KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

EXPLORING THE UNIVERSE WITH GRAVITATIONAL WAVES

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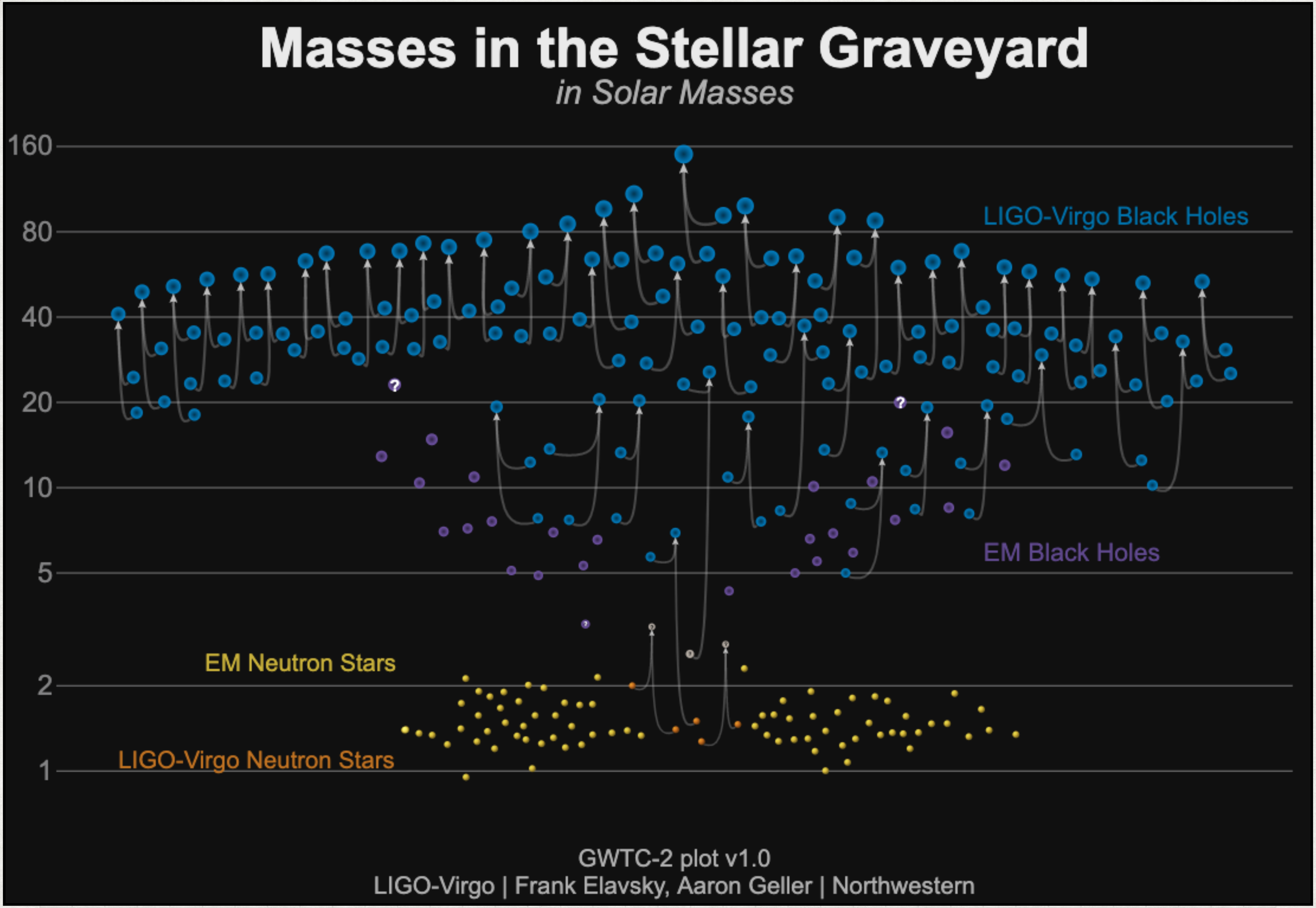
wpi World Premier International Research Center Initiative

科研費 KAKENHI

SEPTEMBER 03, 2021, KAVLI IPMU

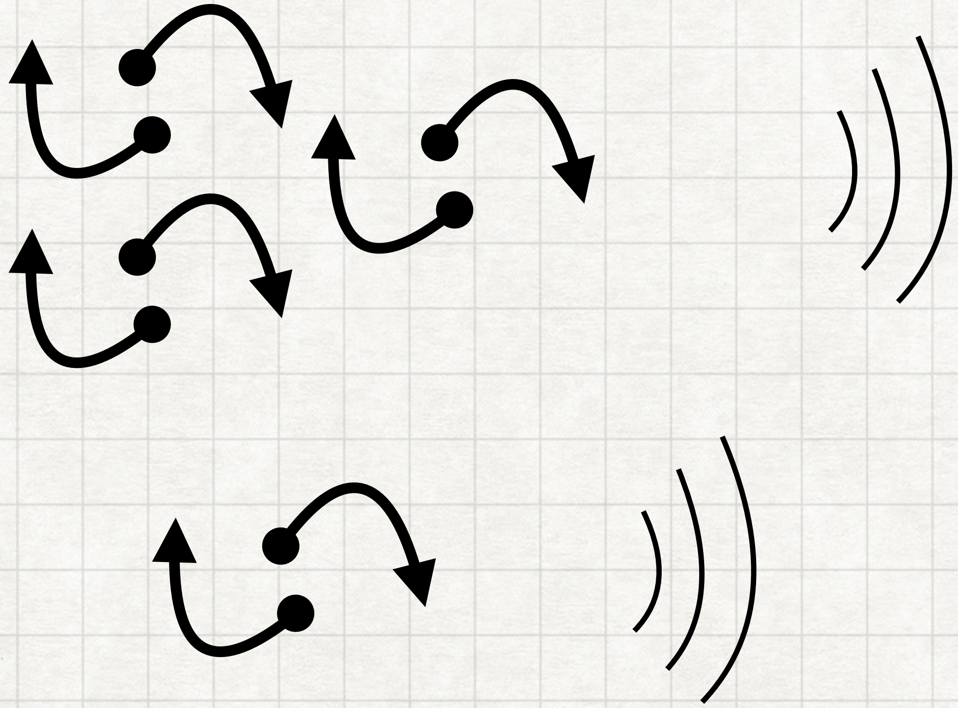

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

IN THIS TALK

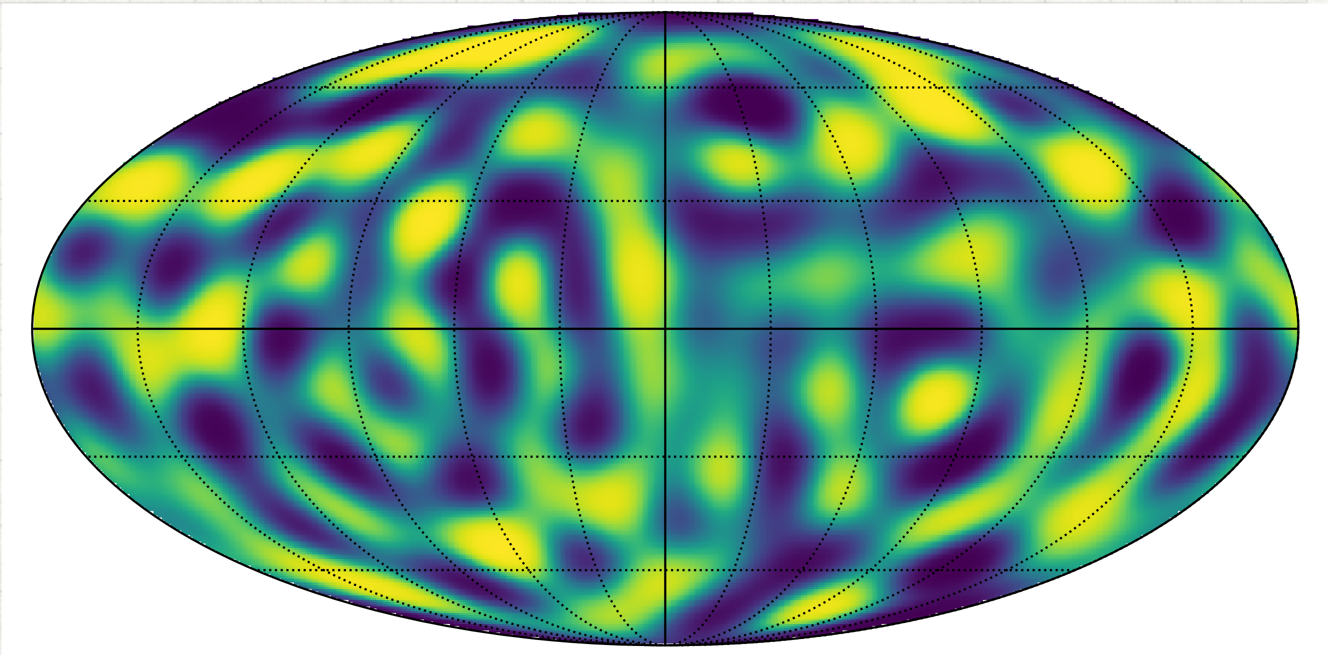
- Part 1: Clustering of black hole binaries.
- Part 2: Astrophysical gravitational wave background.
- Part 3: Are stellar mass black holes of primordial origin?
- Part 4: What can GWs teach us about the early universe?

Part 1: Resolved GW sources

Based on: **Learning how to surf: reconstructing the origin and propagation of GWs with Gaussian Processes, arXiv: 2105.04262**



Clustering of resolved compact object binaries



The resulting observable is the projected number count.

Tomographic cross-corrs: what are they good for?

$$h''_\alpha + \left[2 + \alpha_M(z)\right] \mathcal{H} h'_\alpha - \vec{\nabla}^2 h_\alpha = 0$$

$$\alpha_M(z) \equiv \mathrm{d}M^2_{\mathrm{eff}}/\mathrm{d}\ln a$$

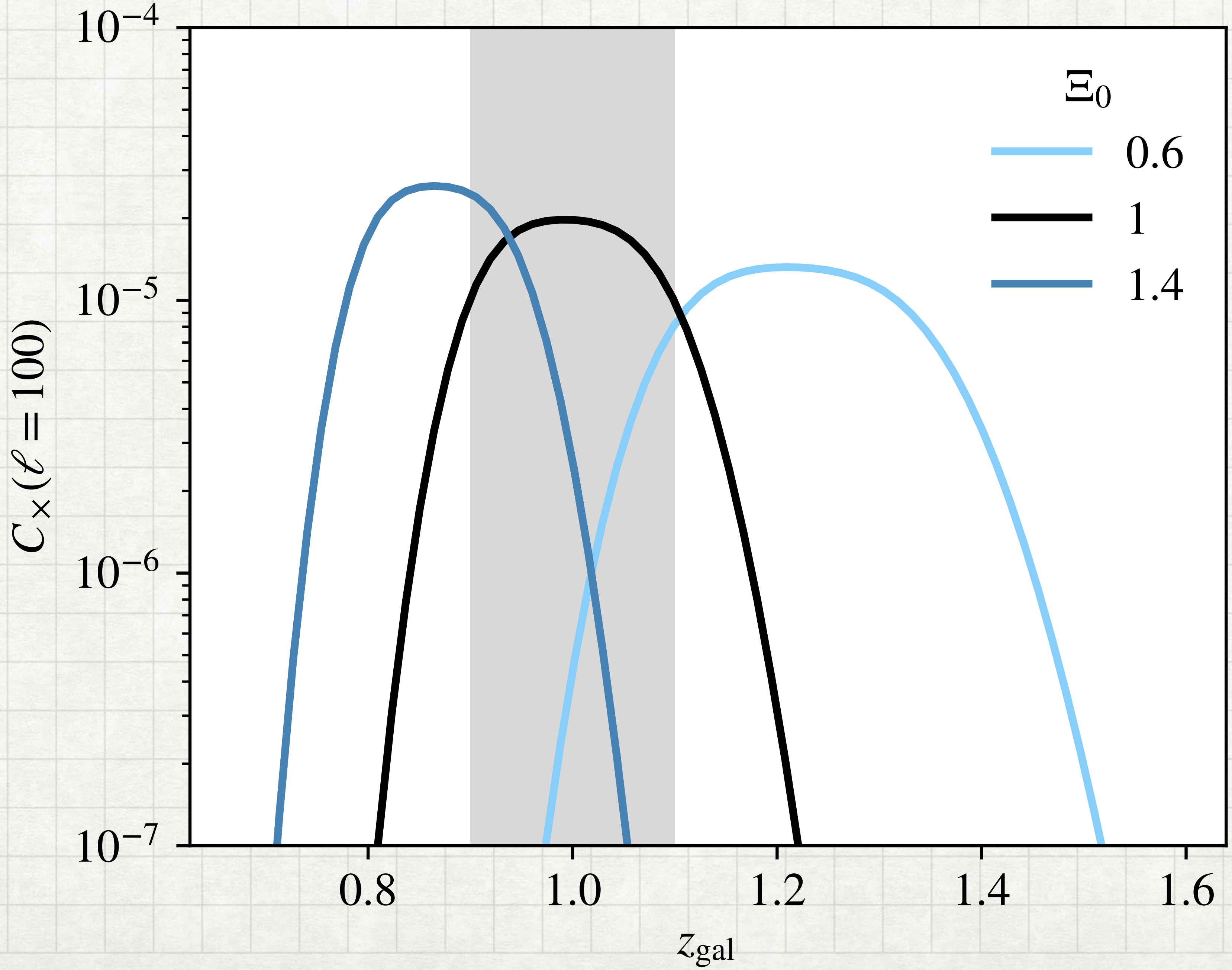
$$S_\phi = \int \mathrm{d}^4x \sqrt{-g} \left(\frac{1}{2} M^2_{\mathrm{eff}}(\phi) R + K(\phi, X) - G_3(\phi, X) \Box \phi \right)$$

$$\frac{D_{\mathrm{L,GW}}(z)}{D_{\mathrm{L,EM}}(z)} = \exp\left\{ -\frac{1}{2} \int_0^z \mathrm{d}\tilde{z} \, \frac{\alpha_M(\tilde{z})}{(1+\tilde{z})} \right\} = \Xi_0 + \frac{1 - \Xi_0}{(1+z)^n}$$

Common parametrization

Tomographic cross-corrs: what are they good for?

$$\frac{D_{\mathrm{L,GW}}(z)}{D_{\mathrm{L,EM}}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$



Tomographic cross-corrs: what are they good for?

