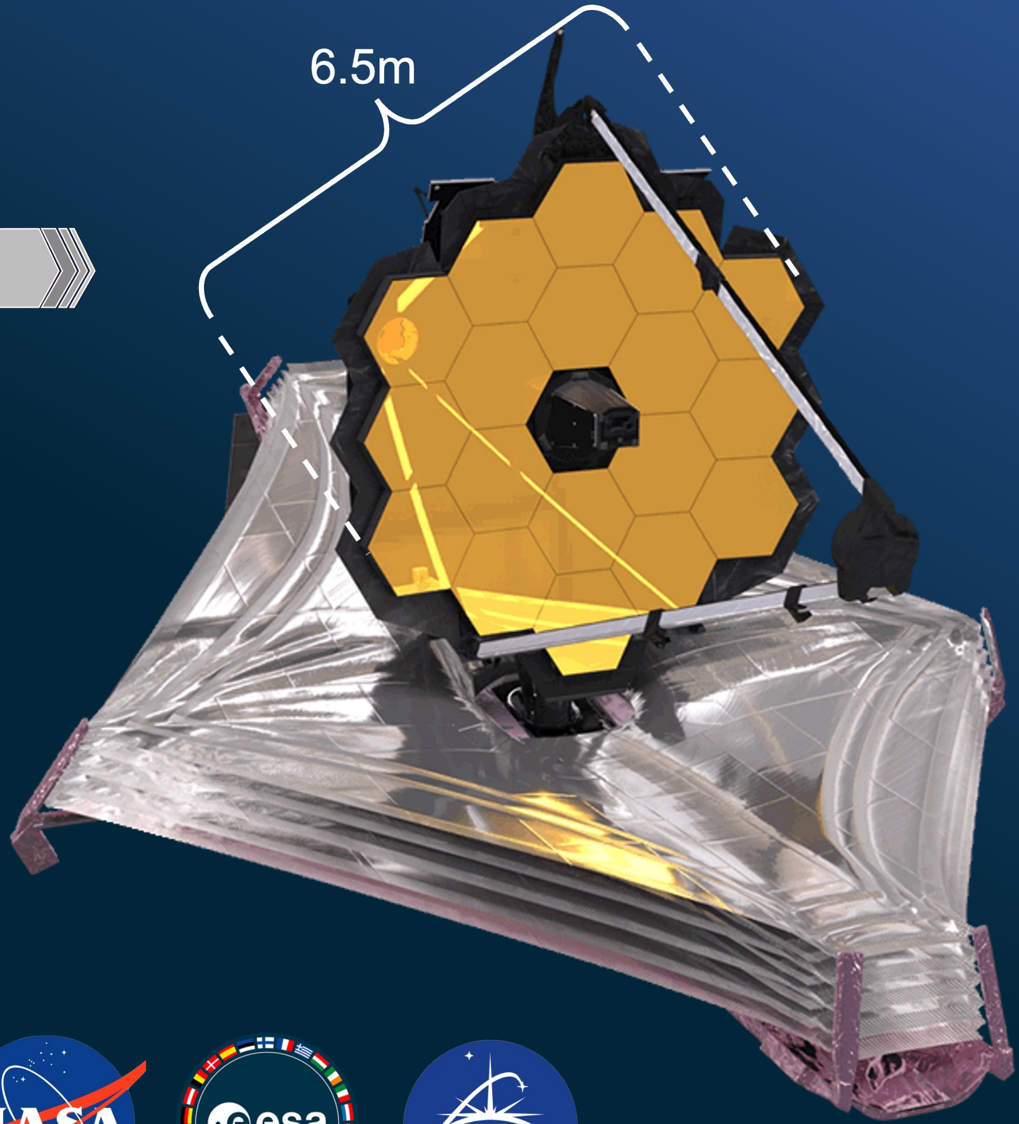
James Webb Space Telescope

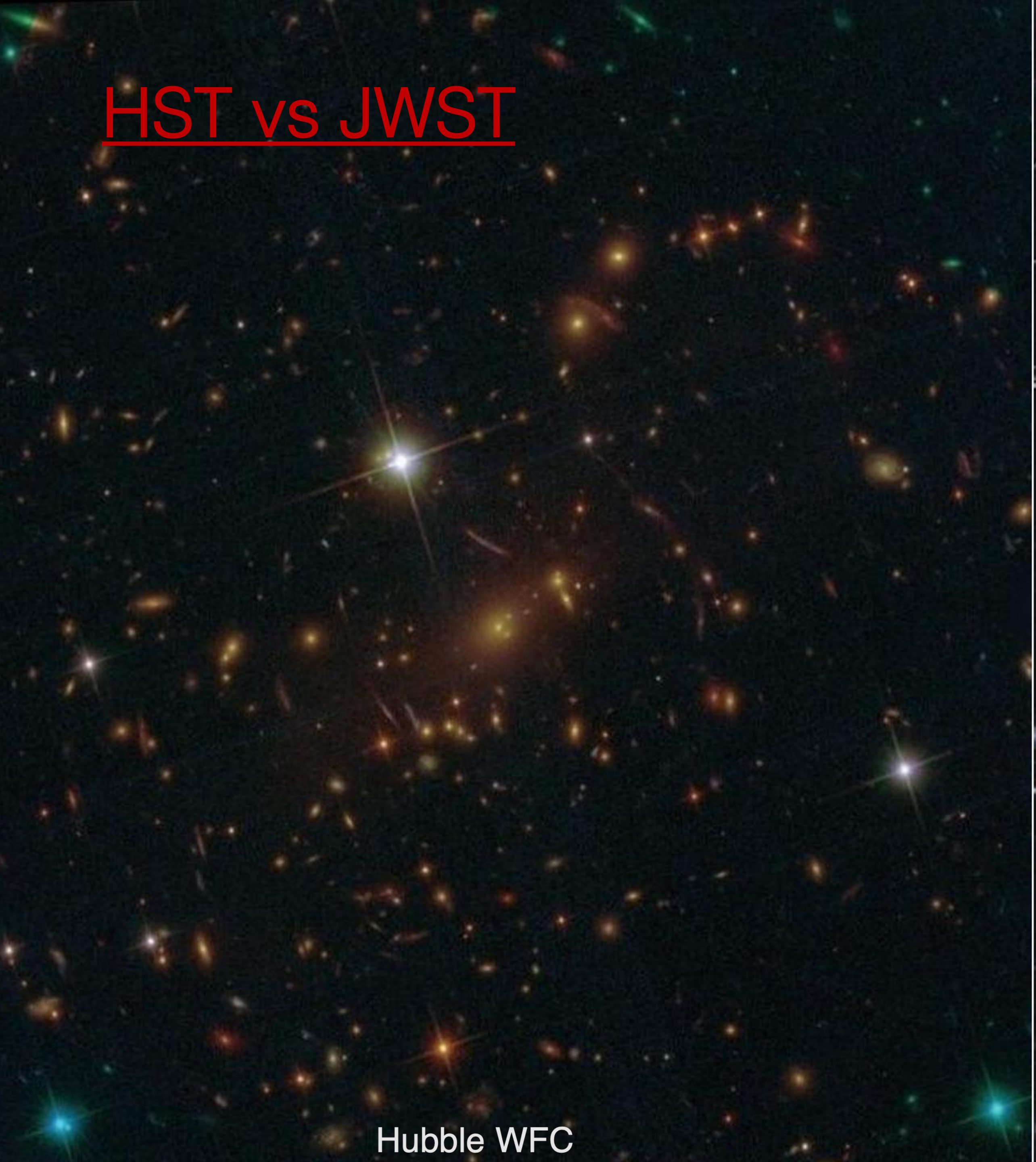
James Webb Space Telescope







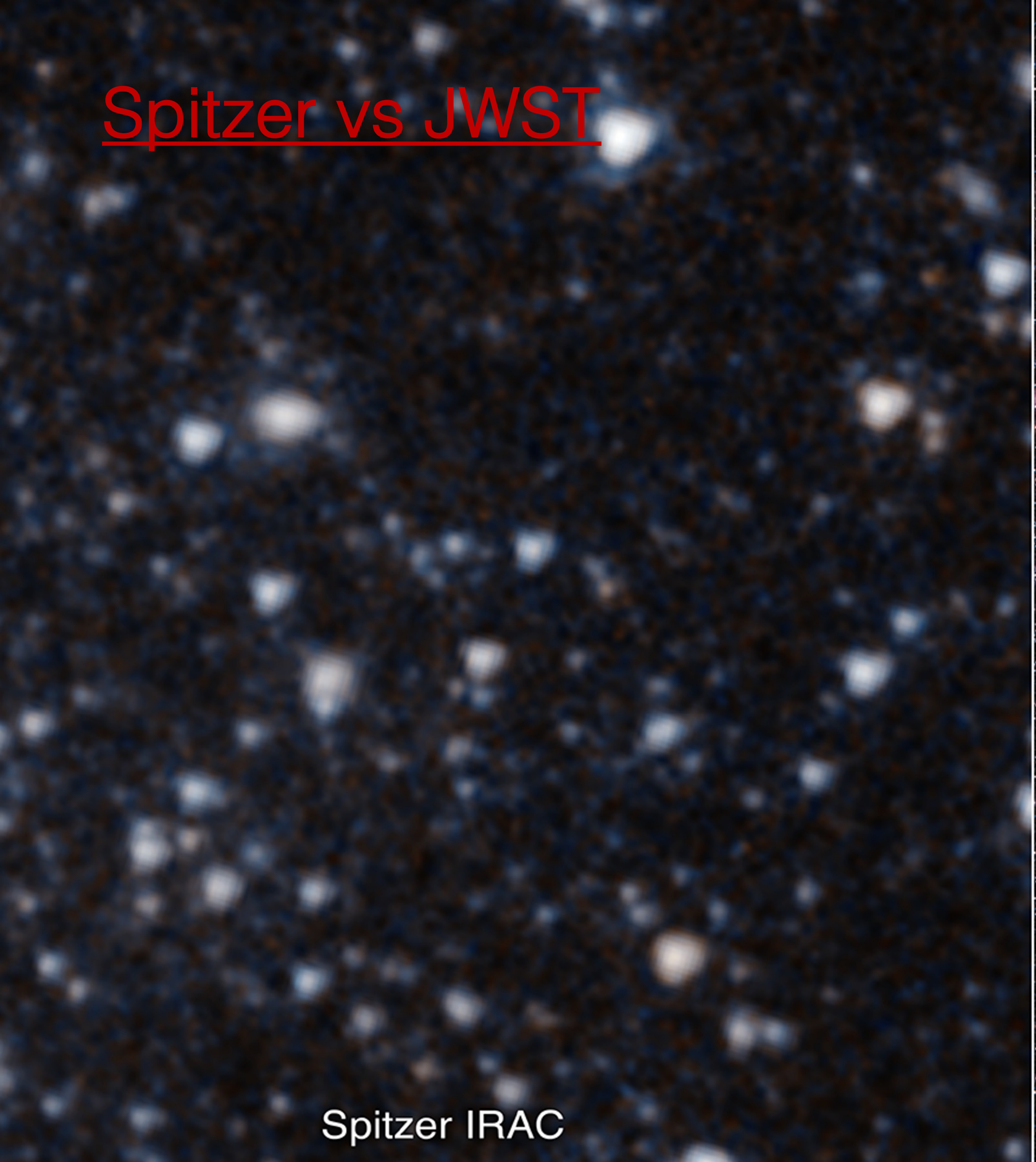
HST vs JWST



Hubble WFC

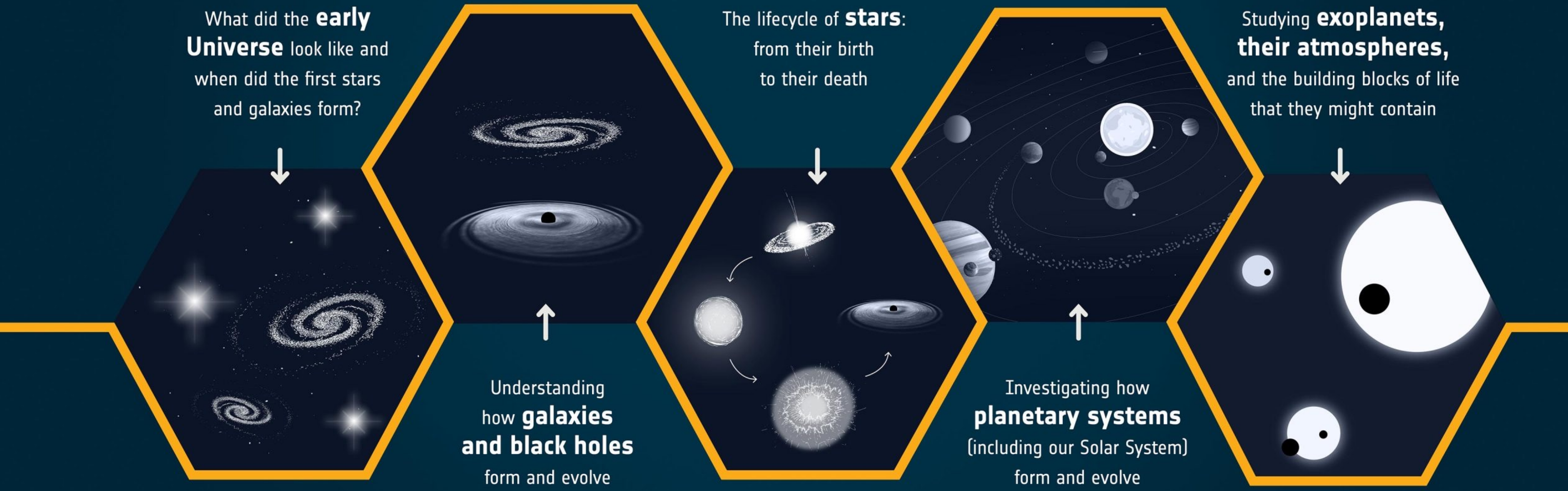
Webb NIRCam

Spitzer vs JWST



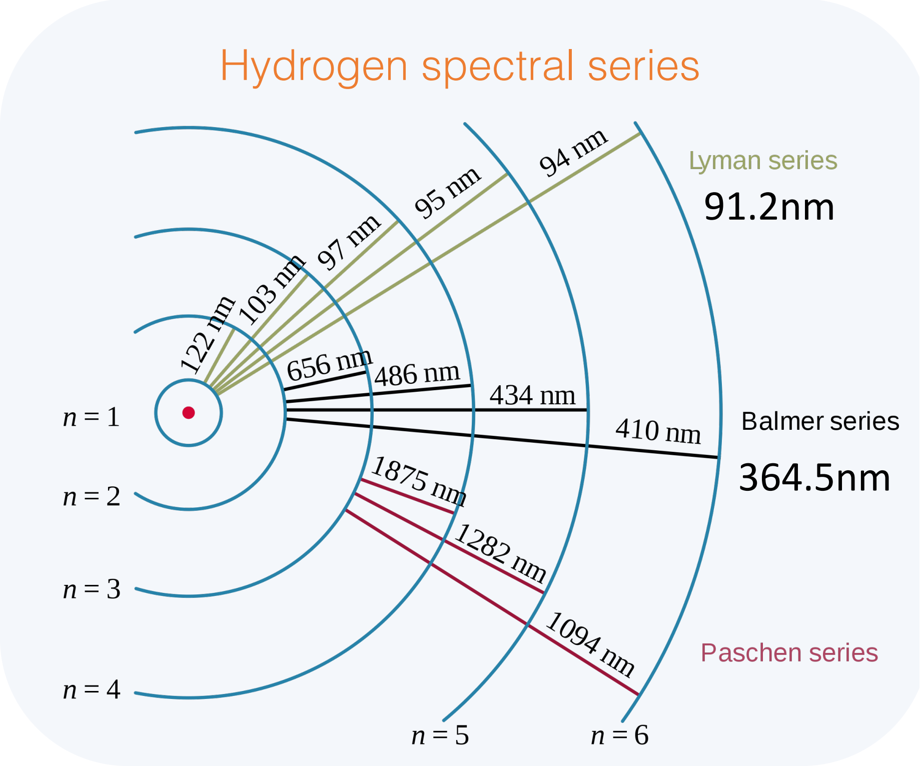
JWST science

Webb is designed to answer outstanding questions about the Universe and to make breakthrough discoveries in all fields of astronomy.

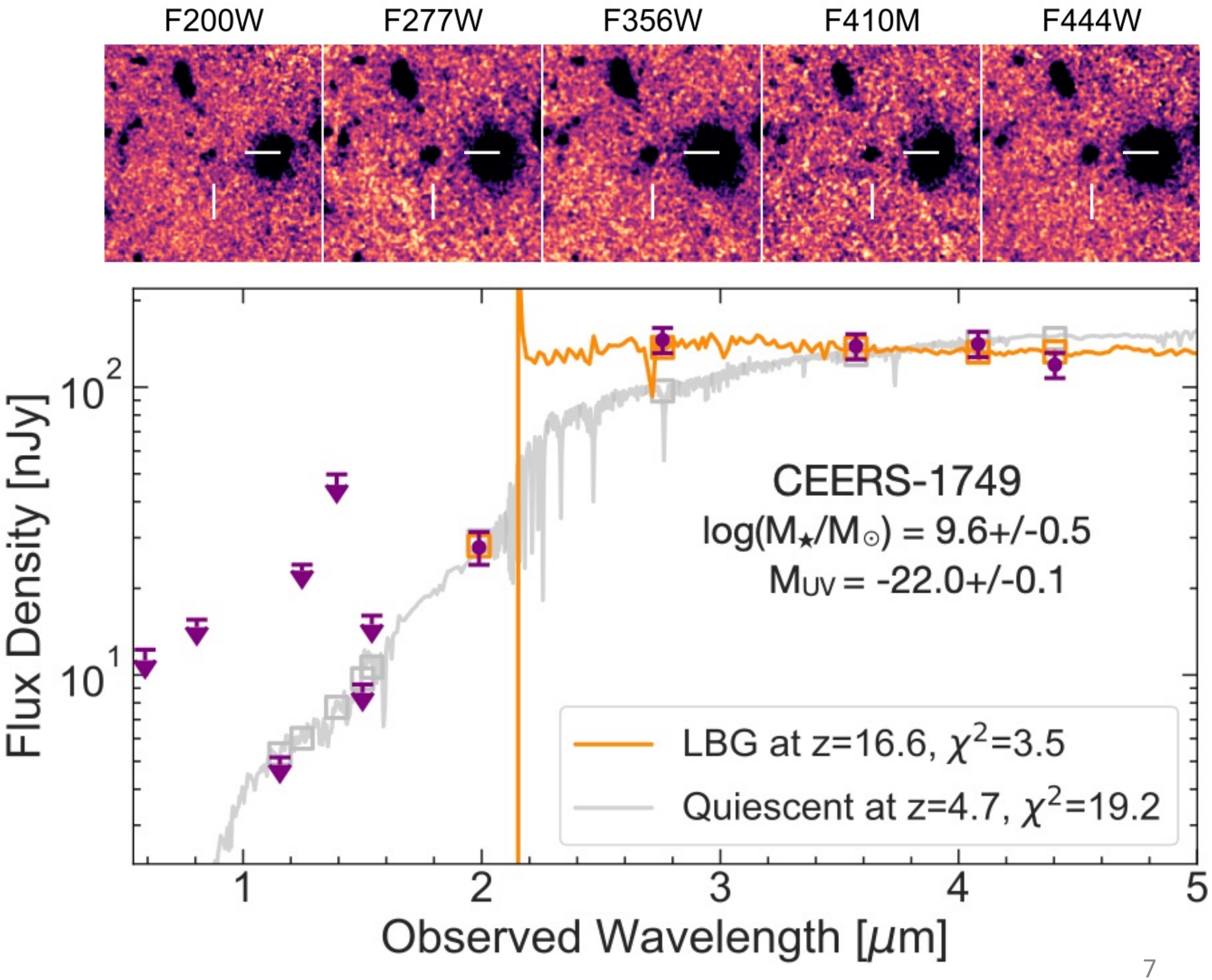


Searches for luminous early galaxies

1. Observed wavelength of the Lyman or Balmer break determintes the redshift.
