Title: Exploring the universe with gravitational waves

Speakers: Valeri Vardanyan

Series: Cosmology & Gravitation

Date: September 21, 2021 - 11:00 AM

URL: https://pirsa.org/21090003

Abstract: In this talk, I will present recent results about gravitational wave cosmology. I will argue that the spatial clustering of gravitational wave sources provides a wealth of invaluable information concerning the origin of binary black holes and the propagation law of gravitational waves. The former can clarify whether the observed black hole binaries are of stellar or primordial origin. The latter is important for constraining deviations from General Relativity on cosmological scales because such deviations predict modified propagation of gravitational waves compared to General Relativity. I will then explore the possibility of observed black holes having primordial origin and present its consequences for expected merger rates of such black holes and neutron stars. Time permitting, I will also summarize our recent progress made in the field of primordial gravitational waves and the implications for the inflationary models.

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

EXPLORING THE UNIVERSE WITH GRAVITATIONAL WAVES

VALERI VARDANYAN

wpi World Premier International Research Center Initiative

科研費 KAKENHI

SEPTEMBER 21, 2021

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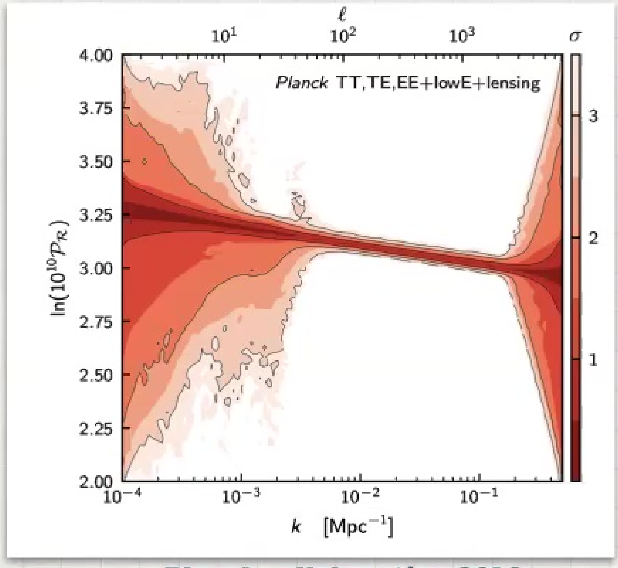
STANDARD MODEL OF THE UNIVERSE

- **Inflation in the early universe**
- **Quantum fluctuations explain the observed CMB anisotropies and source the LSS of the late universe**
- **Simplest working scenario: single field ϕ with a flat potential**
- **Produces almost scale-invariant curvature power spectrum**

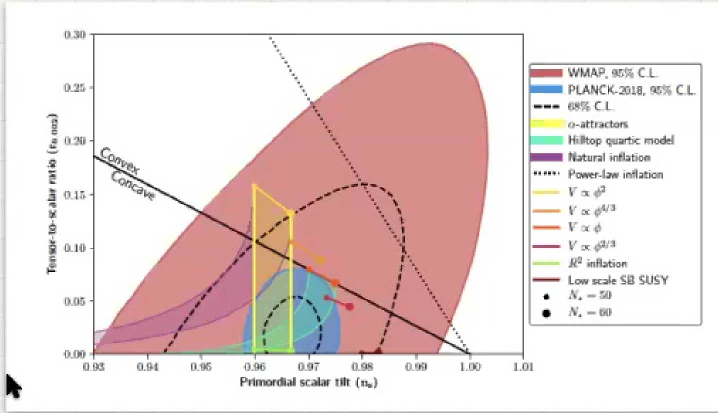


Planck collaboration 2018

$$P_{\mathcal{R}}(k) = \left(\frac{H}{2\pi}\right)^2 \left(\frac{H}{\dot{\phi}}\right)^2 = A_s k^{n_s - 1}$$