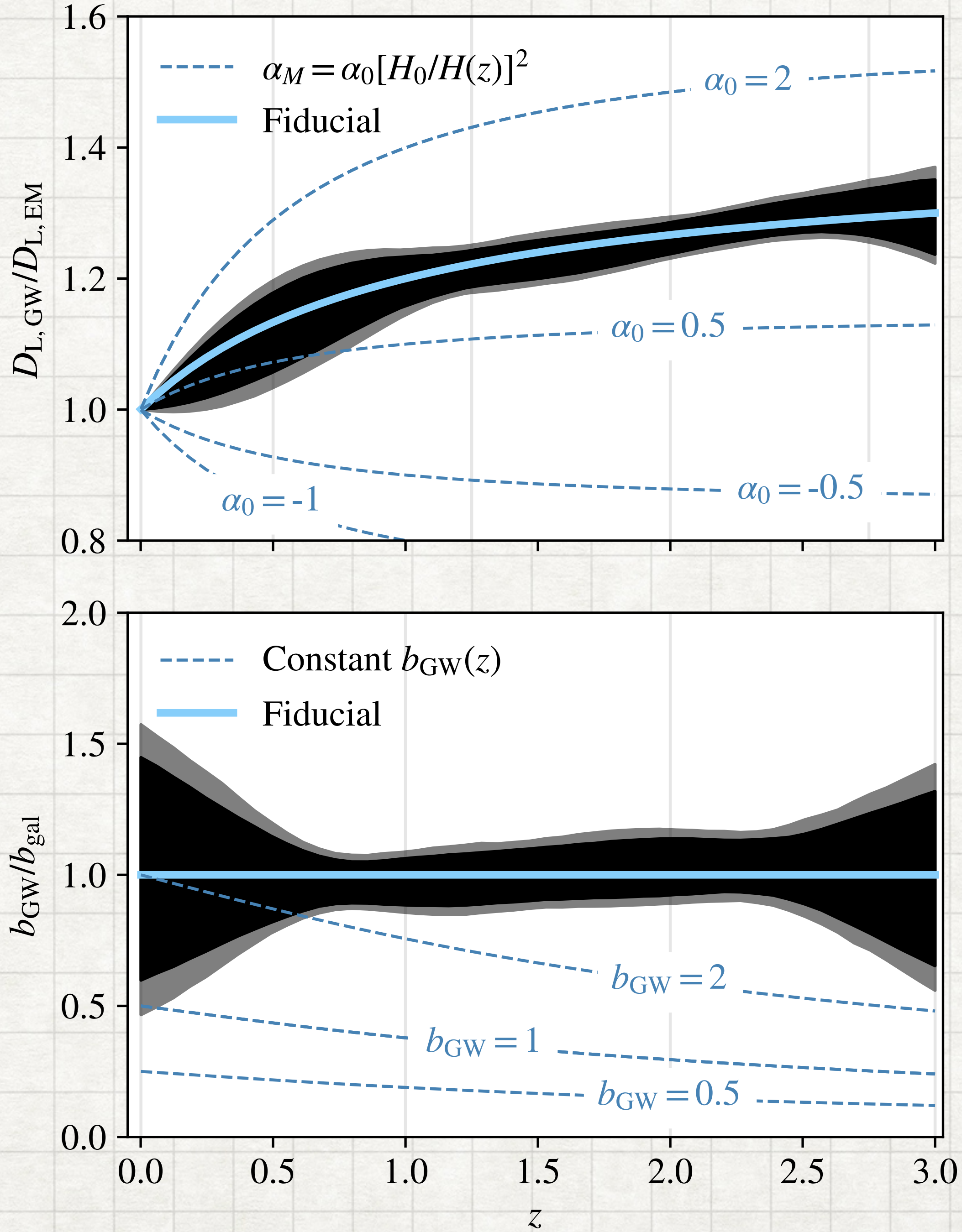
Not very general

$$\frac{D_{\mathrm{L,GW}}(z)}{D_{\mathrm{L,EM}}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

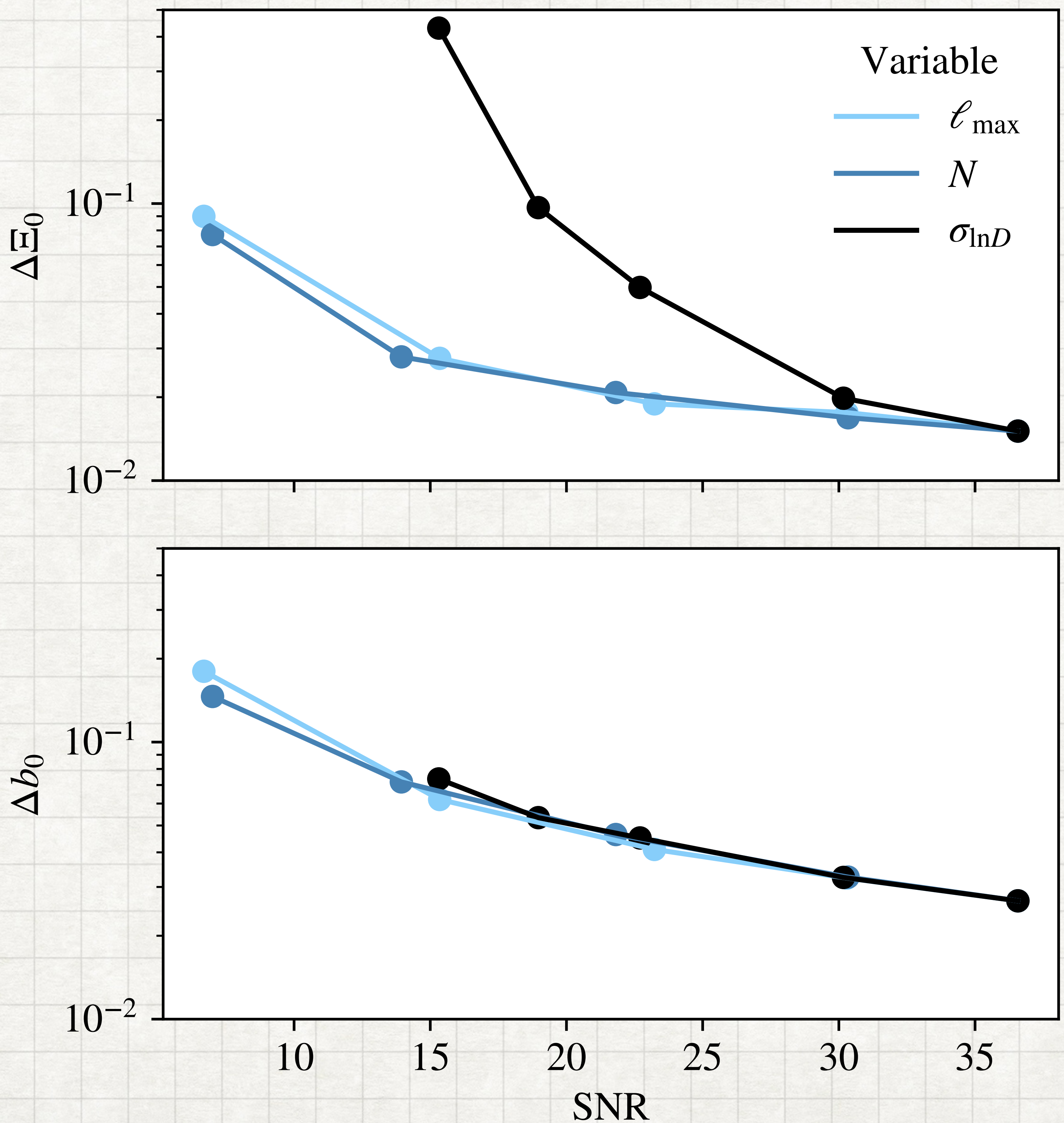
Also the GW bias is unknown

$$\frac{b_{\mathrm{GW}}(z)}{b_{\mathrm{gal}}(z)}$$

Reconstruct the shapes of these functions.