2. Observed amplitude after the break determines the stellar mass.

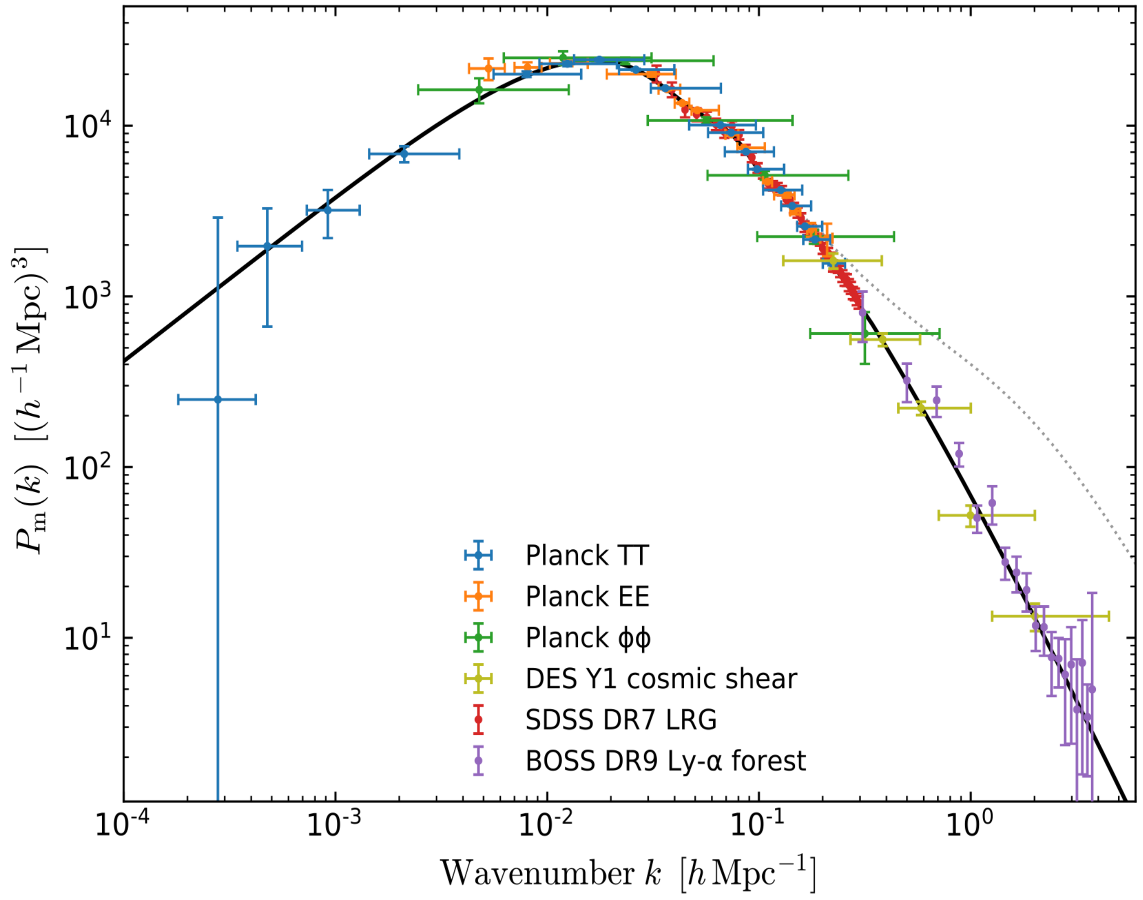


Naidu et. al., arXiv:2208.02794



How heavy galaxies do we expect at high-*z* ?

LCDM matter power spectrum:



matter power spectrum

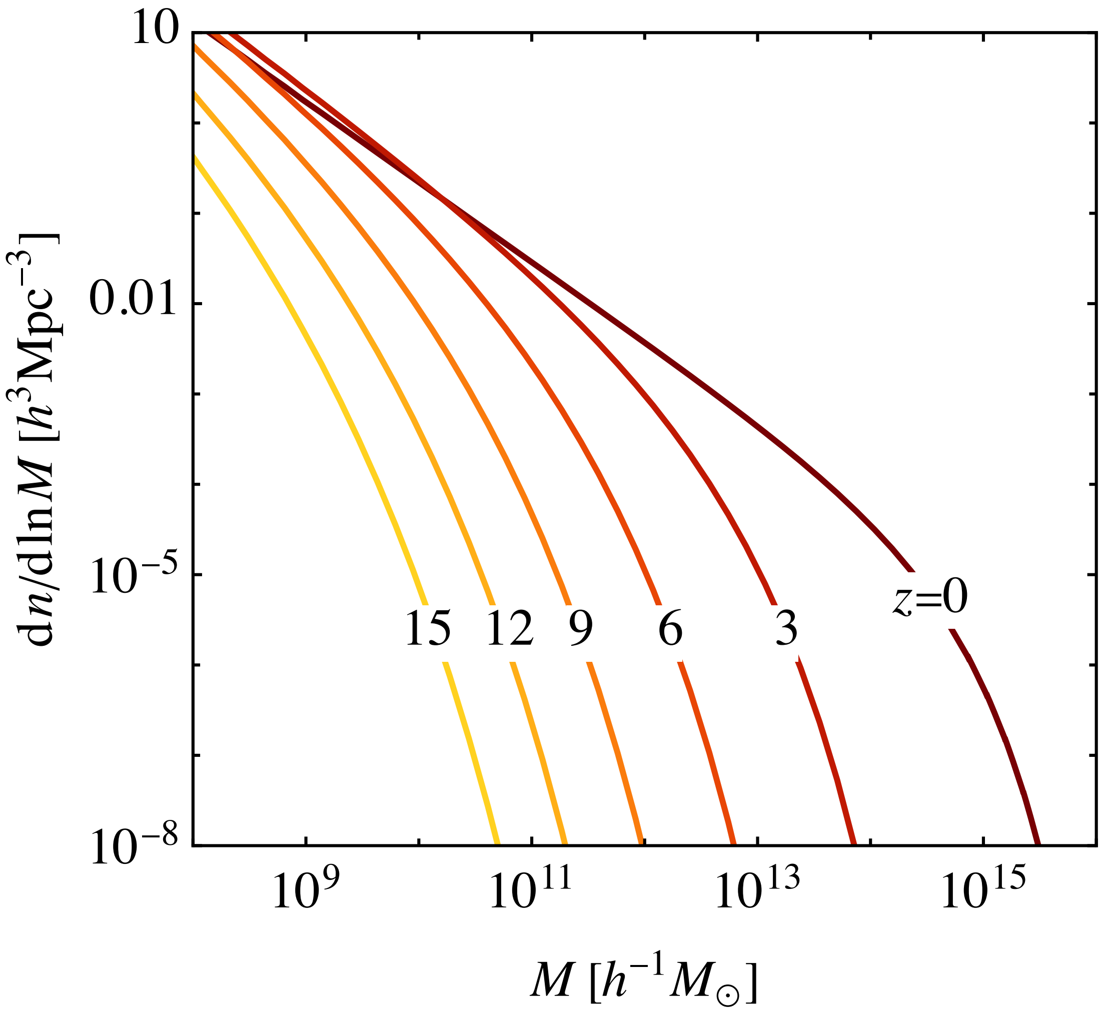
$$\sigma_M^2 = \frac{1}{2\pi^2}\int \mathrm{d}k\, k^2 \mathcal{P}(k) W^2(kR)\Big|_{R=R(M)}$$

halo mass function

$$\frac{\mathrm{d}n}{\mathrm{d}\ln M} = \frac{\rho_m}{M}\nu f(\nu)\frac{\mathrm{d}\nu}{\mathrm{d}\ln M}\,, \qquad \nu \equiv \frac{\delta_c^2}{\sigma_M^2}$$

How heavy galaxies do we expect at high-z ?