PRIMORDIAL GRAVITATIONAL WAVES

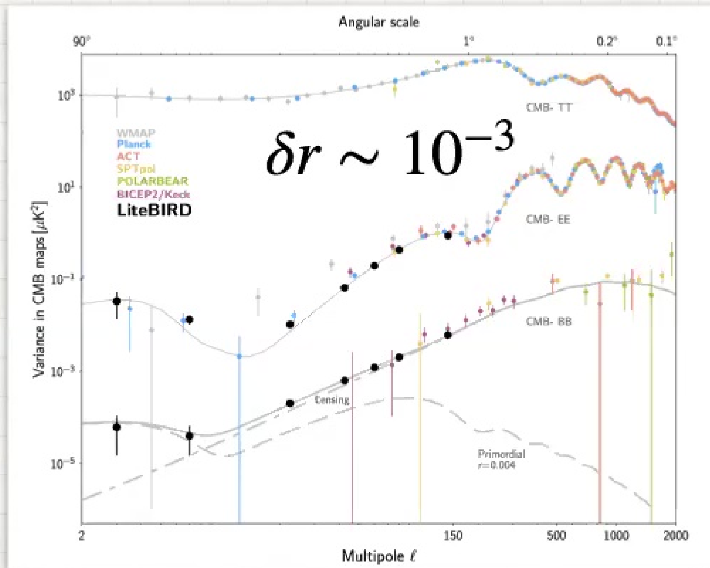
$$P_h(k) = \frac{8}{M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2$$



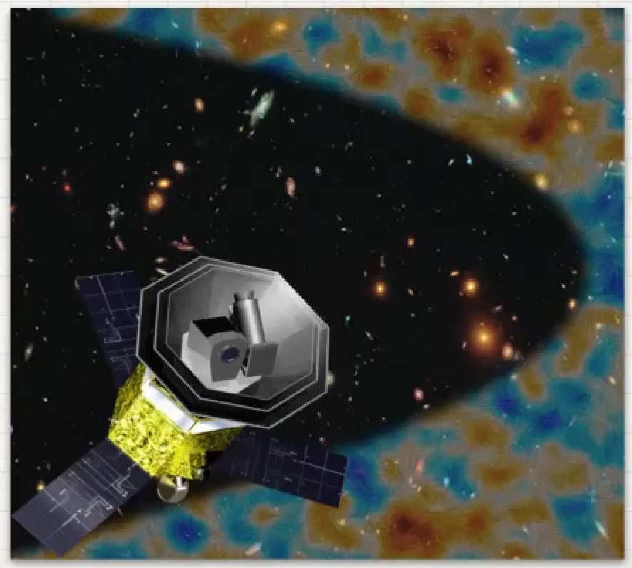
Vacuum GWs. Lyth bound:

$$\frac{\Delta\phi}{M_{\rm Pl}} = \mathcal{O}(1)\left(\frac{r}{0.01}\right)^{1/2},\ V^{1/4} = \mathcal{O}(1)\left(\frac{r}{0.01}\right)^{1/4} 10^{16}\mathrm{GeV}$$

LiteBIRD mission



CMB B-mode polarization



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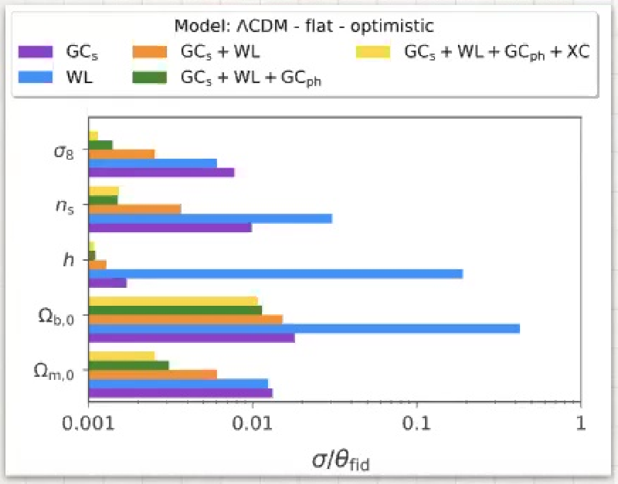
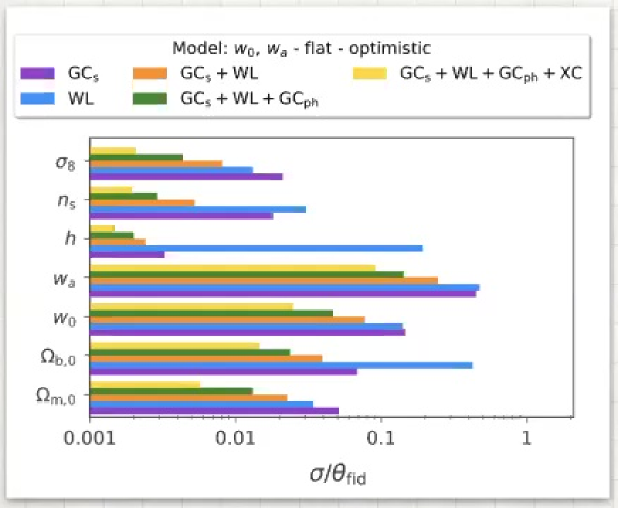
STANDARD MODEL OF THE UNIVERSE