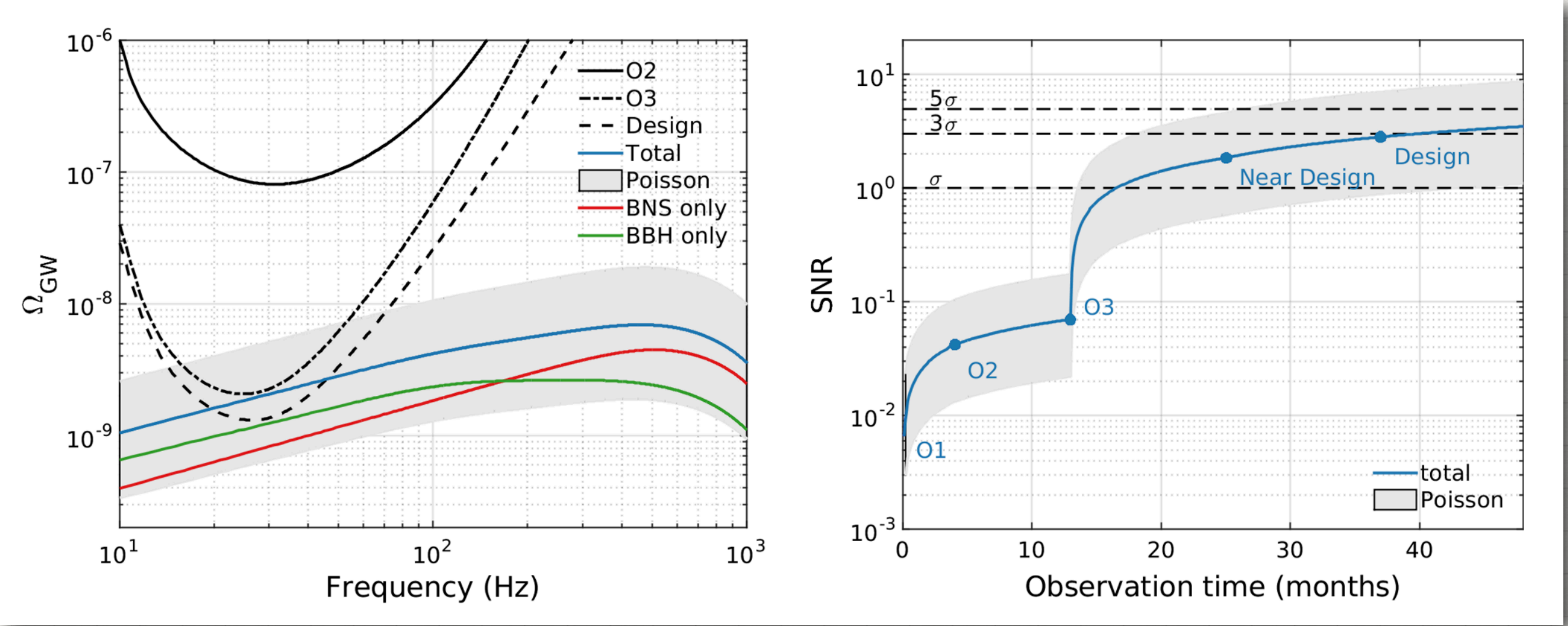
Observational strategy



Part 2: Astrophysical GW background

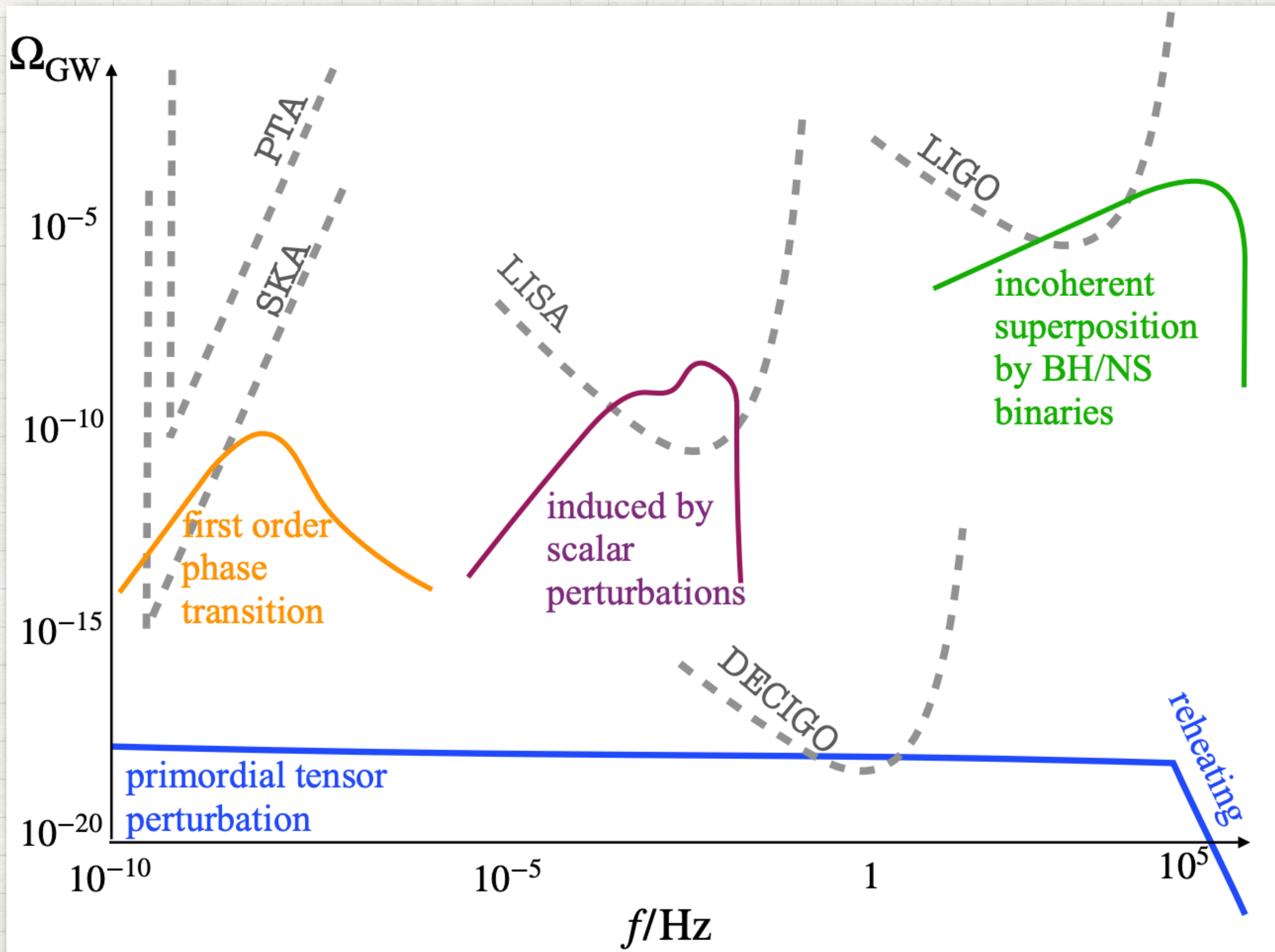
Based on: Cross-correlation of the AGWB with galaxy clustering, arXiv:1910.08353

$$\Omega_{\rm GW}(f,\theta) = \frac{f}{\rho_c H_0}\int_0^{z_{\max}} dz \frac{R_m(z;\theta)dE_{\rm GW}(f_s;\theta)/df_s}{(1+z)E(\Omega_M,\Omega_\Lambda,z)}.$$



LIGO/VIRGO Collaboration: "GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences"

Multitude of sources



Modelling the signal

The map on the sky → $$\Omega_{\mathrm{GW}}(\nu_0, \hat{r}) = \frac{\nu_0}{\rho_{\mathrm{c}}} \frac{\mathrm{d}\rho_{\mathrm{GW}}(\nu_0, \hat{r})}{\mathrm{d}\nu_0 \mathrm{d}^2\hat{r}}$$

Let's model this as → $$\Omega_{\mathrm{GW}}(\hat{r}) \equiv \int \mathrm{d}r\, r^2 \mathscr{K}(r) n(\vec{r})$$

$$\Omega_{\mathrm{GW}}(\hat{r}) = \int \mathrm{d}r\, r^2 \boxed{\mathscr{K}(r)}\, \bar{n}(r) \big(\delta_{\mathrm{GW}}(\vec{r}) + 1 \big)$$

Astrophysical kernel

Modelling the signal

$$\Omega_{\mathrm{GW}}(\hat{r}) = \int \mathrm{d}r \; r^2 \boxed{\mathscr{K}(r)} \bar{n}(r) \Big(\delta_{\mathrm{GW}}(\vec{r}) + 1 \Big)$$

Astrophysical kernel

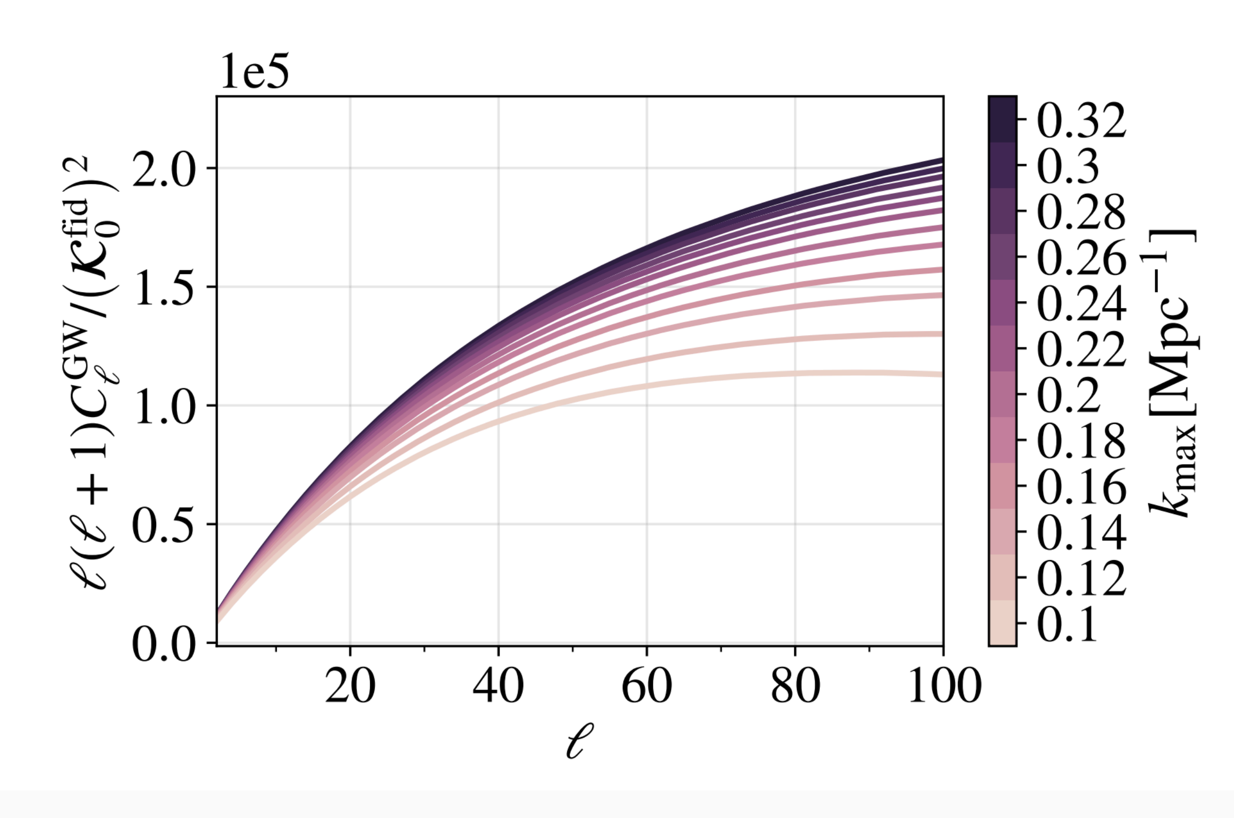
From real space to angular correlations

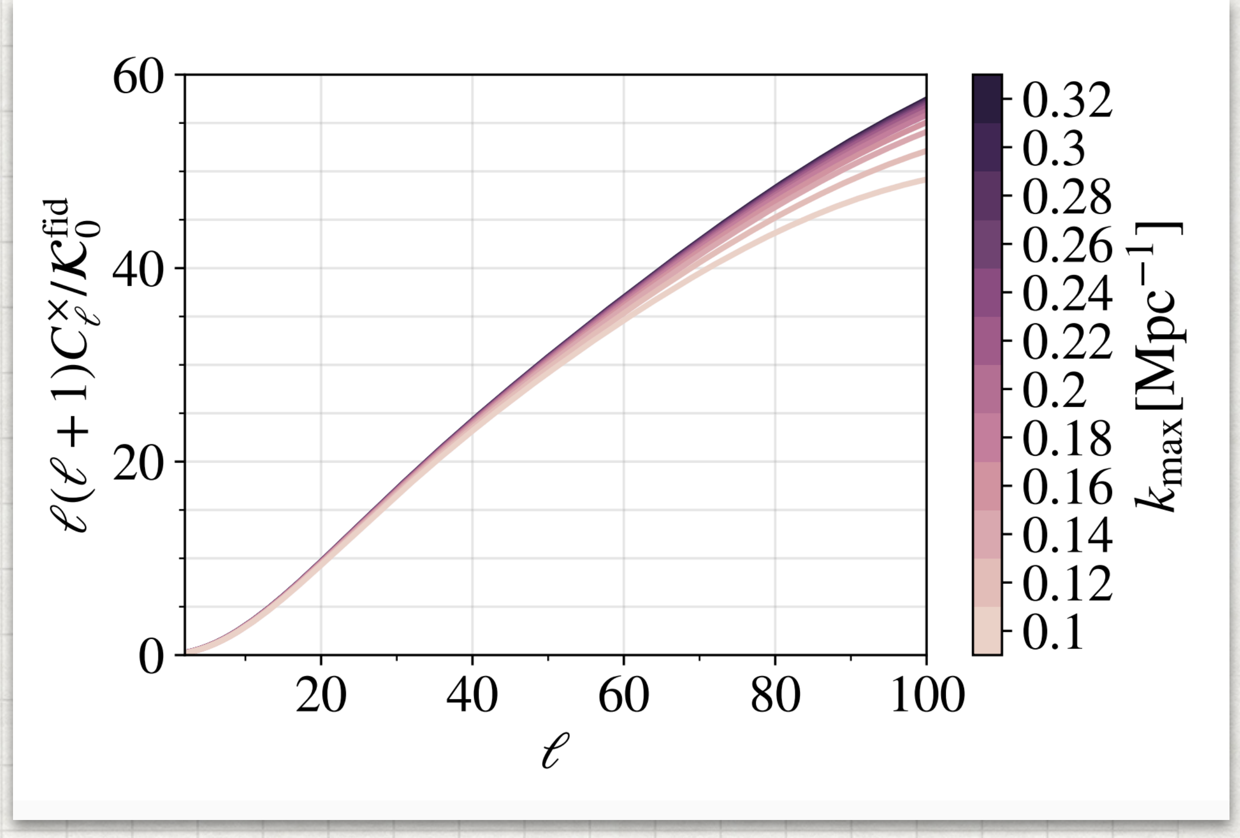
$$C_\ell^{\mathrm{GW}} = 4\pi \int_{k_{\min}}^{k_{\max}} \frac{dk}{k} \, |\, \delta\Omega_\ell \,|^2 \, \mathscr{P}(k) + B_\ell^{\mathrm{GW}}$$

- **Integrands** $\delta\Omega_\ell(k) = \int \mathrm{d}r \; r^2 \mathscr{K}(r) \bar{n}(r) T_{\mathrm{GW}}(k, r) j_\ell \left(kr\right)$