LCDM halo mass function:



expected number of galaxies

$$N = f_{\rm sky} \int_{z_{\rm min}}^{z_{\rm max}} dz \frac{dV_c}{dz} \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM}$$

stellar mass

$$M_* \simeq f_* \frac{\Omega_b}{\Omega_m} M \,, \quad f_* \leq 1$$

<u>CEERS-1749</u>

$$f_{\rm sky} = 2.7 \times 10^{-7}\ (40 \mathrm{arcmin}^2)$$

$$z_{\rm min} = 15$$

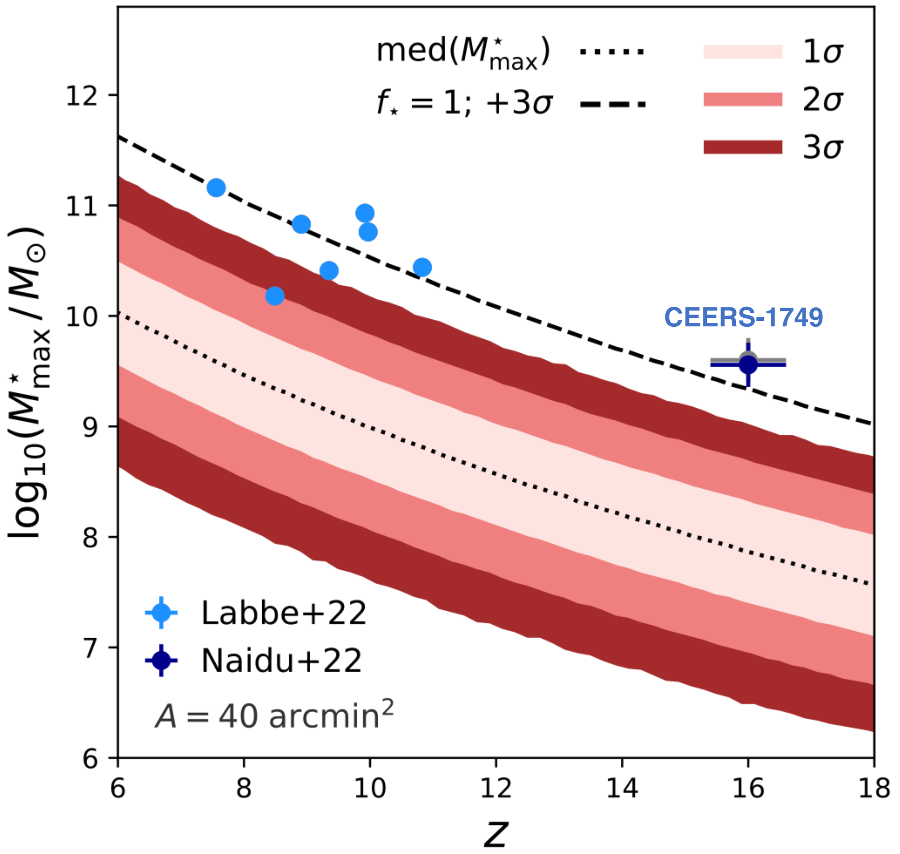
$$M_{\rm min} = 2.4 \times 10^{11} M_\odot$$

$$\Longrightarrow \quad N \sim 10^{-7} \ll 1 \,.$$

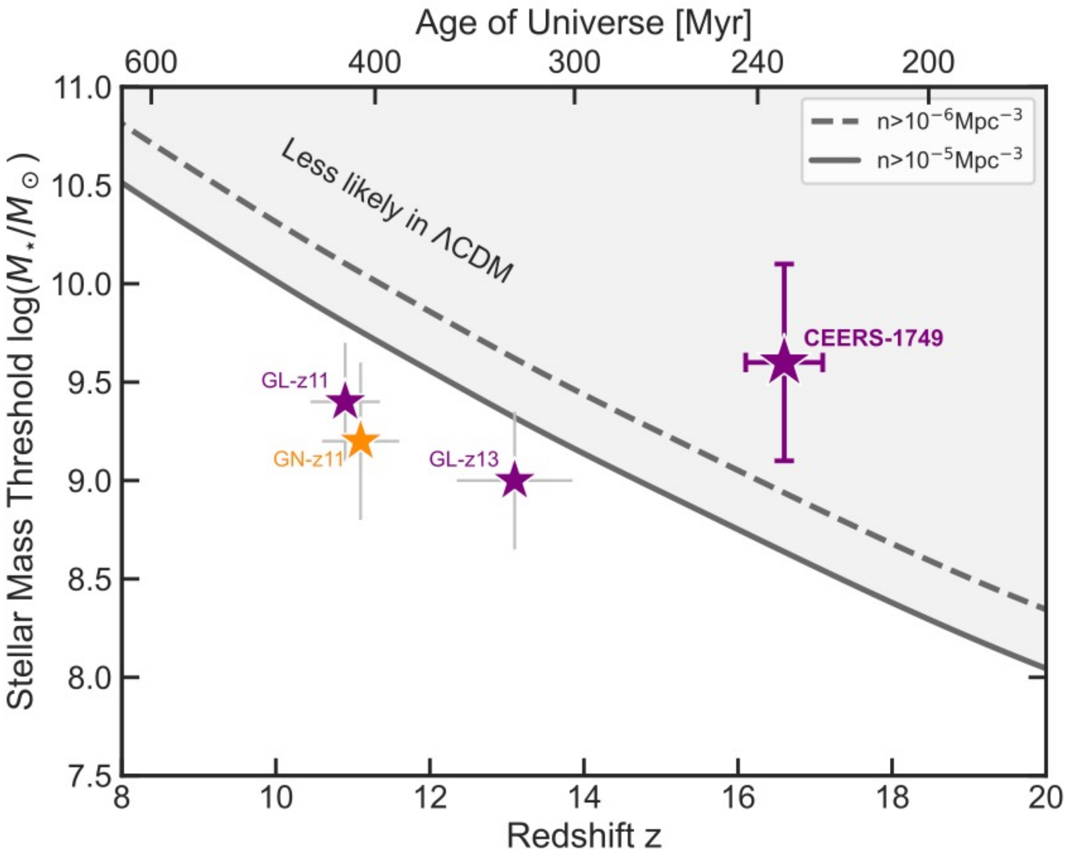
Tension with LCDM

Even for $f_* = 1$ the observations indicate $> 3\sigma$ tension when compared to LCDM:

Lovell et. al., arXiv:2208.10479



Naidu et. al., arXiv:2208.02794



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New physics explanations

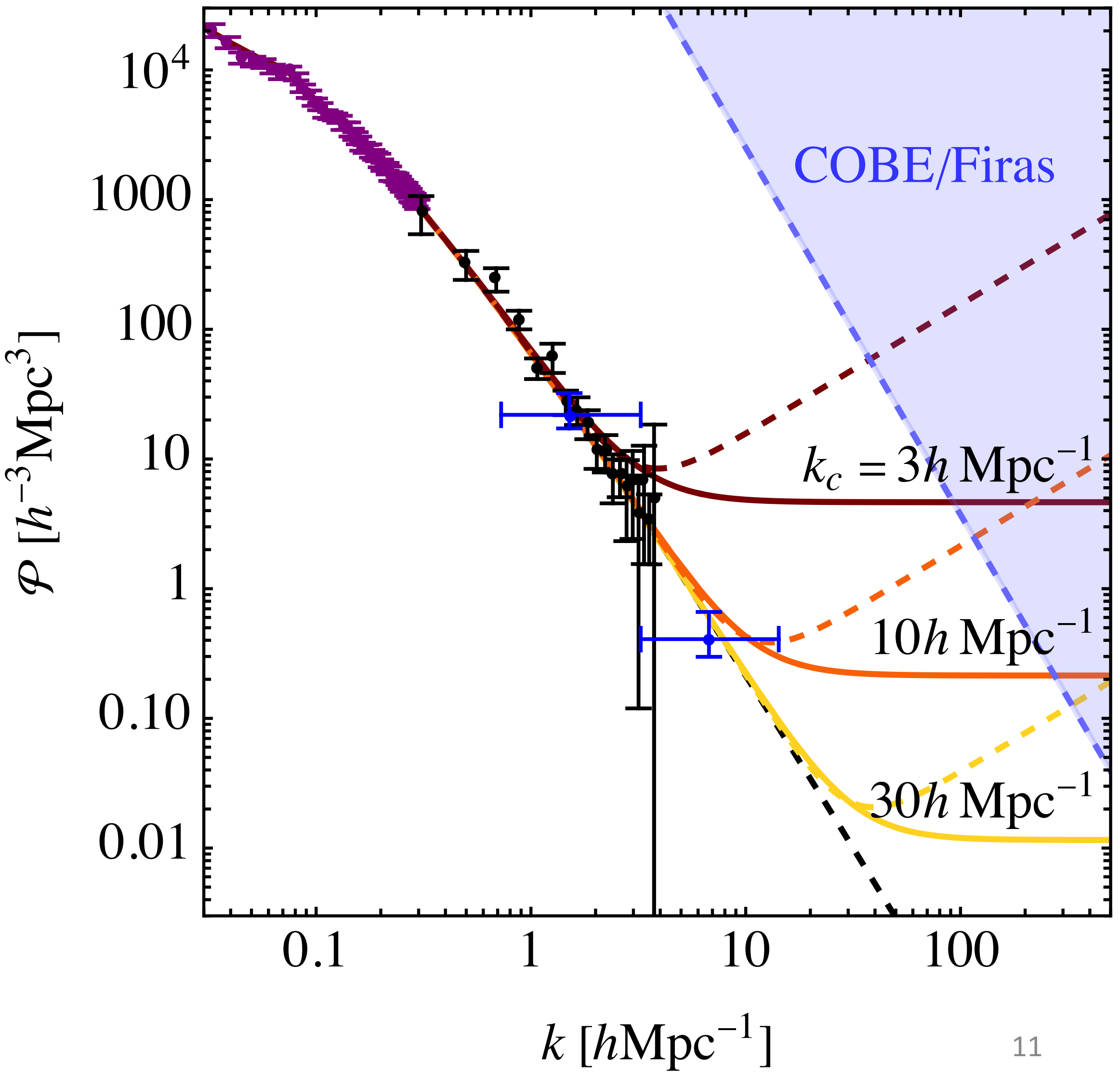
Hütsi, et. al. arXiv: 2211.02651 (to appear in PRD)

enhanced matter power spectrum at $k = \mathcal{O}(10)h\mathrm{kpc}^{-1}$

$$\mathcal{P}(k) = \mathcal{P}_{\mathrm{CDM}}(k) + \mathcal{P}_{\mathrm{CDM}}(k_c)\left(\frac{k}{k_c}\right)^n$$

enhanced halo mass function at $M < 10^{11} M_\odot$

more heavy high-z galaxies



1. Axion miniclusters

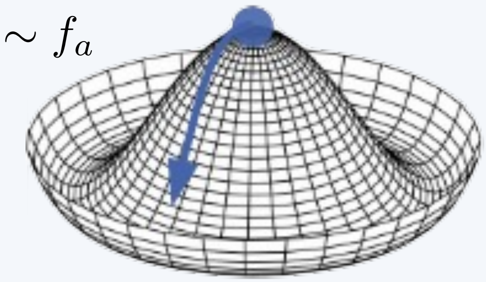
Axion = pNG boson of Peccei-Quinn symmetry:

$$V(\phi) = \frac{\lambda}{4!}\left(|\phi|^2 - \frac{f_a^2}{2}\right)^2 \qquad \Longrightarrow \text{ after SSB:} \qquad \phi = \frac{f_a}{\sqrt{2}}\, e^{ia/f_a}$$

If the PQ symmetry breaks after inflation the axion field acquires large fluctuations that lead to the formation of axion miniclusters [E. W. Kolb and I. I. Tkachev, Phys. Rev. Lett. 71 (1993)]:

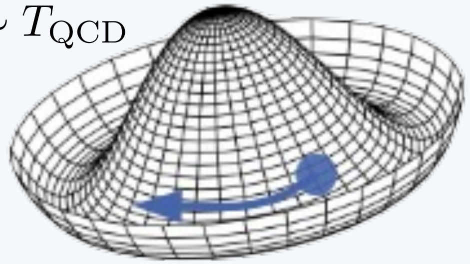
PQ symmetry breaking:
$0 \leq \theta_a < 2\pi$.