- **ΛCDM in the late universe**
- **Assumes GR + cosmological constant**
- **Still large wiggle-room for interesting alternatives**

- **Modified background history (e.g. $w_0 - w_a$ extension)**
- **Extra degrees of freedom at cosmological scales (e.g. scalar-tensor theories)**

EUCLID collaboration, forecast

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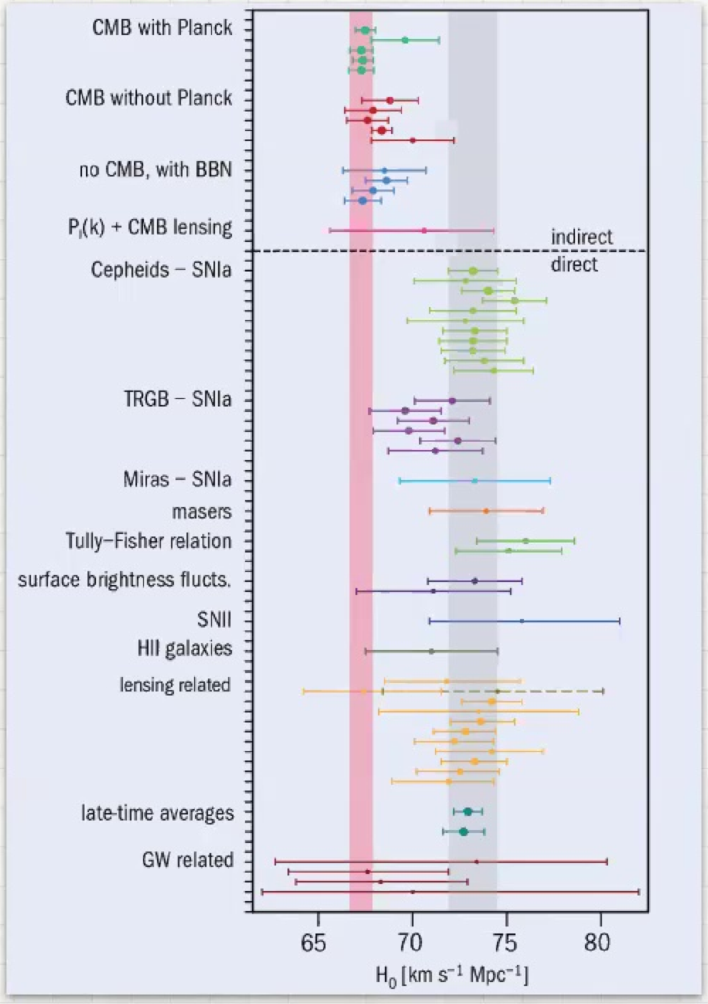
STANDARD MODEL OF THE UNIVERSE