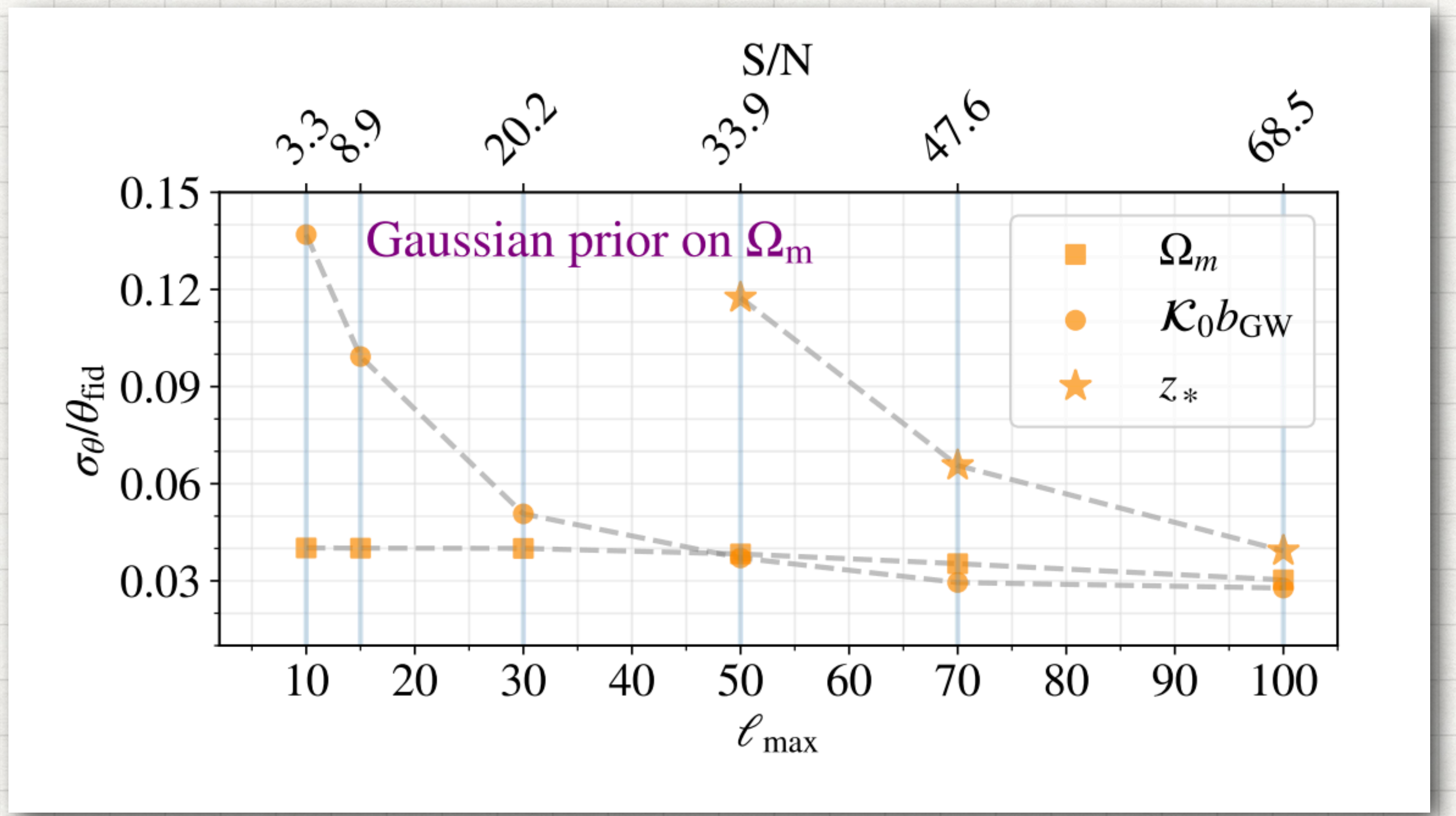
No relativistic corrections for now!

Sensitivity on non-linearities



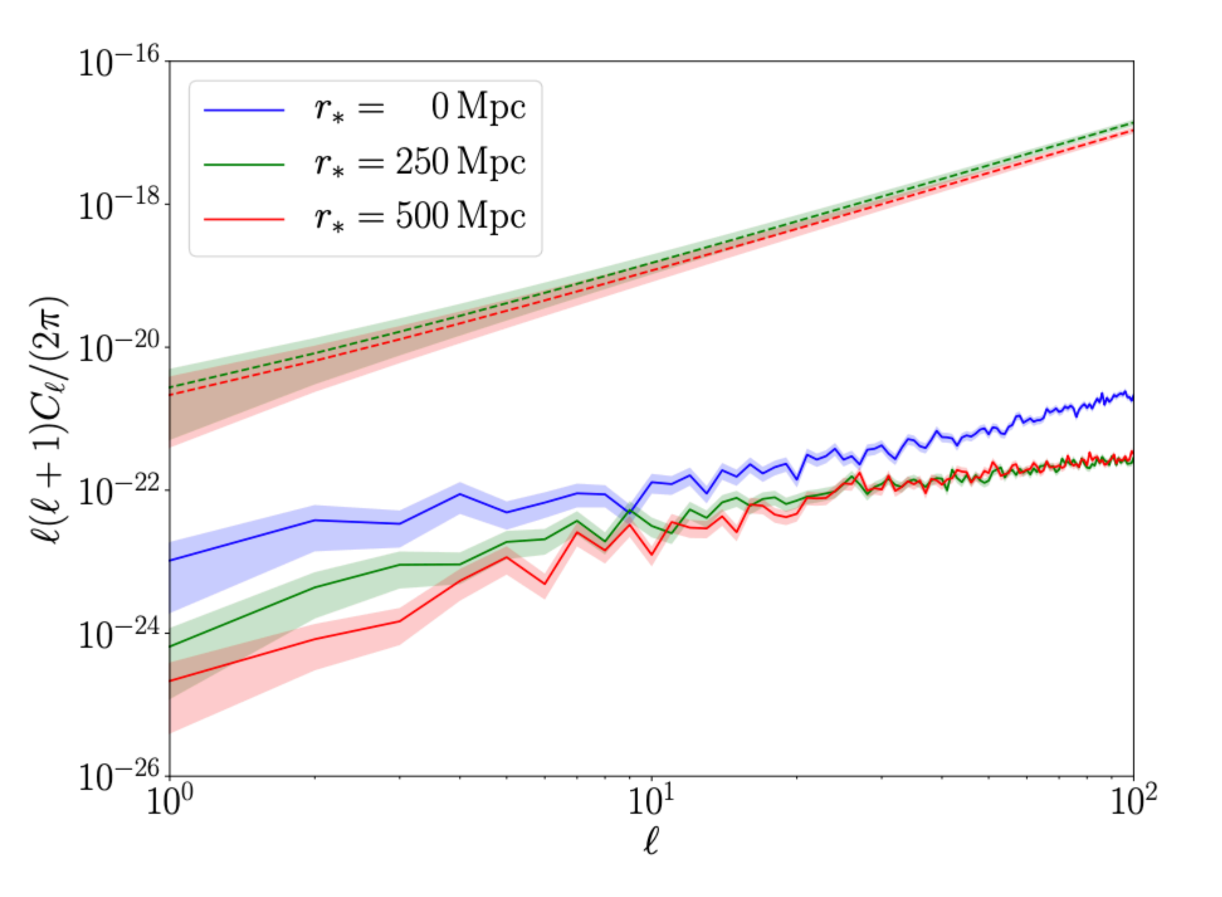


What to expect?



- **The anisotropies will first be detected via the cross-correlation**
- **Sensitive to the features in the astrophysical kernel** $\mathscr{K}(z)$
- **Useful for cosmology if** $\ell_{max} \sim 100$ **is detected**

The shot-noise issue



$$B_\ell^{\mathrm{GW}} = \int dr \frac{\tilde{\mathcal{K}}^2(r)}{\bar{n}(r)r^2}\left[1 + \frac{1+z(r)}{R(r)T_O}\right]$$

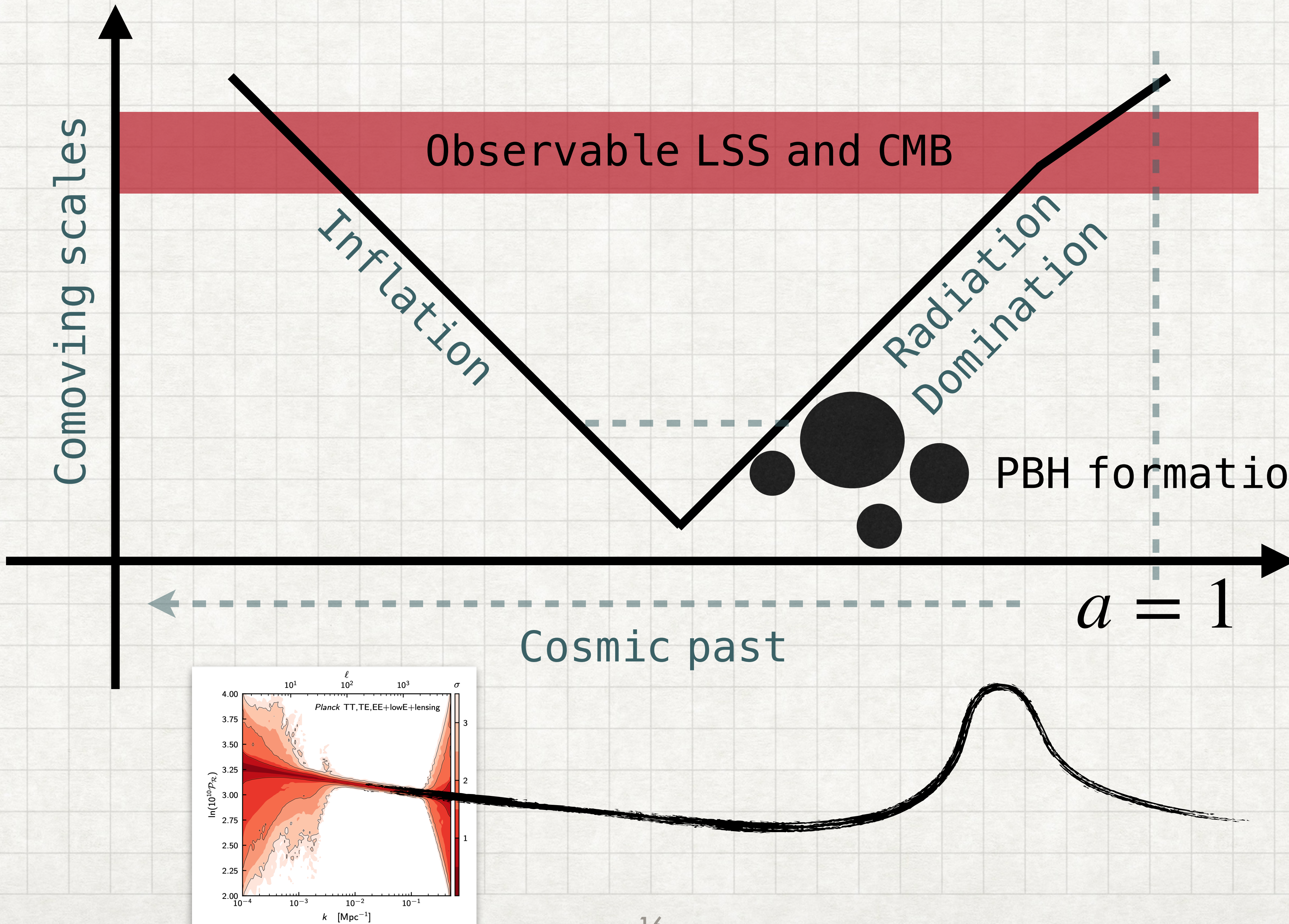
Jenkins, Sakellariadou, 2019
Canas-Herrera, Contigiani, Vardanyan, 2019
Alonso, Cusin, Ferreira, Pitrou, 2020

$$\mathrm{Var}C_\ell^{\times} = \frac{\left(C_\ell^{\mathrm{GW}} + B_\ell^{\mathrm{GW}}\right)\left(C_\ell^{\mathrm{GC}} + B_\ell^{\mathrm{GC}}\right) + \left(C_\ell^{\times} + B_\ell^{\times}\right)^2}{2\ell + 1}$$

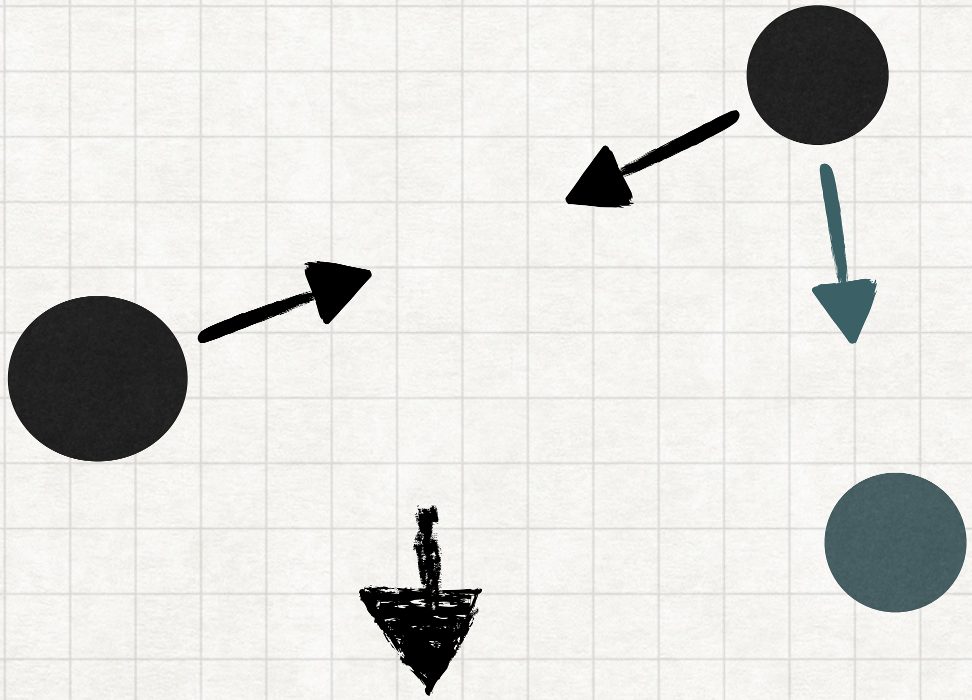
Cross-corr variance can be huge due to contamination from the auto-corr