$T \sim f_a$



QCD effects break the rotational symmetry:

$T \sim T_{\rm QCD}$



White noise fluctuations for the axion field:

$$n = 0$$

$$k_c = 3h\mathrm{Mpc}^{-1}\left(\frac{m_a}{10^{-18}\mathrm{eV}}\right)^{0.6}$$

$$k_{\rm cut} = 300\mathrm{Mpc}^{-1}\sqrt{\frac{m_a}{10^{-18}\mathrm{eV}}}$$

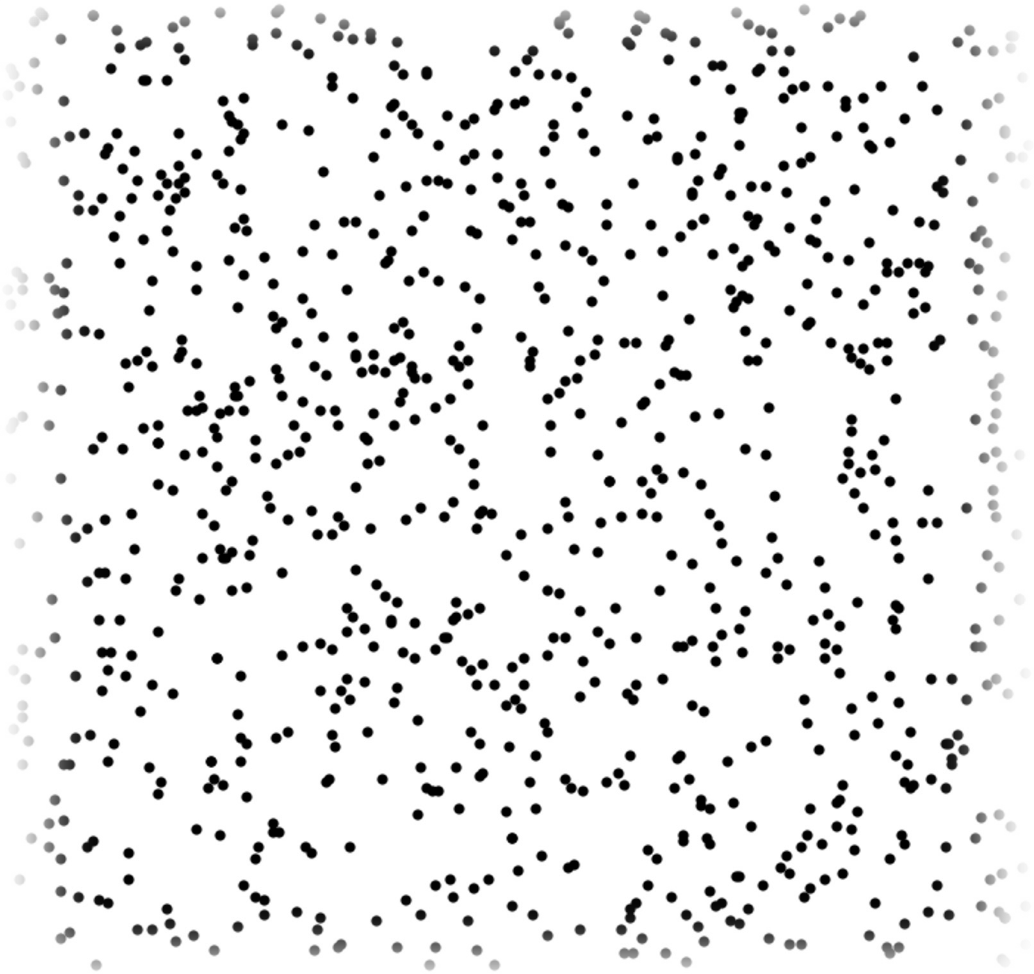
2. Primordial black holes

On small scales the random locations of PBH introduces a shot noise, $n = 0$, in their density:

$$k_c = 6h\text{Mpc}^{-1}\left(\frac{f_{\text{PBH}}m_{\text{PBH}}}{10^4 M_\odot}\right)^{-0.4}$$

with a cut given by the average PBH separation:

$$k_{\text{cut}} = 900h\text{Mpc}^{-1}\left(\frac{f_{\text{PBH}}10^4 M_\odot}{m_{\text{PBH}}}\right)^{1/3}$$



$$k_c < k_{\text{cut}} \quad \text{if} \quad f_{\text{PBH}} > 10^{-4}(m_{\text{PBH}}/10^4 M_\odot)^{-0.09}$$

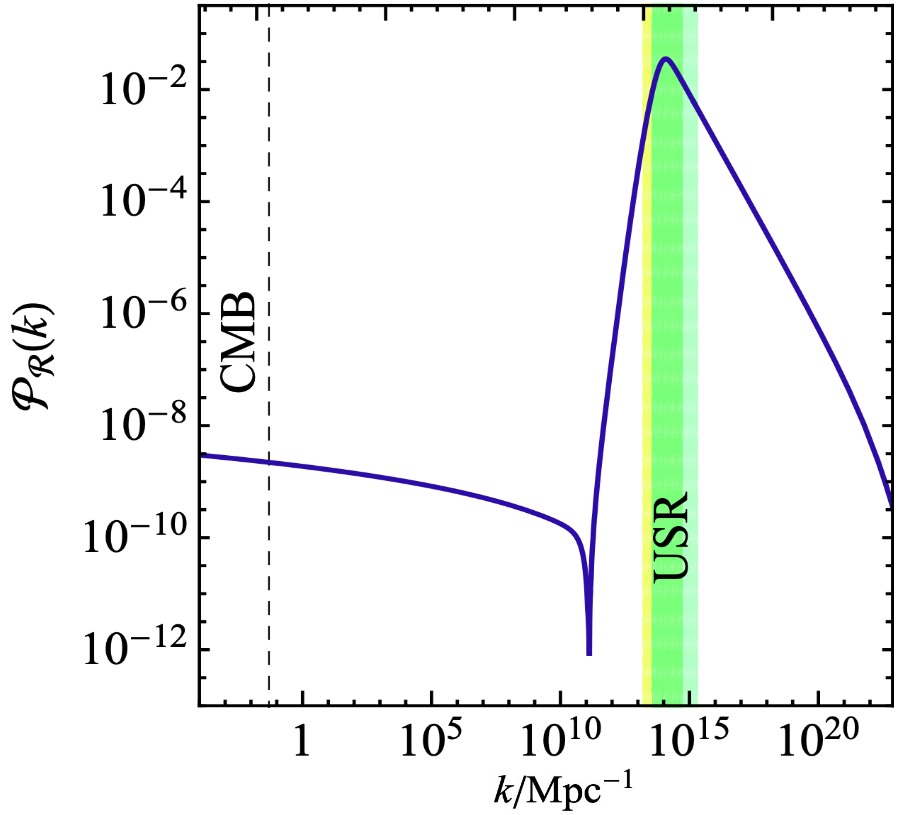
$\Longrightarrow$ excluded by accretion constraints on PBHs.

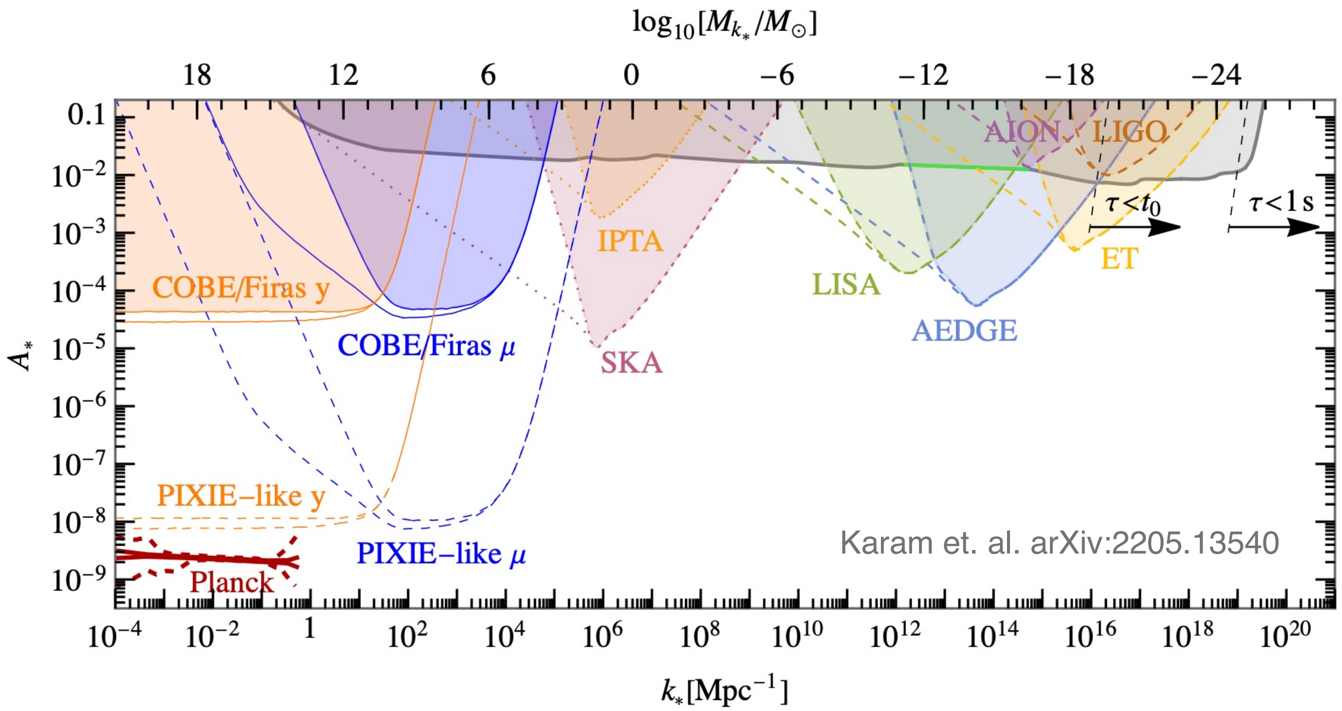
However, this can be achieved also from PBHs formed in dense clusters.

3. Primordial curvature fluctuations

- Features in the inflaton potential can lead to enhanced curvature fluctuations at small scales.
- $n > 0$
- Adiabatic fluctuations $\Longrightarrow$ strong constraints from CMB distortions