Part 3: PBH mergers

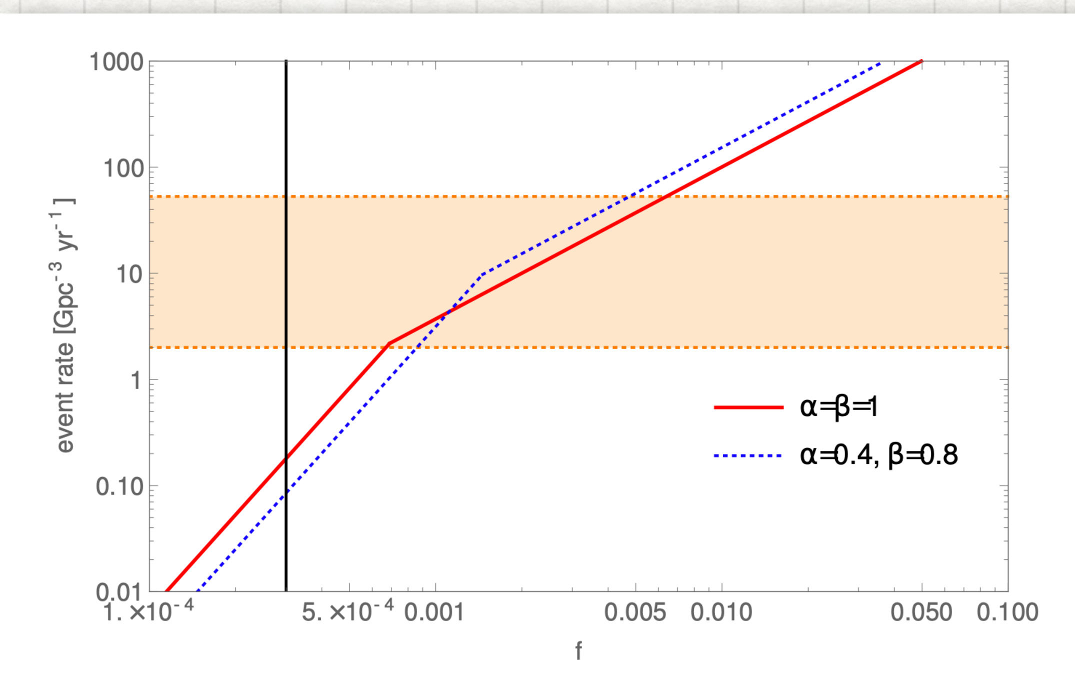
In prep: **in collaboration with Misao Sasaki, Volodymyr Takhistov, Ying-li Zhang**



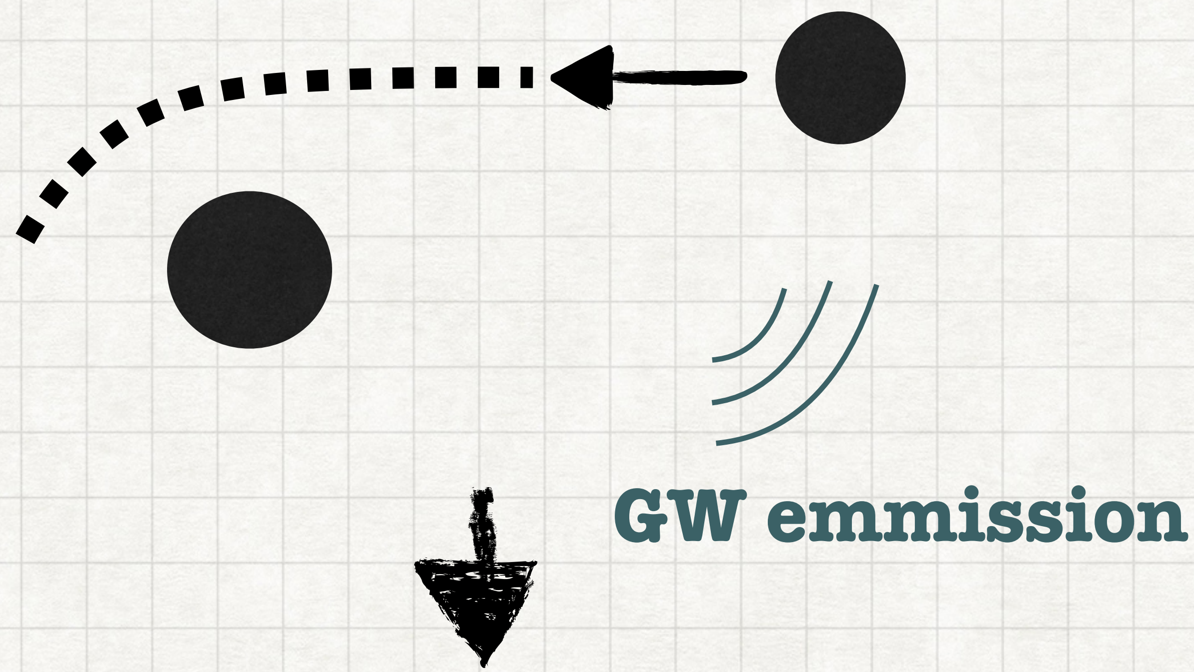
Part 3: PBH mergers



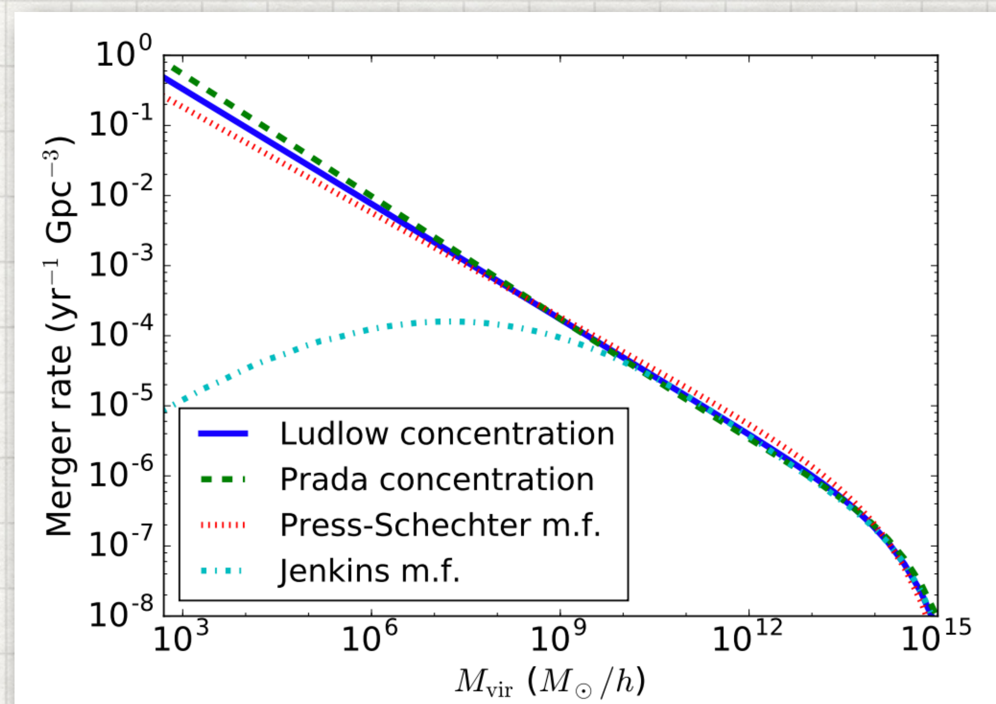
PBH binary



Sasaki, Suyama, Tanaka, Yokoyama, 2016
Nakamura, Sasaki, Tanaka, Thorne, 1997

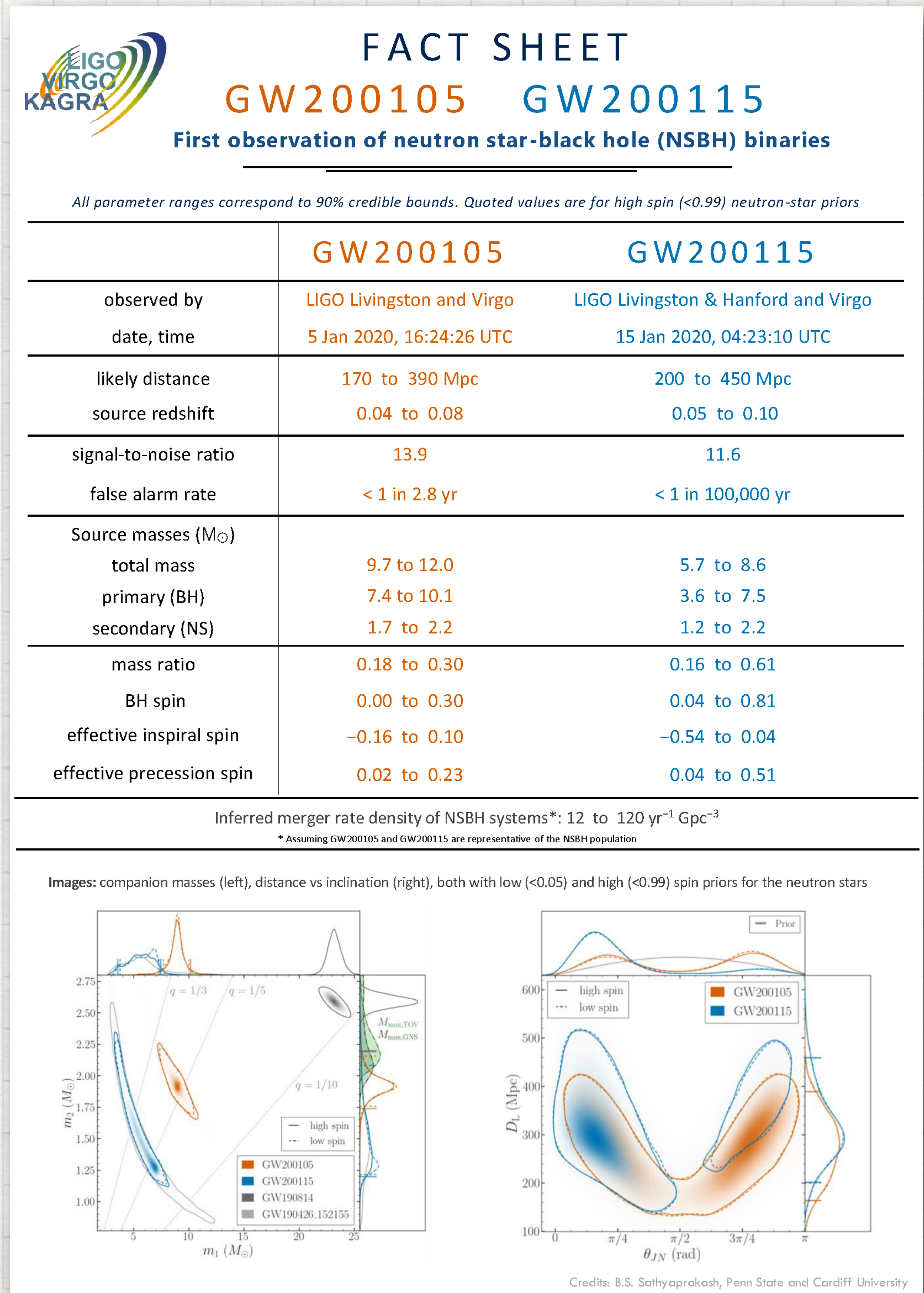


PBH binary



Bird et al, 2016

PBH-Neutron star binaries?