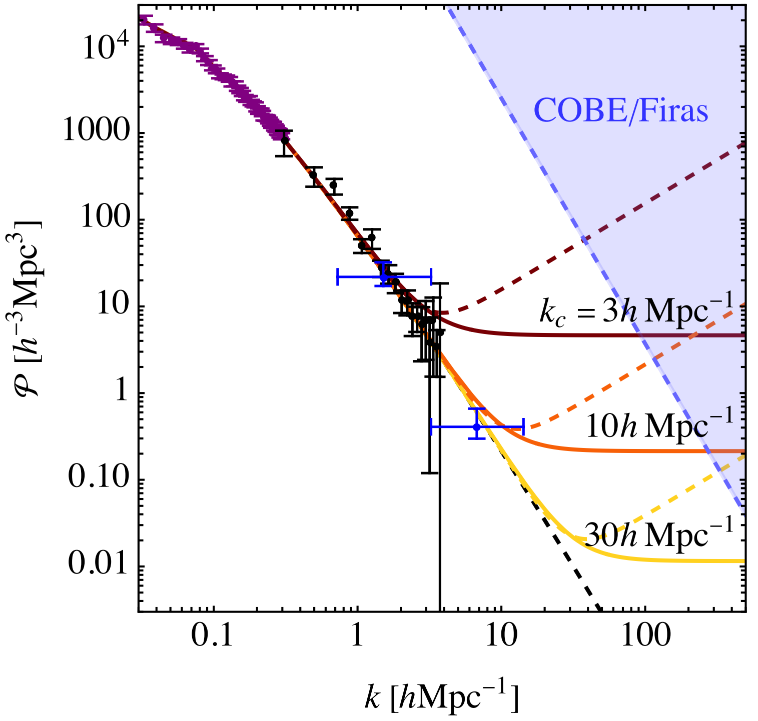
Karam et. al. arXiv:2205.13540

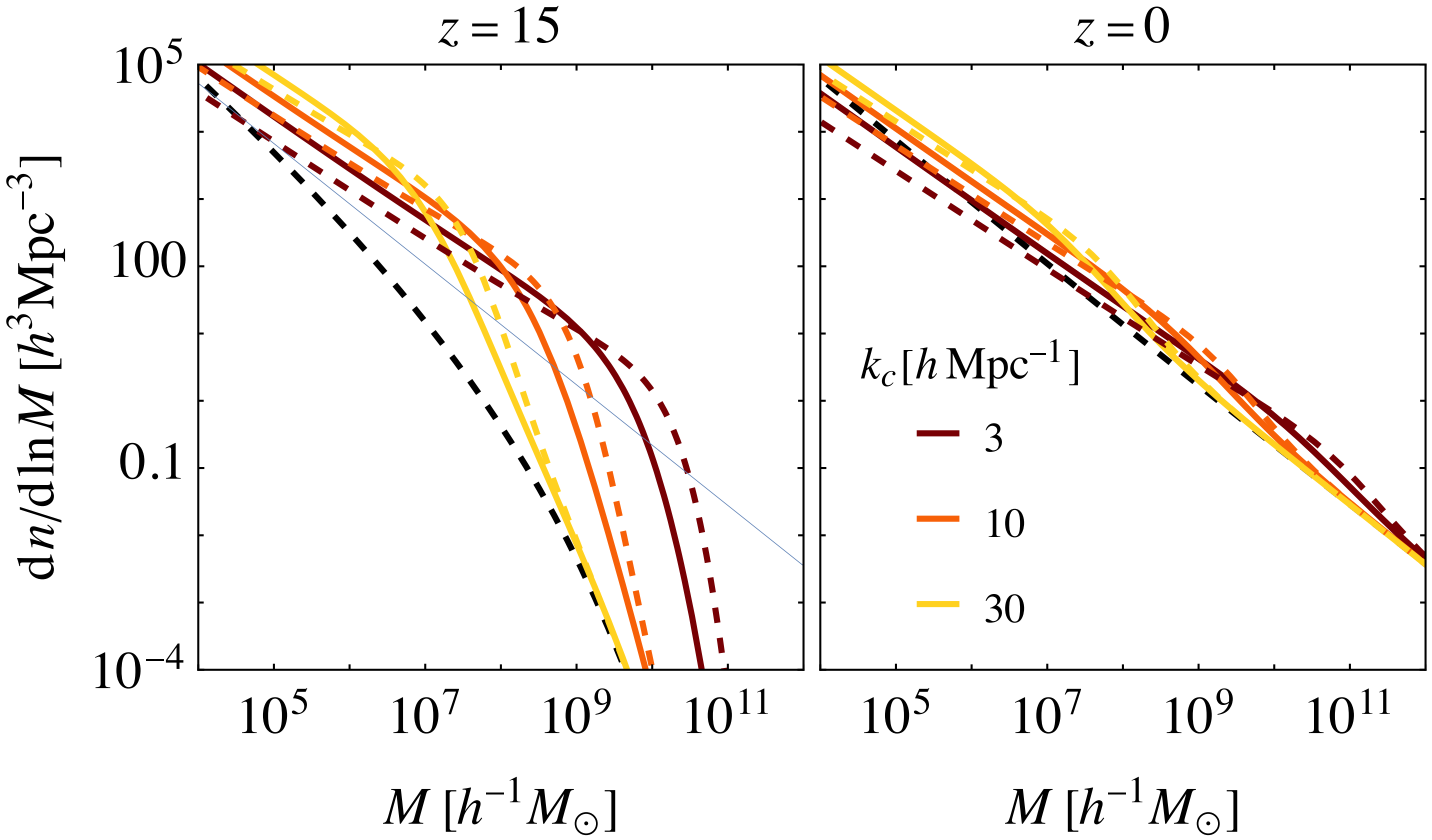




Halo mass function

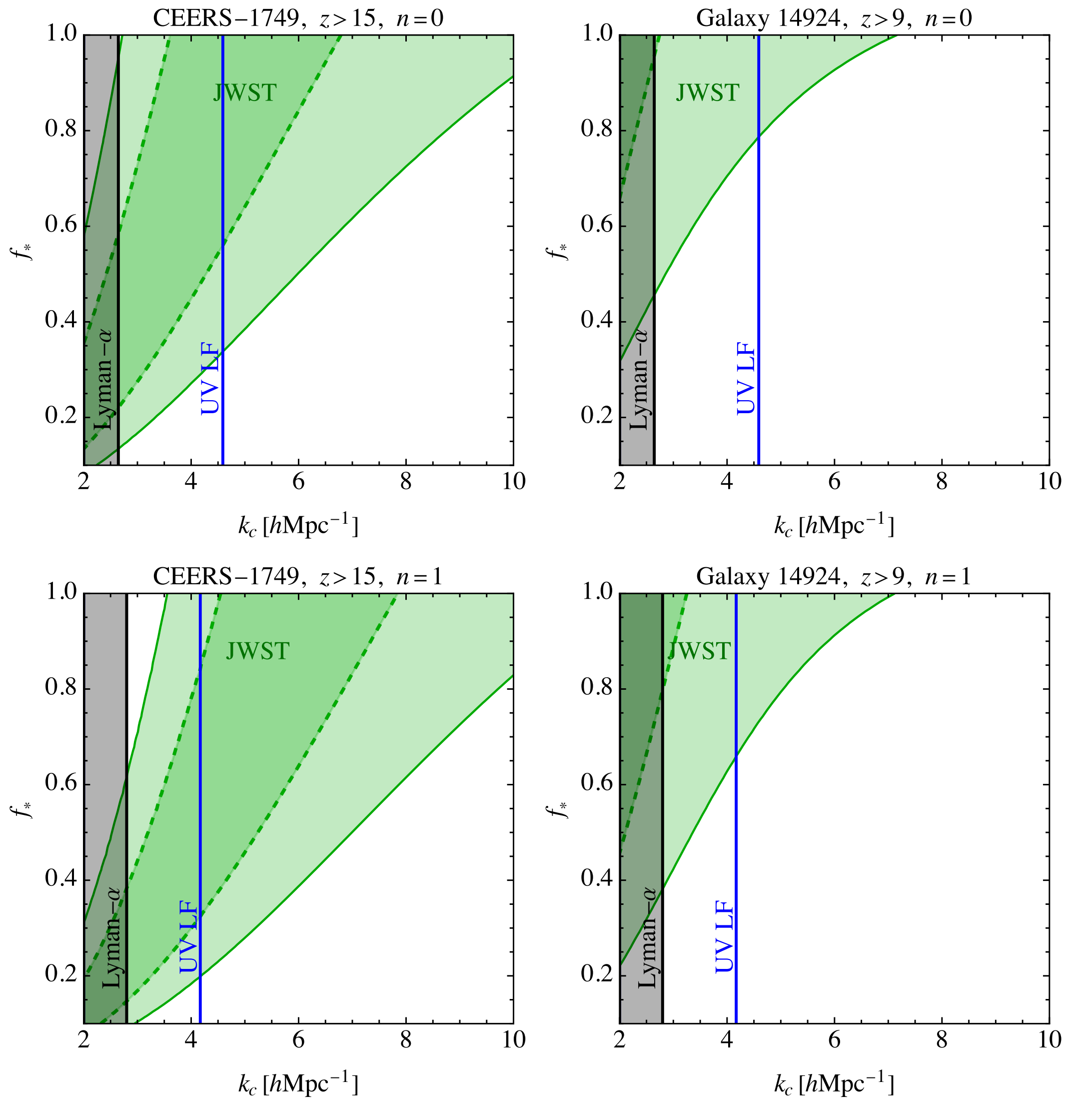
Hütsi, et. al. arXiv: 2211.02651





Results

Hütsi, et. al. arXiv: 2211.02651



1. **axion miniclusters:** $m_a \sim 10^{-18}\mathrm{eV}$, excluded by BH superradiance constraints,
2. **PBHs:** works if 0.5% of all DM is in PBH clusters of mass $\sim 10^6 M_\odot$,
3. **primordial curvature fluctuations:** steeply growing curvature power spectrum that terminates below the CMB distortion constraints.

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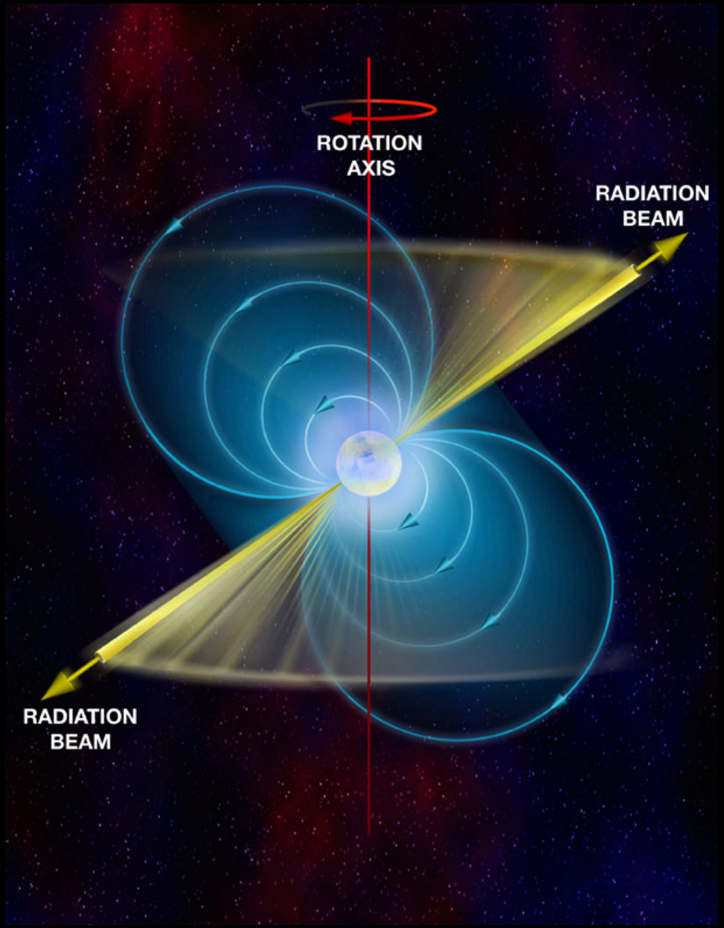
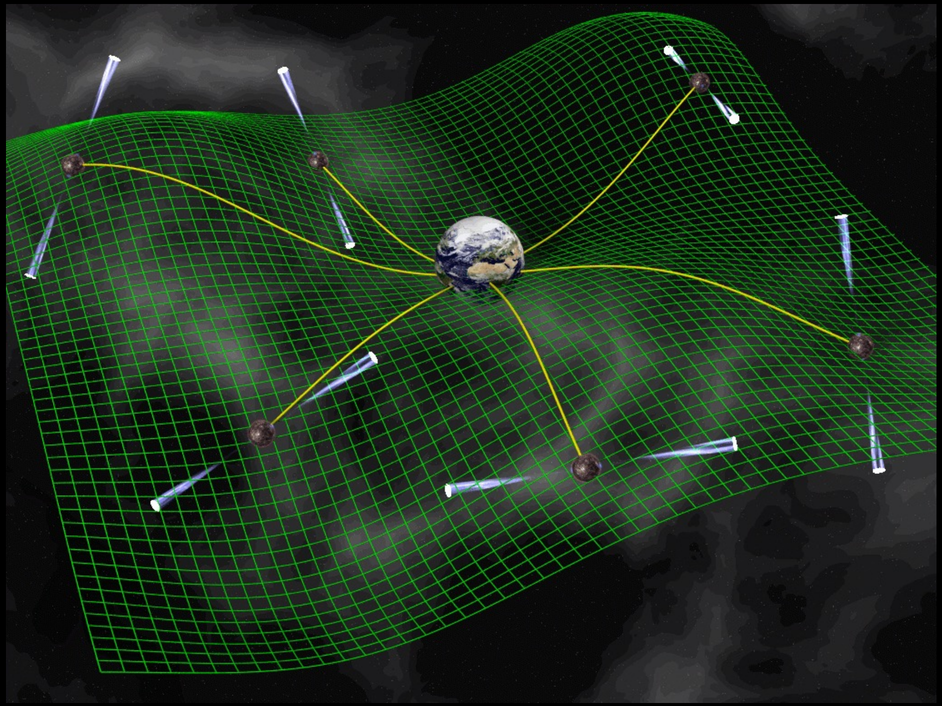
Pulsar timing arrays

Pulsar timing arrays

Millisecond pulsars are rapidly rotating neutron stars:

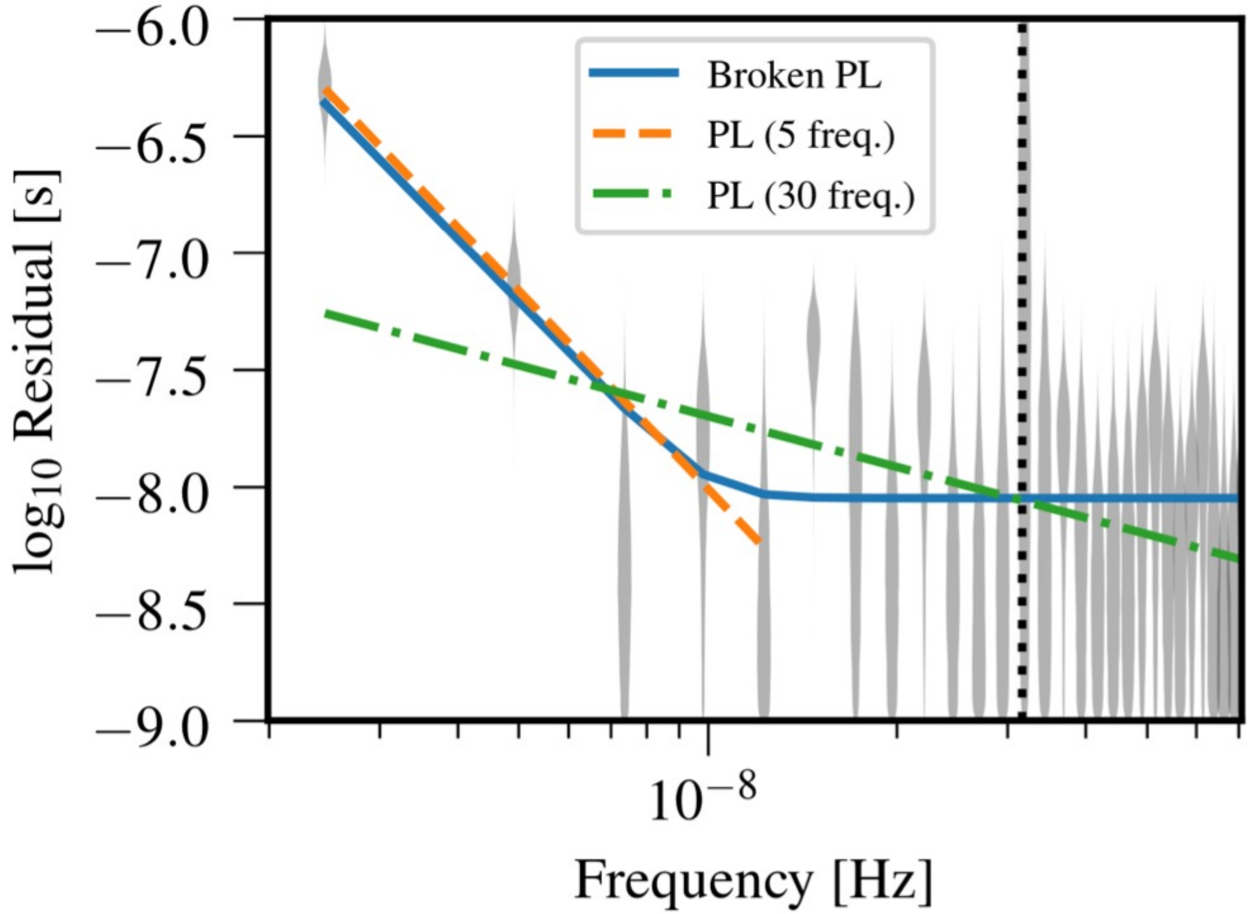


- NANOGrav, EPTA, IPTA…
- Analyze the pulsar timing sequences from a set of millisecond pulsars.
- Gravitational waves induce variations in the timing.