FACT SHEET

GW200105 GW200115

First observation of neutron star-black hole (NSBH) binaries

All parameter ranges correspond to 90% credible bounds. Quoted values are for high spin (<0.99) neutron-star priors

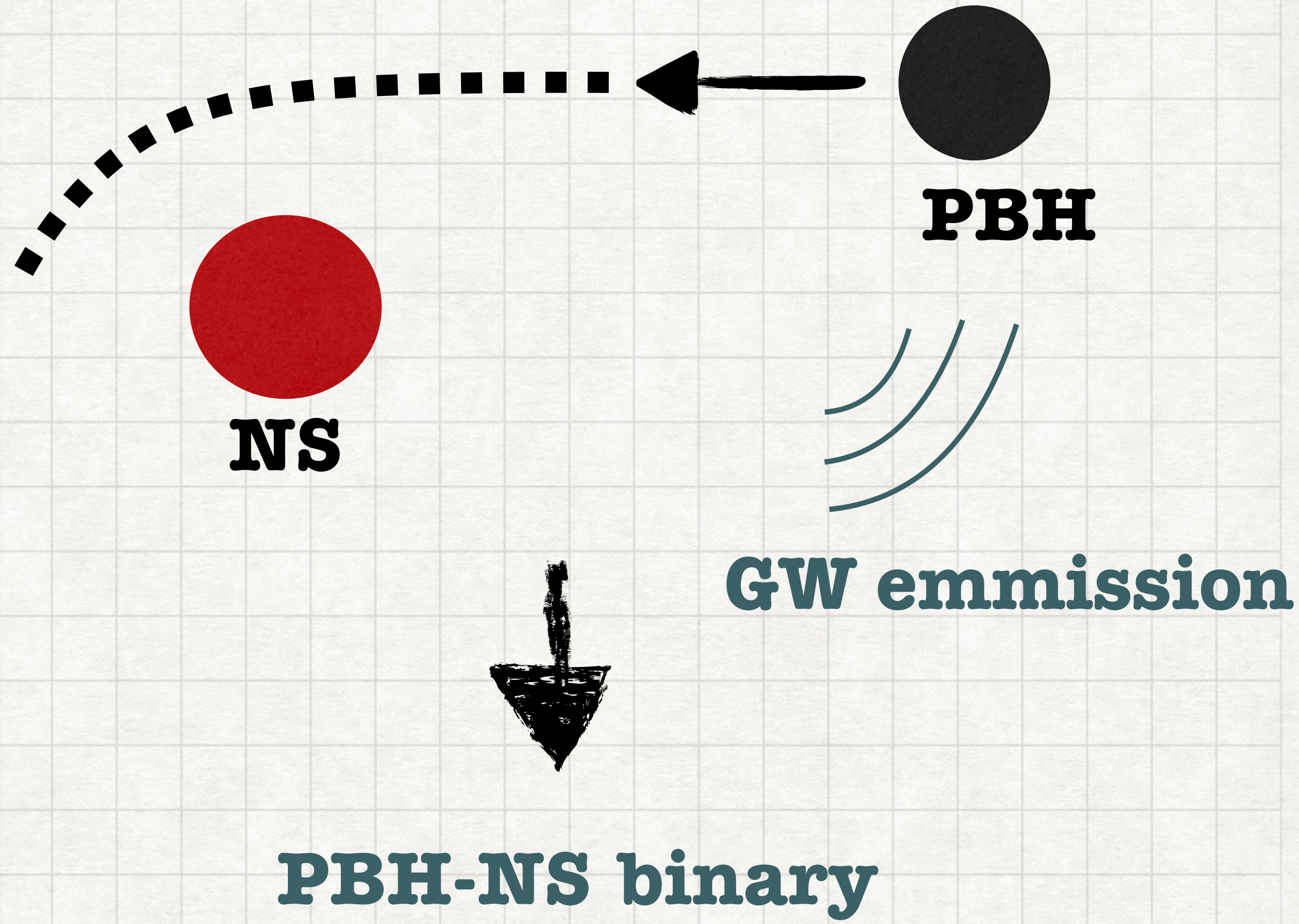
	GW200105	GW200115
observed by	LIGO Livingston and Virgo	LIGO Livingston & Hanford and Virgo
date, time	5 Jan 2020, 16:24:26 UTC	15 Jan 2020, 04:23:10 UTC
likely distance	170 to 390 Mpc	200 to 450 Mpc
source redshift	0.04 to 0.08	0.05 to 0.10
signal-to-noise ratio	13.9	11.6
false alarm rate	< 1 in 2.8 yr	< 1 in 100,000 yr
Source masses ($M_\odot$)		
total mass	9.7 to 12.0	5.7 to 8.6
primary (BH)	7.4 to 10.1	3.6 to 7.5
secondary (NS)	1.7 to 2.2	1.2 to 2.2
mass ratio	0.18 to 0.30	0.16 to 0.61
BH spin	0.00 to 0.30	0.04 to 0.81
effective inspiral spin	−0.16 to 0.10	−0.54 to 0.04
effective precession spin	0.02 to 0.23	0.04 to 0.51

Inferred merger rate density of NSBH systems*: 12 to 120 yr^{-1} Gpc^{-3}

* Assuming GW200105 and GW200115 are representative of the NSBH population

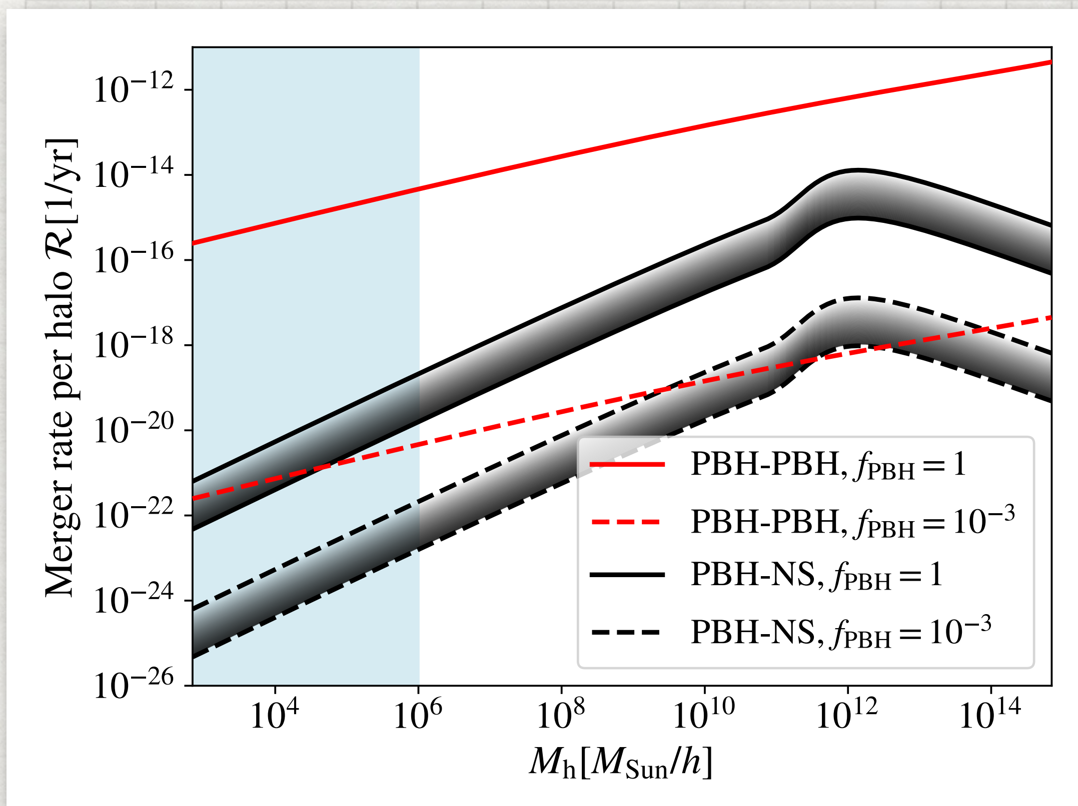
Images: companion masses (left), distance vs inclination (right), both with low (<0.05) and high (<0.99) spin priors for the neutron stars

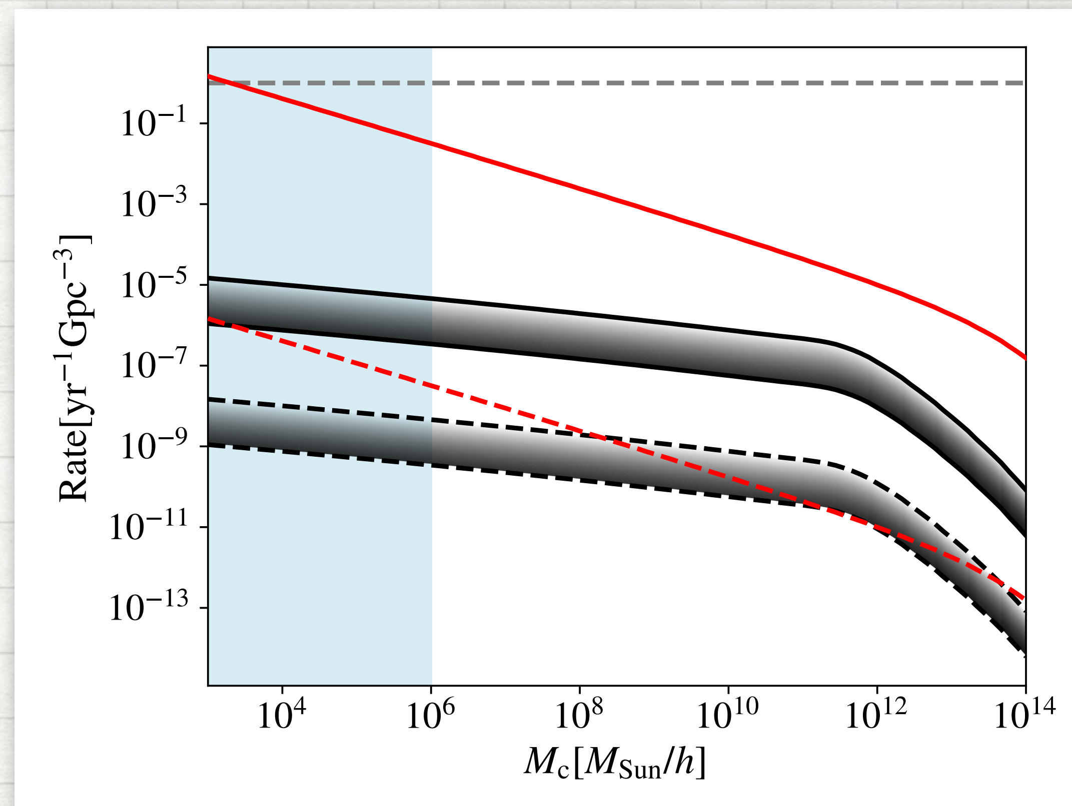
Credits: B.S. Sathyaprakash, Penn State and Cardiff University



PBH-Neutron star binaries?

- **DM halo properties from simulations**
- **Stellar mass — halo mass connection for estimating the number of NS**
- **Capture cross section** $\sigma = 2\pi \left(\frac{85\pi}{6\sqrt{2}} \right)^{2/7} G_N^2 M^{12/7} \mu^{2/7} c^{-10/7} v_{\rm rel}^{-18/7}$





- **Assumes** $\rho_{\rm PBH}(r) = f_{\rm PBH}\rho_{\rm CDM}(r)$
- **Can be enhanced if PBHs are concentrated (equipartition?)**

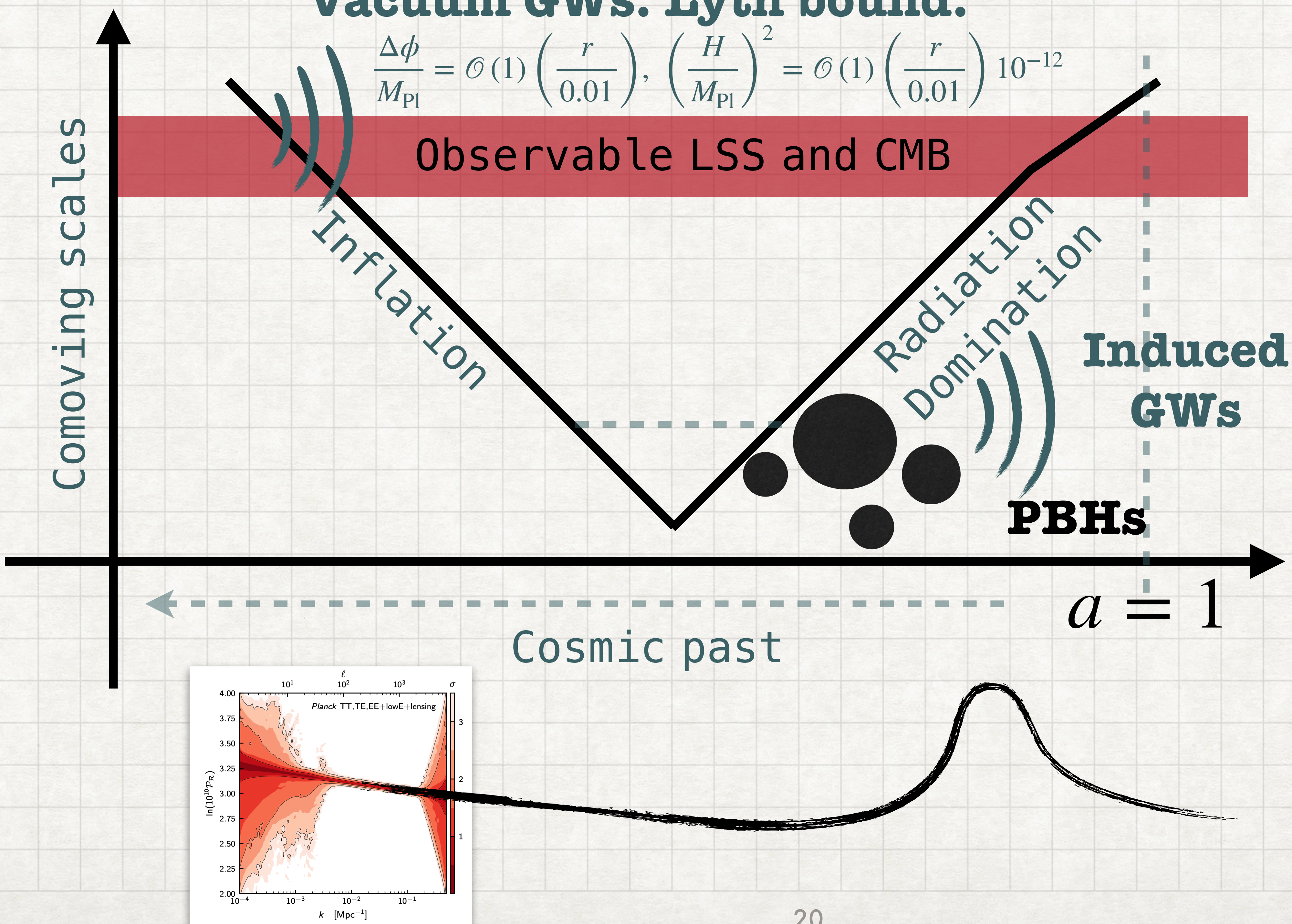
$$\mathscr{R}_{\rm PBH-NS} = f_{\rm PBH}^{-11/28} \mathscr{R}_{\rm PBH-NS}^{\rm no-PDM}$$