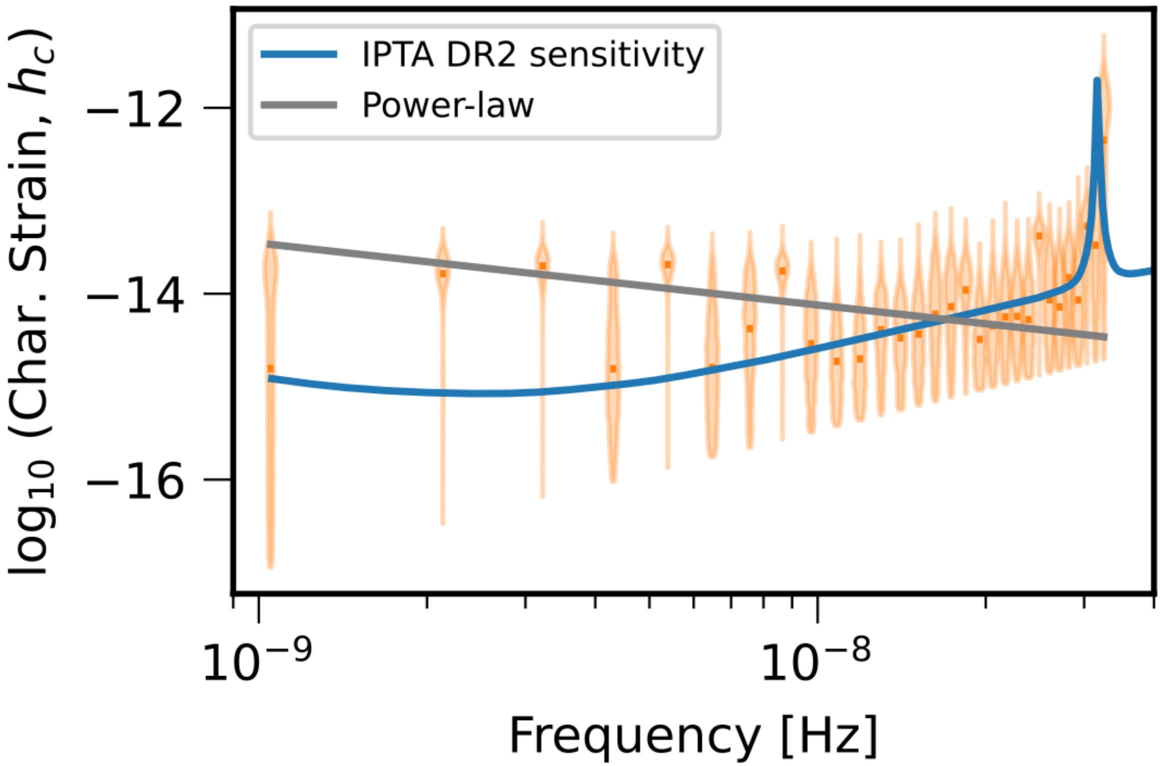


NANOGrav 2020 discovery

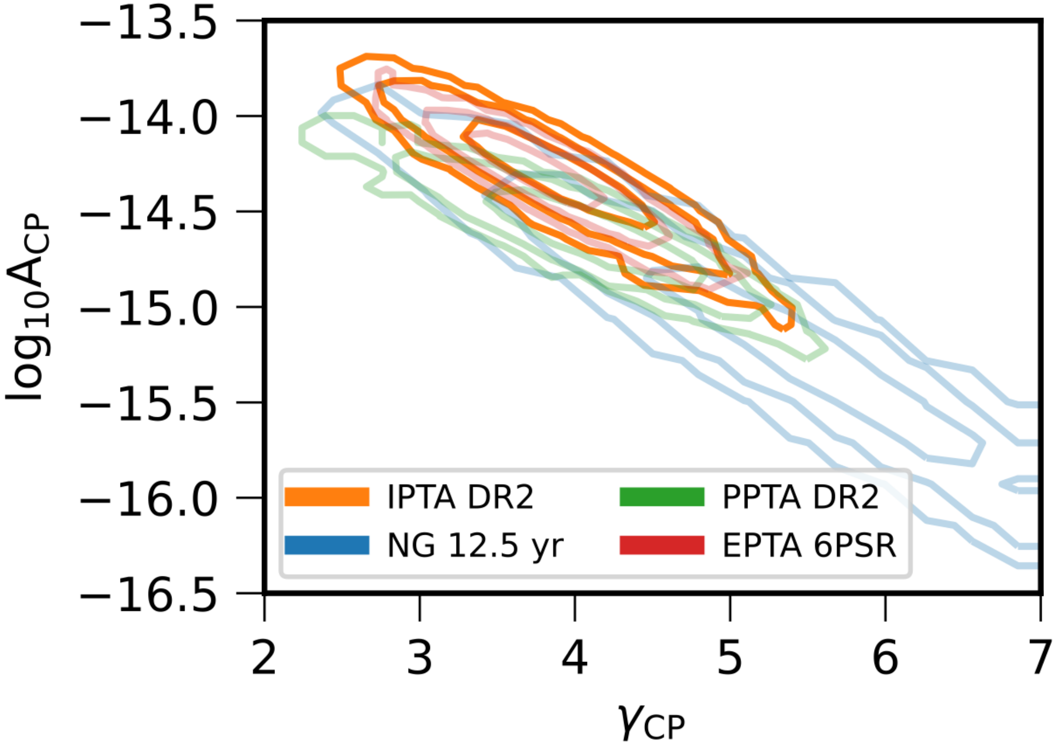
- Analysis of 43 pulsars
- Strong evidence of a common red spectrum.



Confirmed by other PTAs



$$h_c(f) = A\left(\frac{f}{f_{\rm yr}}\right)^{(3-\gamma)/2}$$

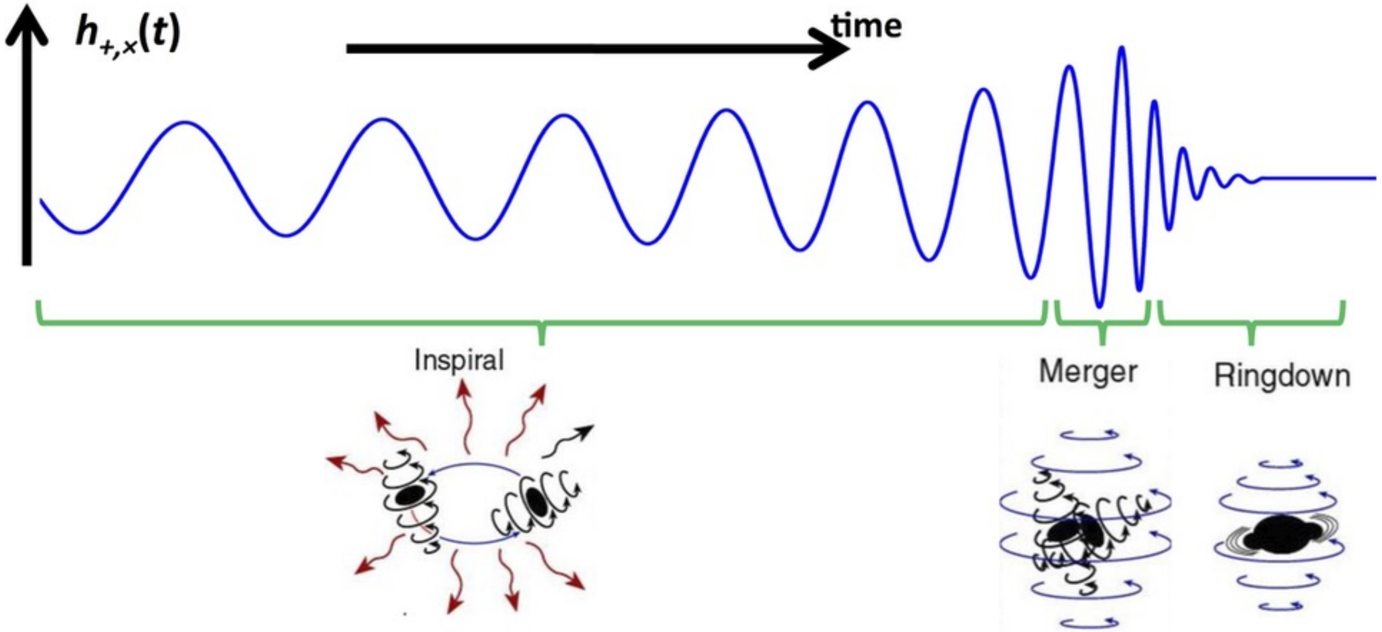


Interpretations

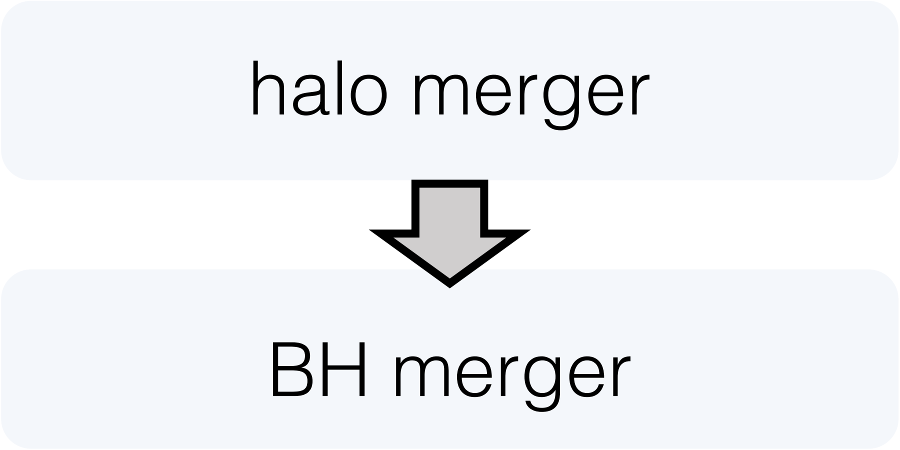
- Supermassive BH inspirals
  - e.g. H. Middleton et. al., Massive black hole binary systems and the NANOGrav 12.5 year results, 2011.01246.
- Cosmic strings
  - e.g. J. Ellis and M. Lewicki, Cosmic String Interpretation of NANOGrav Pulsar Timing Data, 2009.06555.
- Primordial black hole formation
  - e.g. V. Vaskonen and H. Veermäe, Did NANOGrav see a signal from primordial black hole formation?, 2009.07832.
- Cosmological phase transitions
  - e.g. Y. Nakai, M. Suzuki, F. Takahashi and M. Yamada, Gravitational Waves and Dark Radiation from Dark Phase Transition: Connecting NANOGrav Pulsar Timing Data and Hubble Tension, 2009.09754.
- Axions
  - e.g. W. Ratzinger and P. Schwaller, Whispers from the dark side: Confronting light new physics with NANOGrav data, 2009.11875.
- Inflation
  - e.g. S. Vagnozzi, Implications of the NANOGrav pulsar timing results for inflation, 2009.13432.

SMBH inspirals

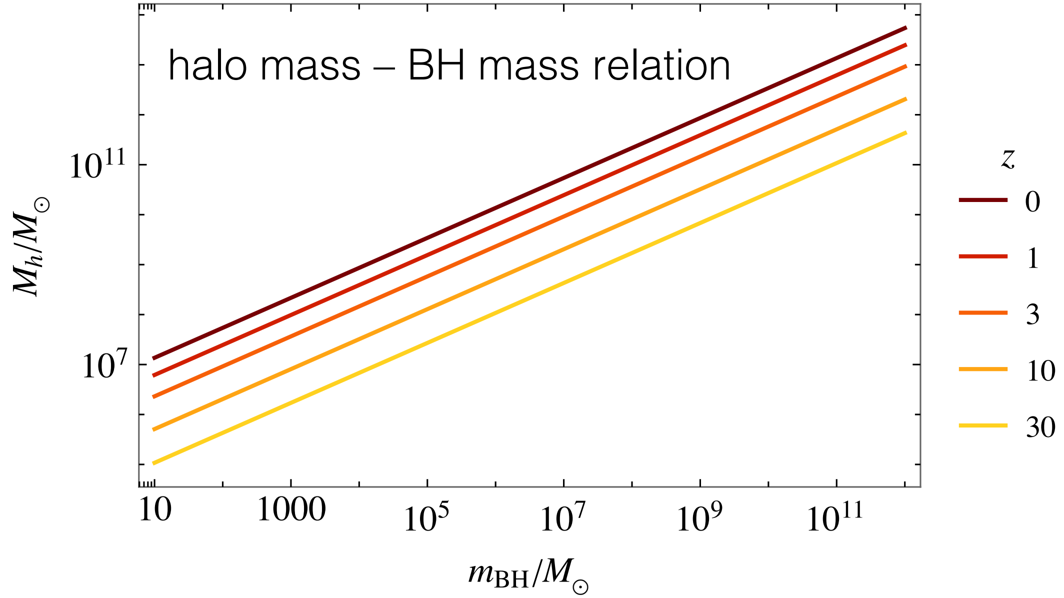
- A population of supermassive BH binaries generates a stoctastic GW background.
- PTAs are sensitive to the power-law tail of the background arising from inspirals.