Part 4: Primordial GWs

Based on: Beating the Lyth bound by parametric resonance during inflation, arXiv: 2105.12554

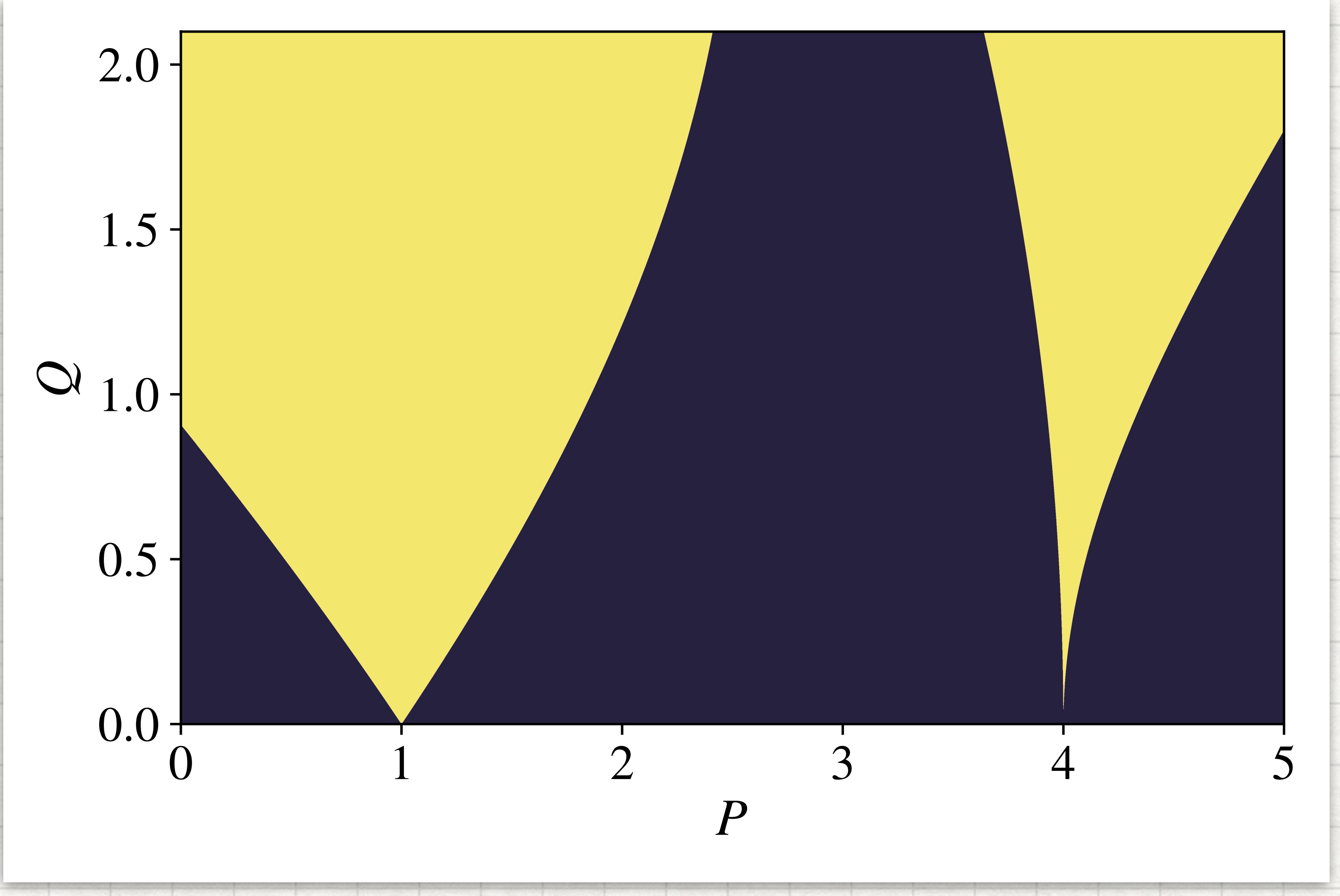
Vacuum GWs. Lyth bound:

$$\frac{\Delta\phi}{M_{\rm Pl}} = \mathcal{O}(1)\left(\frac{r}{0.01}\right), \quad \left(\frac{H}{M_{\rm Pl}}\right)^2 = \mathcal{O}(1)\left(\frac{r}{0.01}\right)10^{-12}$$



Inducing GWs during inflation

- **Parametric resonance** $u(\tau)'' + \left[P - 2Q\cos(2\tau)\right] u(\tau) = 0$
- **Exponential enhancement if in the resonance band**



- **Consider** $\mathscr{L} = -\frac{1}{2}\left(\partial\phi\right)^2 - \frac{1}{2}\left(\partial\chi\right)^2 - V(\phi,\chi)$

$V(\chi)$ → **Sources inflation**

$V(\phi) = -V_0\sqrt{2\epsilon_\phi}\frac{\phi}{M_{\rm Pl}} + \Lambda(\phi)\cos\left(\frac{\phi}{f_{\rm a}}\right) + V_{\rm m}(\phi)$ → **Oscillating field**

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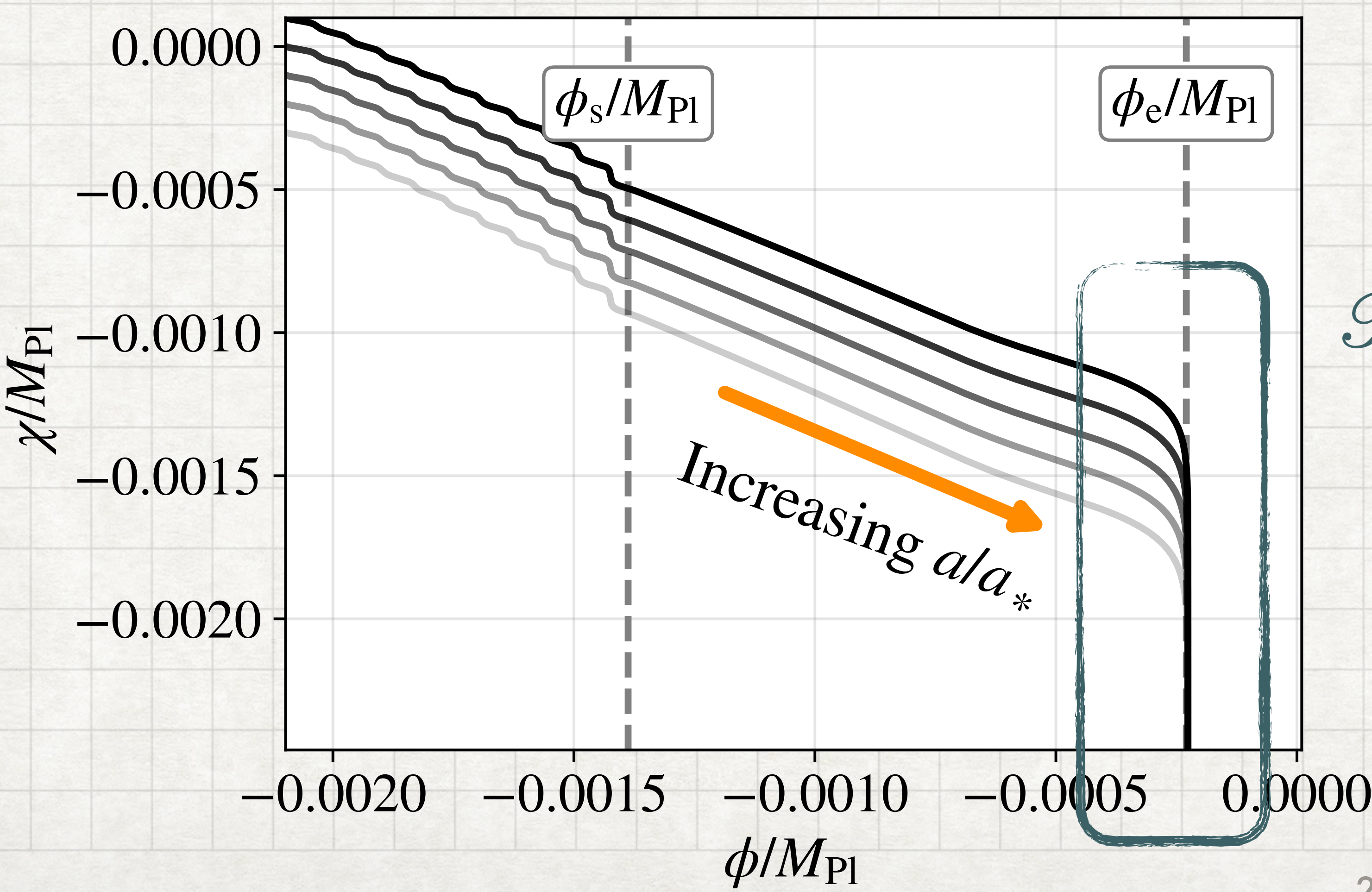


$$\mathscr{R}_{\rm c} \sim \frac{\partial N}{\partial\phi^a}\delta\phi^a \sim \frac{\partial N}{\partial\chi}\delta\chi$$

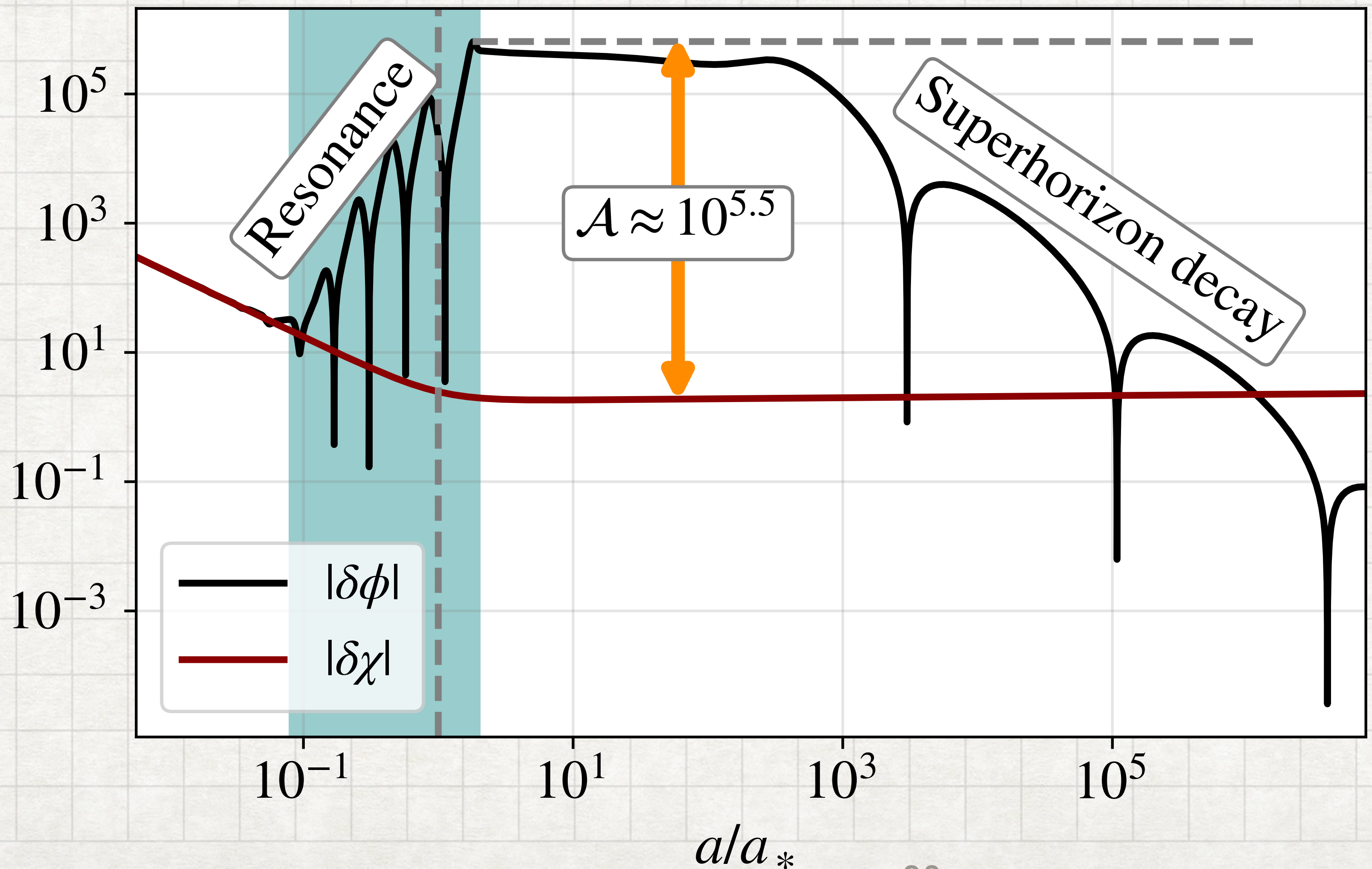
Mode functions

Non-linear source

$$\ddot{\delta\chi}_k + 3H\dot{\delta\chi}_k + \frac{k^2}{a^2}\delta\chi_k = \frac{\sqrt{2\epsilon_\chi}}{M_{\rm Pl}}\left[\ddot{\phi}\delta\phi_k + \boxed{\mathcal{S}_k}\right],$$