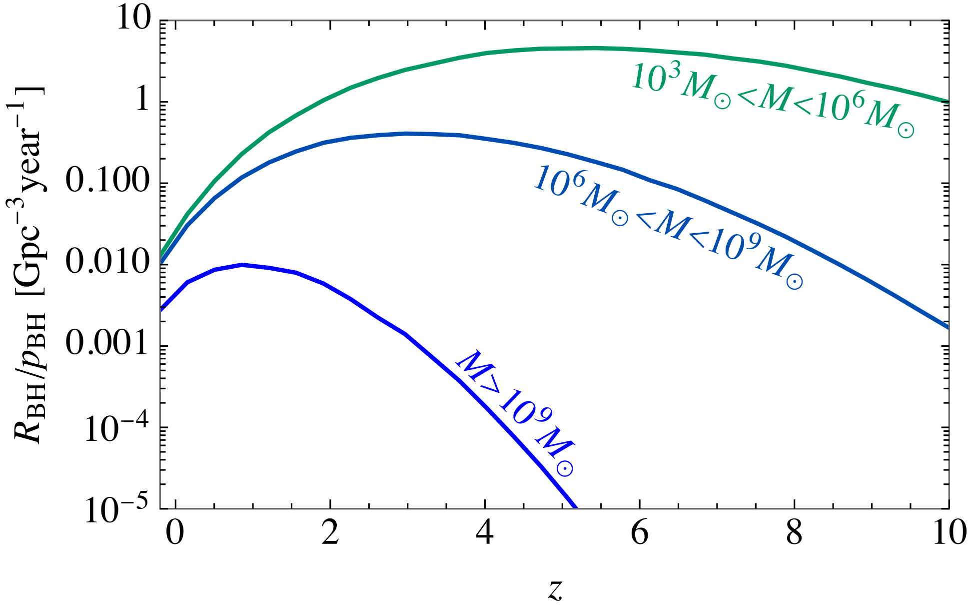


Model of SMBH merger rate



$$\frac{\mathrm{d}R_{\rm BH}}{\mathrm{d}m_1\mathrm{d}m_2} \approx p_{\rm BH}\frac{\mathrm{d}M_1}{\mathrm{d}m_1}\frac{\mathrm{d}M_2}{\mathrm{d}m_2}\frac{\mathrm{d}R_h}{\mathrm{d}M_1\mathrm{d}M_2}$$





GW background

mean GW energy density spectrum:

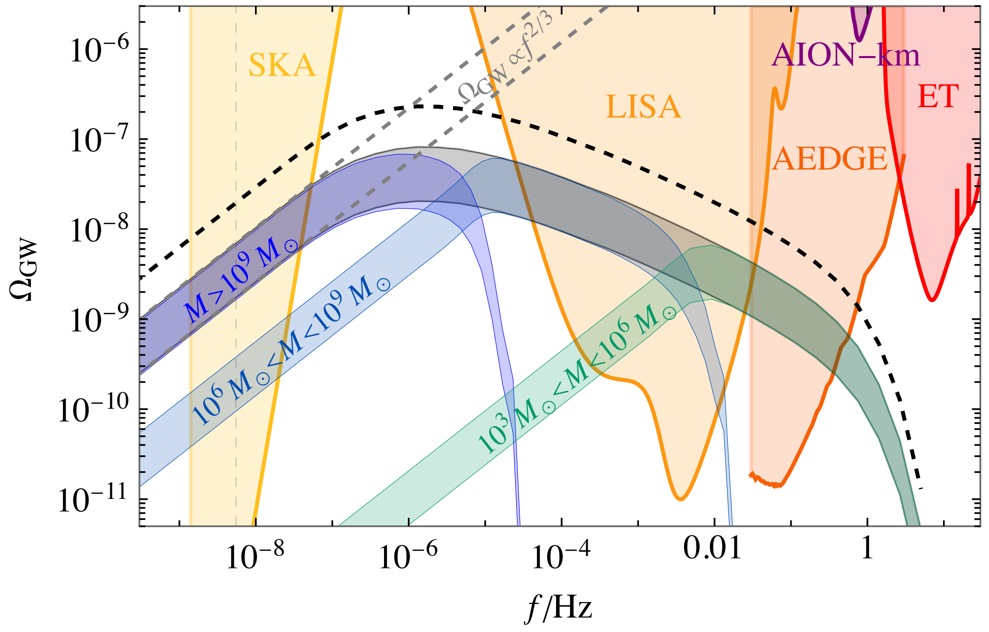
$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln f} = \int {\rm d}\lambda\, \frac{2\pi}{5}\frac{f^3|\tilde h(f)|^2}{\rho_c}$$

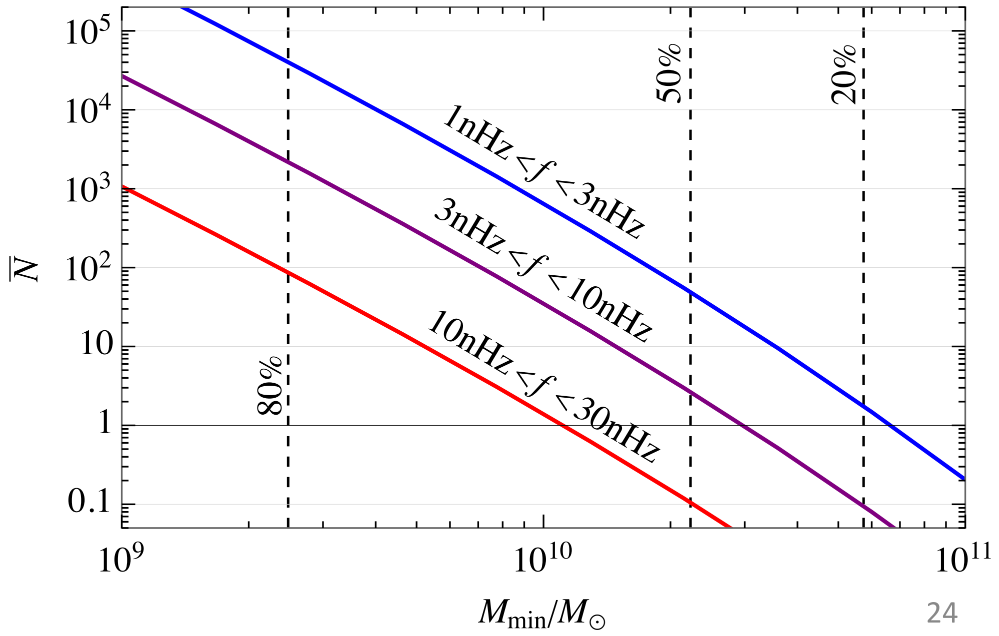
$${\rm d}\lambda = {\rm d}m_1{\rm d}m_2{\rm d}z\, \frac{V_c'(z)}{1+z}\frac{{\rm d}R_{\rm BH}(t)}{{\rm d}m_1{\rm d}m_2}$$

$$|\tilde h(f)| = \sqrt{\frac{5}{24}}\frac{[(1+z)\mathcal{M}]^{\frac56}}{\pi^{\frac23}D_L} \times \begin{cases} f^{-\frac76} & f < f_{\rm merg} \\ f_{\rm merg}^{-\frac12} f^{-\frac23} & f_{\rm merg} \le f < f_{\rm ring} \\ f_{\rm merg}^{-\frac12} f_{\rm ring}^{-\frac23}\frac{\sigma^2}{4(f-f_{\rm ring})^2+\sigma^2} & f_{\rm ring} \le f < f_{\rm cut}\,, \end{cases}$$

NANOGrav:

$$p_{\rm BH} = \mathcal{O}(0.1)$$

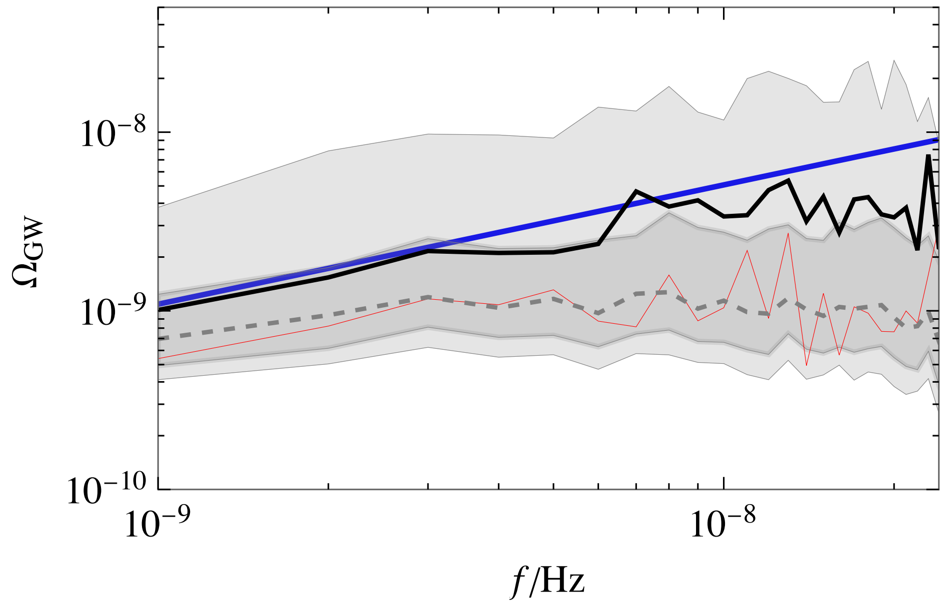


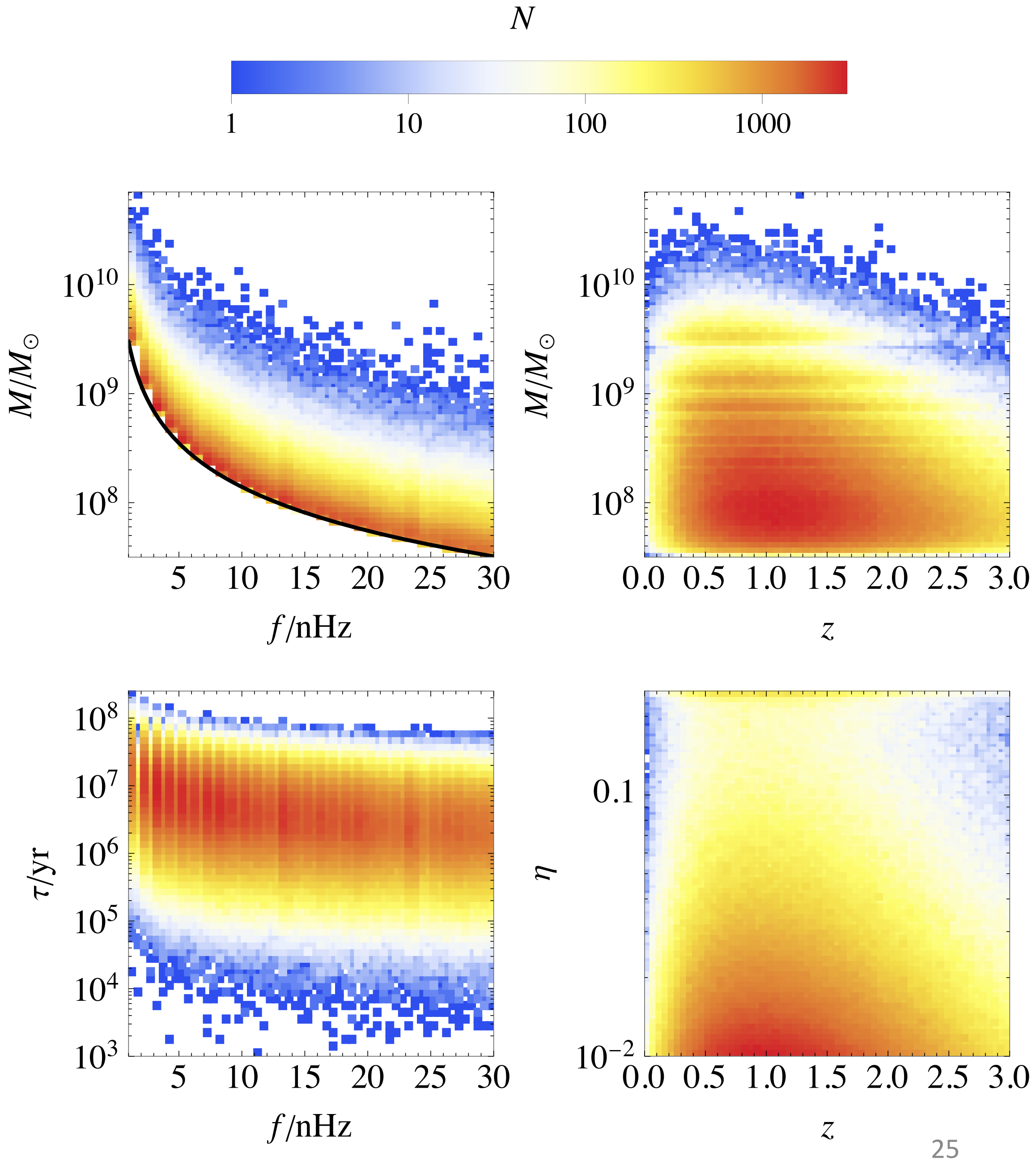


GW background

Random realizations of the SMBH population in the PTA sensitivity band:

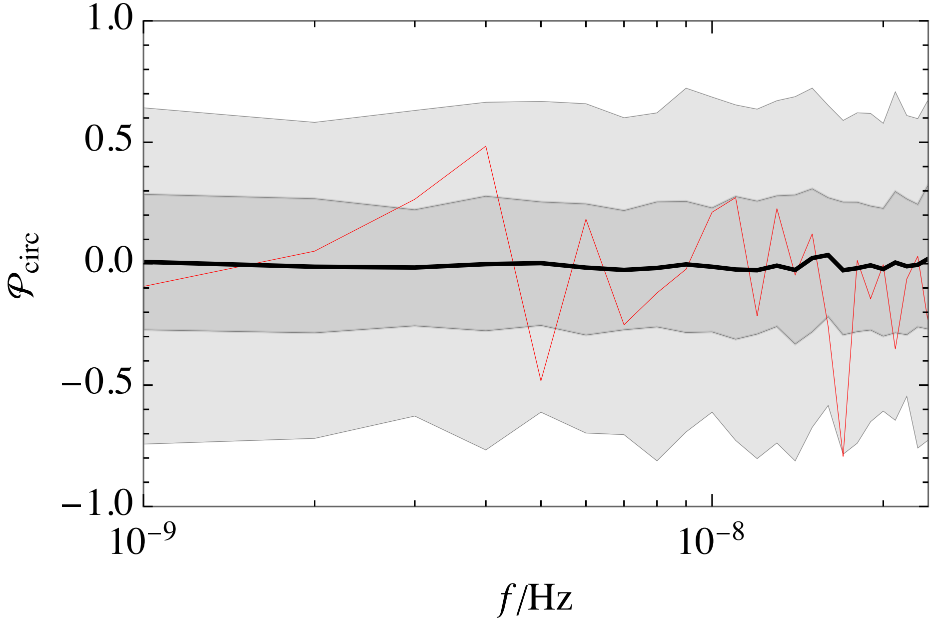
$$\Omega_{\rm GW}(f_j) = \frac{1}{\ln(f_{j+1}/f_j)} \sum_{k=1}^{N(f_j)} \Omega^{(1)}_{\rm GW}(\vec{\theta}_k)$$



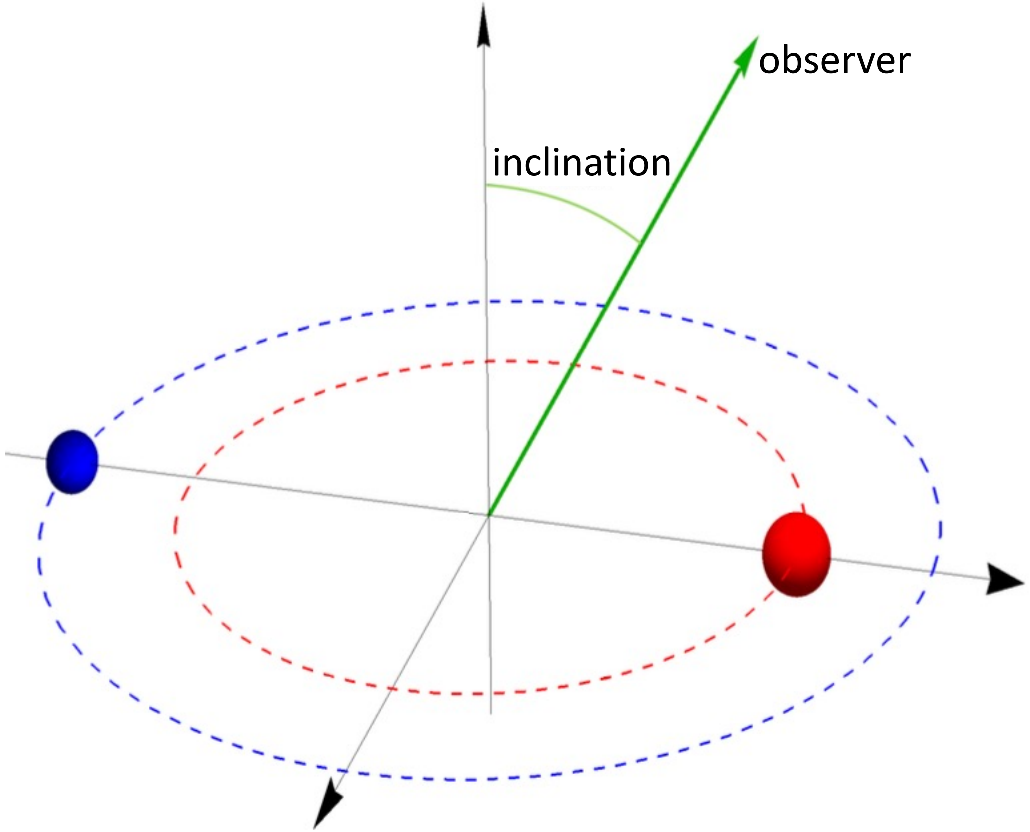


GW circular polarization

$$\mathcal{P}_{\rm circ}(f) = \frac{|\tilde{h}_L(f)|^2 - |\tilde{h}_R(f)|^2}{|\tilde{h}_L(f)|^2 + |\tilde{h}_R(f)|^2}$$



- 0° inclination: circularly polarized signal.
- 90° inclination: linearly polarized signal.

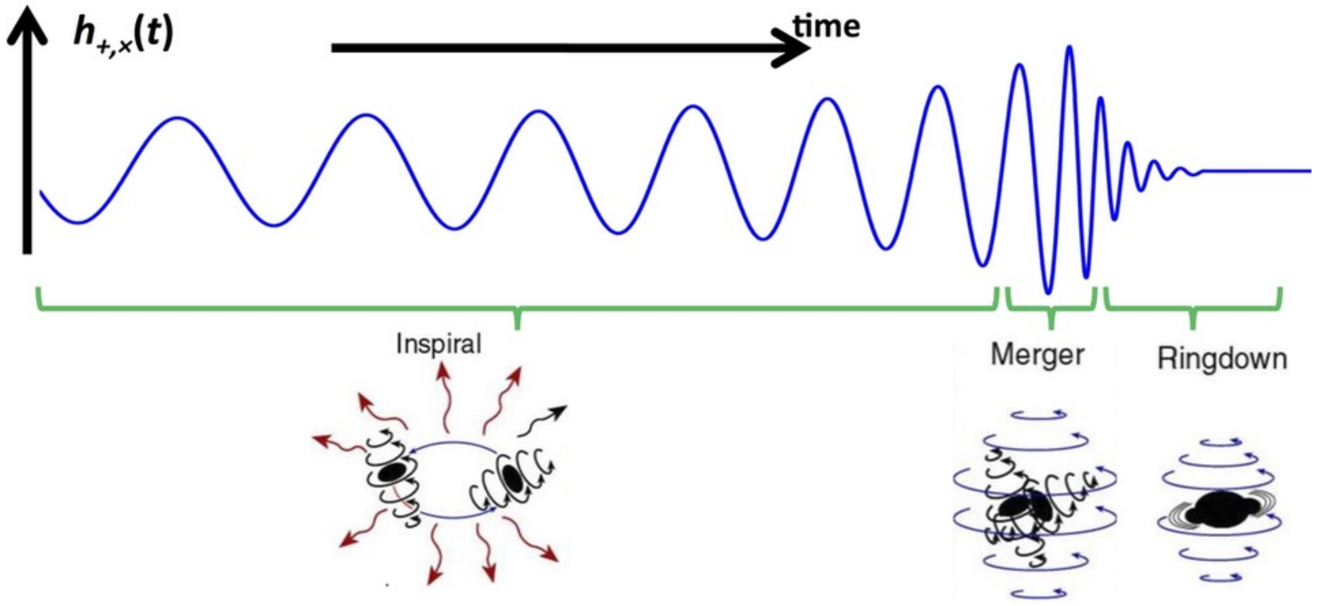


Prospects for future GW observatories

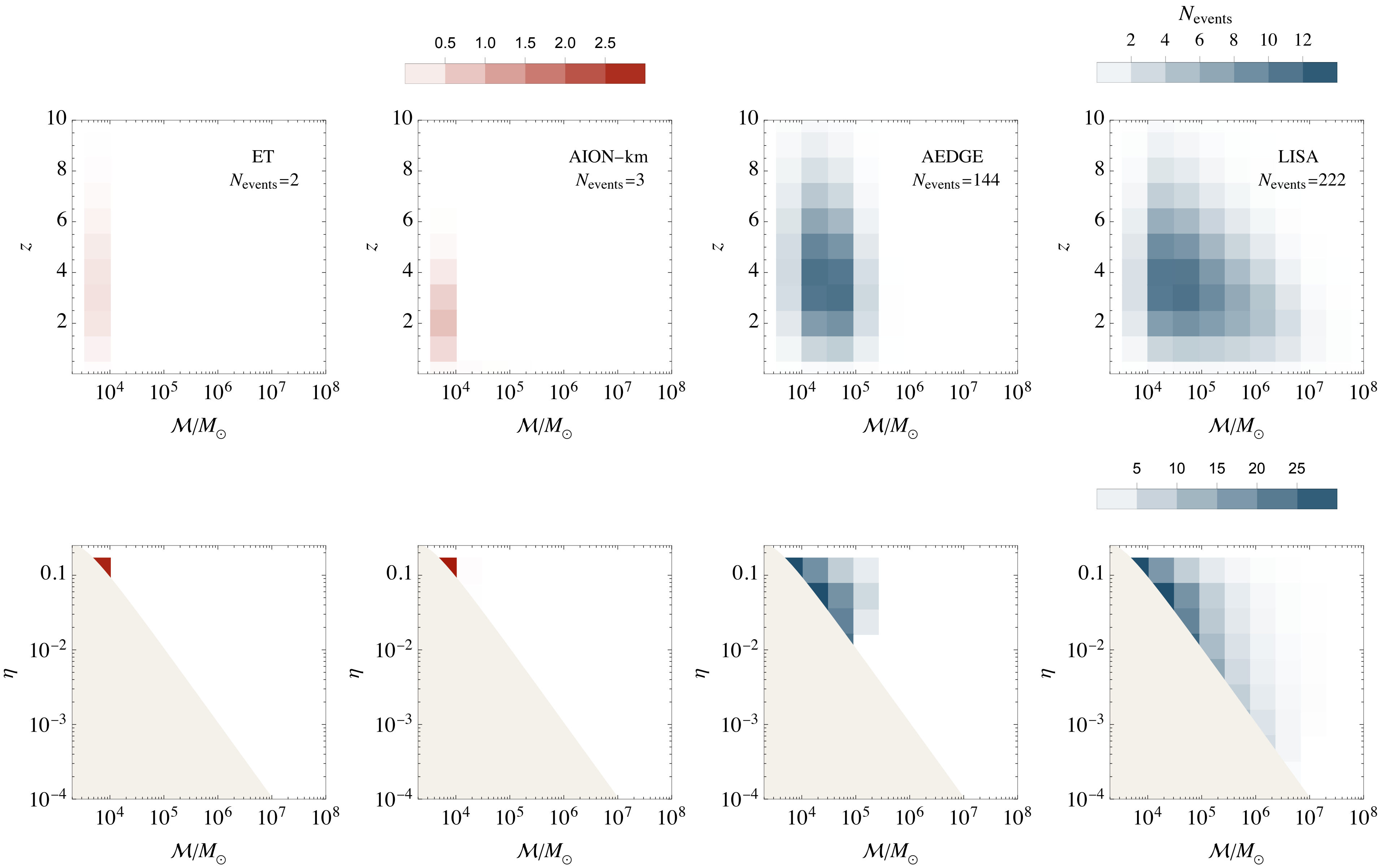
1. Short GW signals from BH binary mergers

2. Continuous GW signals from inspiralling BH binaries

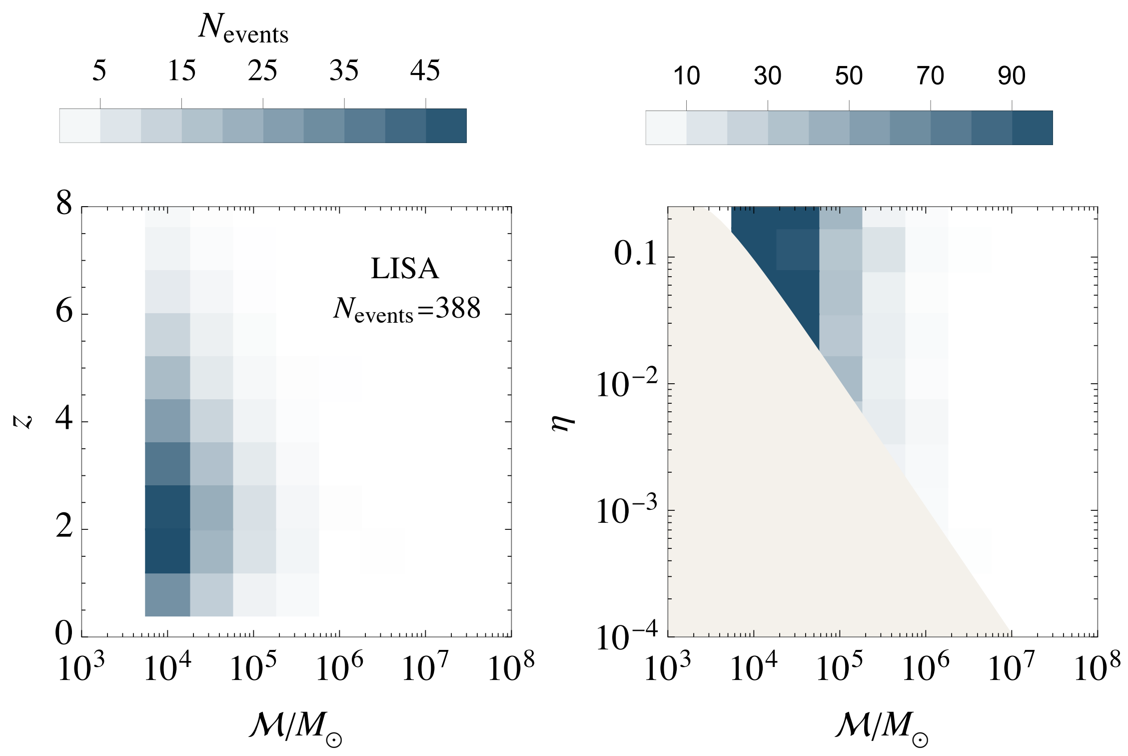
3. GW background from BH binaries



BH binary mergers



Inspiralling BH binaries



Conclusions

- JWST has observed luminous early galaxies indicate a $> 3\sigma$ tension with LCDM.
- Beyond LCDM physics ⇒ enhanced matter power spectrum at $k_c \approx 5h\mathrm{Mpc}^{-1}$, however, almost extremal star formation efficiency is needed.
- PTAs have reported evidence for a common-spectrum stoctastic process, that possibly originates from GWs.
- GWs from SMBHs: significant deviations from a simple power-law spectrum are expected and potentially large circular polarization.
- The observed amplitude indicates, extrapolating the merger rate to lower masses, that e.g. LISA will see about 200 BH binary mergers per year.
- Combining JWST and PTA results? More early galaxies ⇒ more BHs ⇒ more GWs.