Harmonic oscillations

$$\ddot{\delta\phi}_k + 3H\dot{\delta\phi}_k + \left(\frac{k^2}{a^2} + \boxed{\mathcal{M}^2_{\rm eff}}\right)\delta\phi_k = 0$$

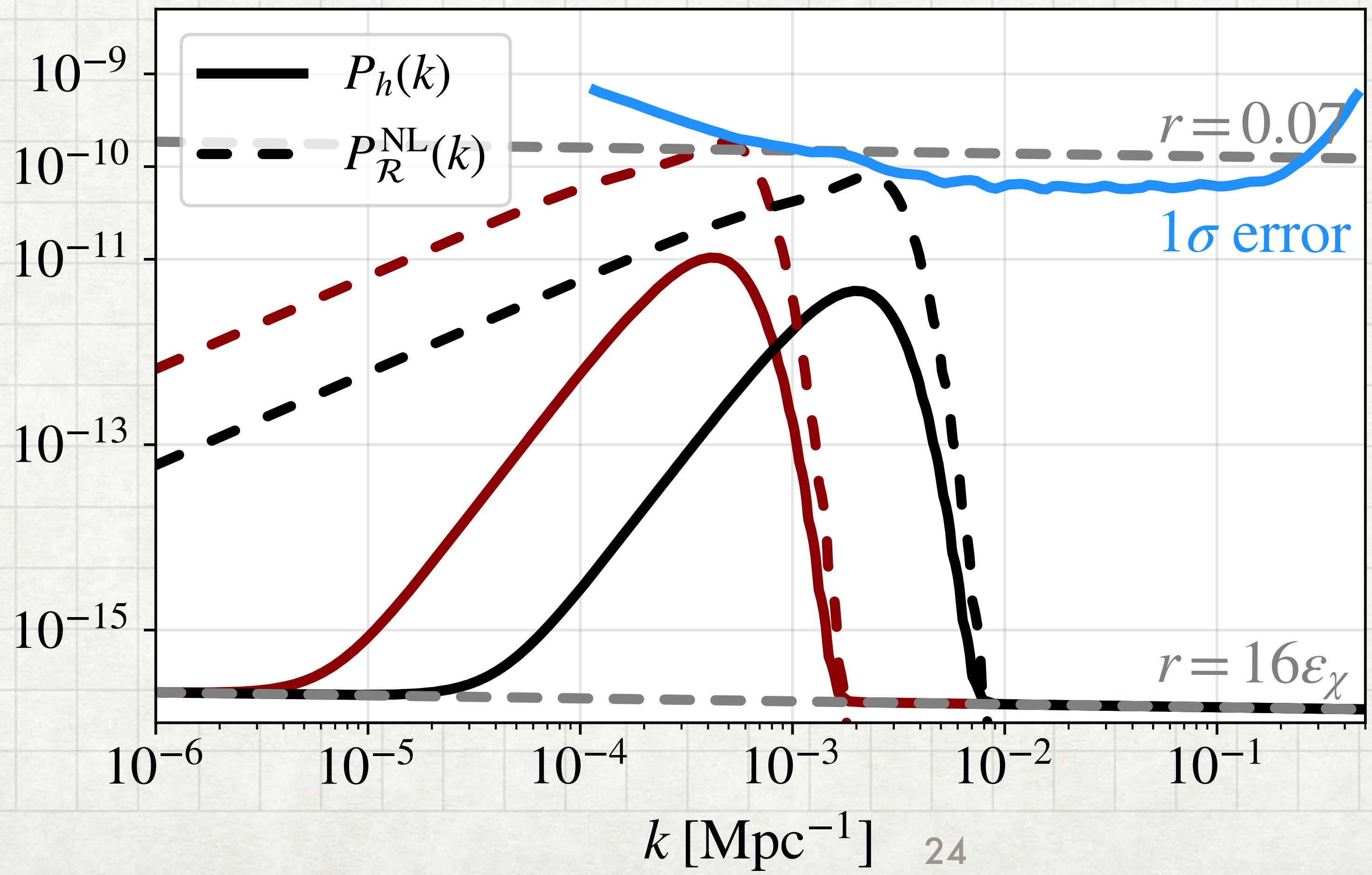


Enhanced tensor modes

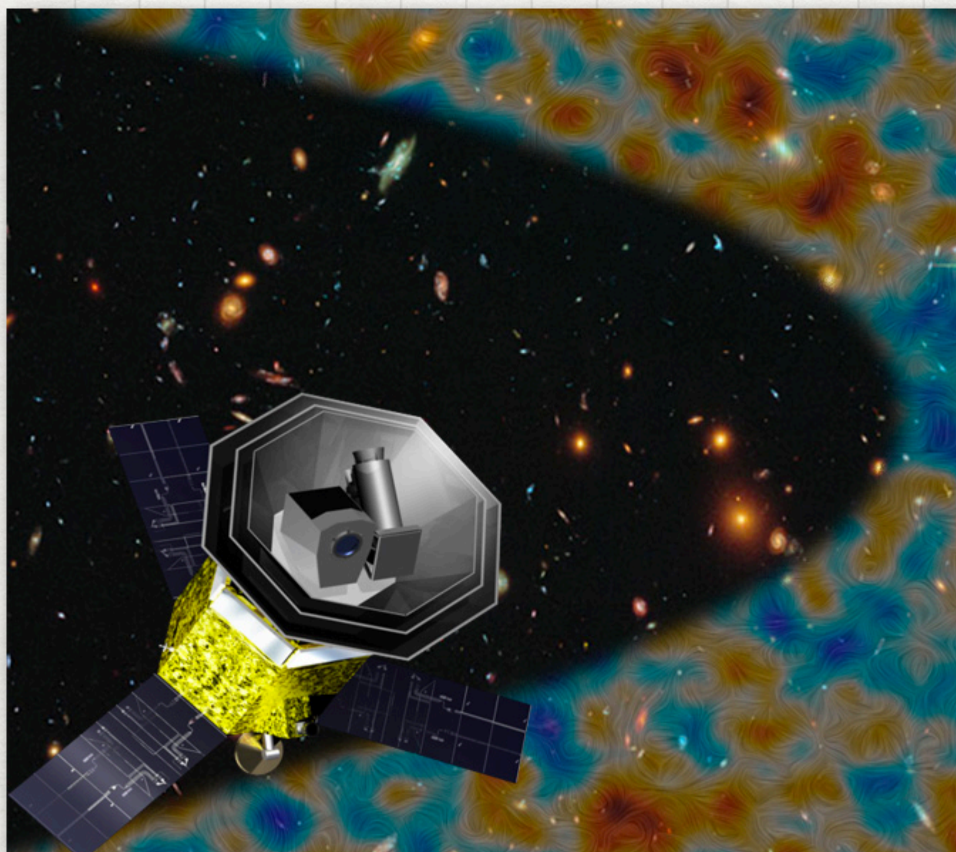
$$\ddot{h}_k^\lambda + 3H\dot{h}_k^\lambda + \frac{k^2}{a^2}h_k^\lambda = \boxed{\mathcal{T}_k^\lambda(t)}$$

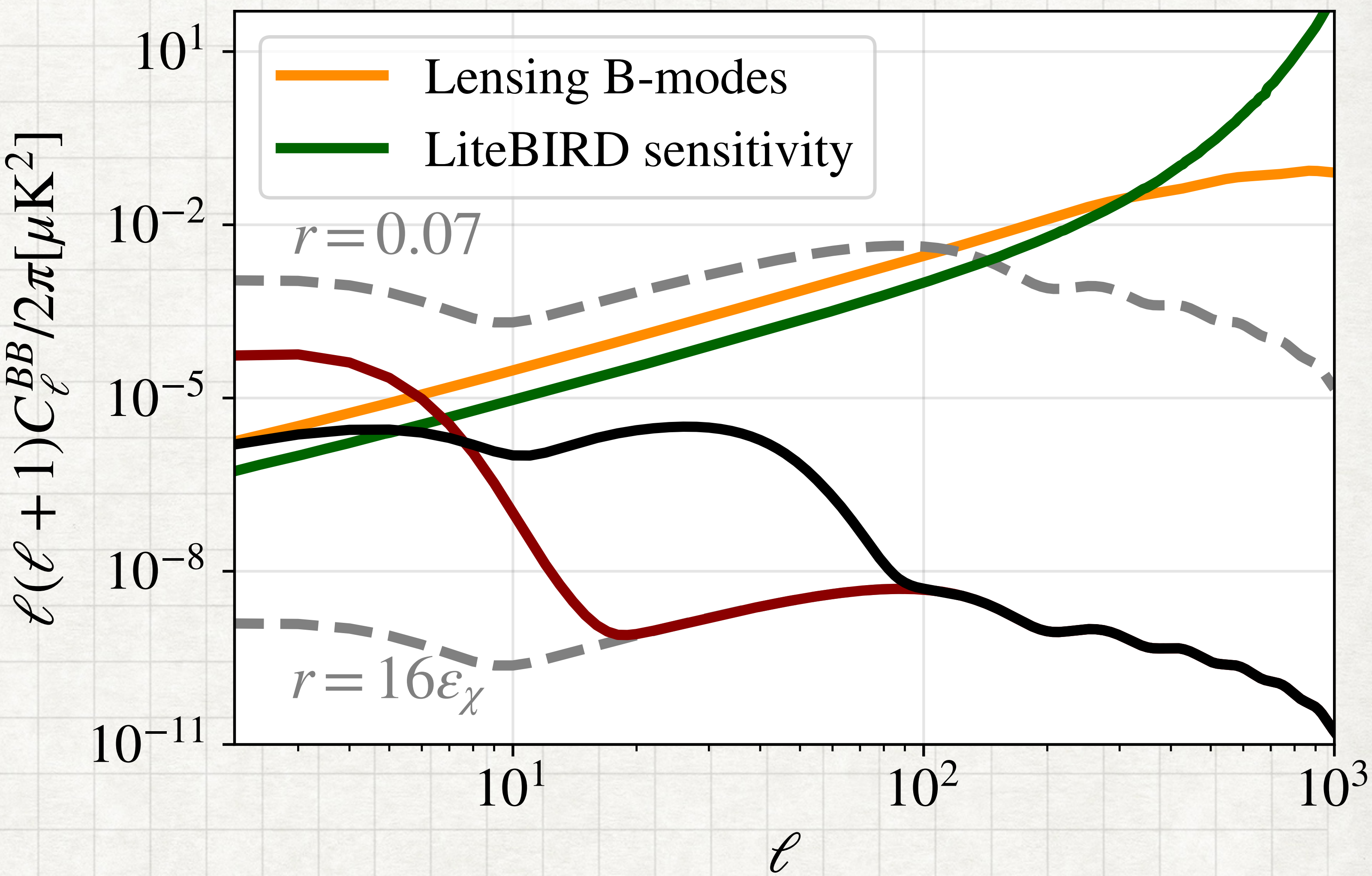
Non-linear source

$$\mathcal{T}_k^\lambda(t) = \frac{2}{M_p^2}\int \frac{d^3\mathbf{p}}{(2\pi)^3} e_{ij}^\lambda(\mathbf{k}) \frac{p_i p_j}{a^2} \delta\phi_{|\mathbf{p}|}\delta\phi_{|\mathbf{k}-\mathbf{p}|}$$



Detectability





Summary

- 1. Astrophysical black hole clustering and correlations with galaxy distribution: how to use redshift-unknown sources for cosmology?

- 2. AGWB: a complementary probe. Important for interpreting possible future detection. Can probe high-redshift populations.

- 3. The origin of LIGO-Virgo-KAGRA black holes: PBH-PBH is likely, PBH-NS — not that much.

- 4. How to enhance primordial GWs: parametric resonance during inflation and induced gravitational waves.