Compilation from di Valentini et al, 2021

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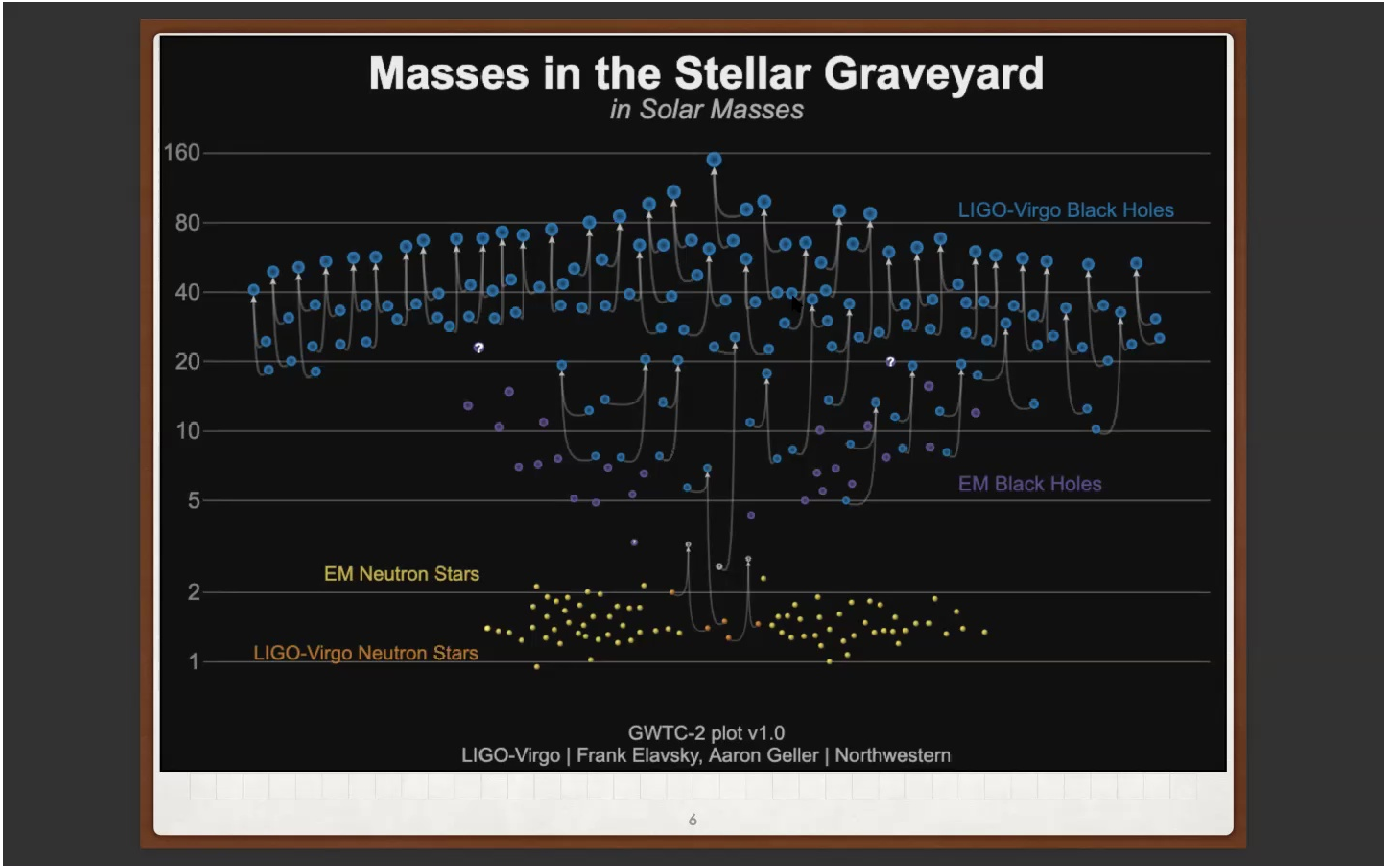
Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
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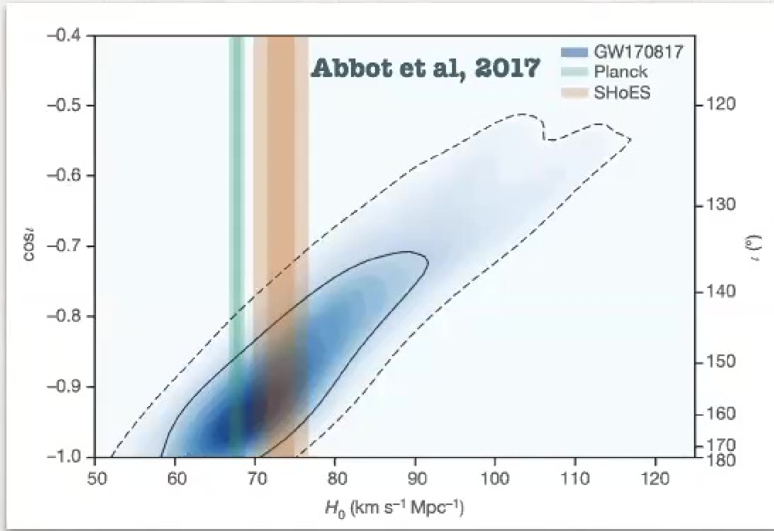
STANDARD SIRENS (SCHUTZ, 1986)

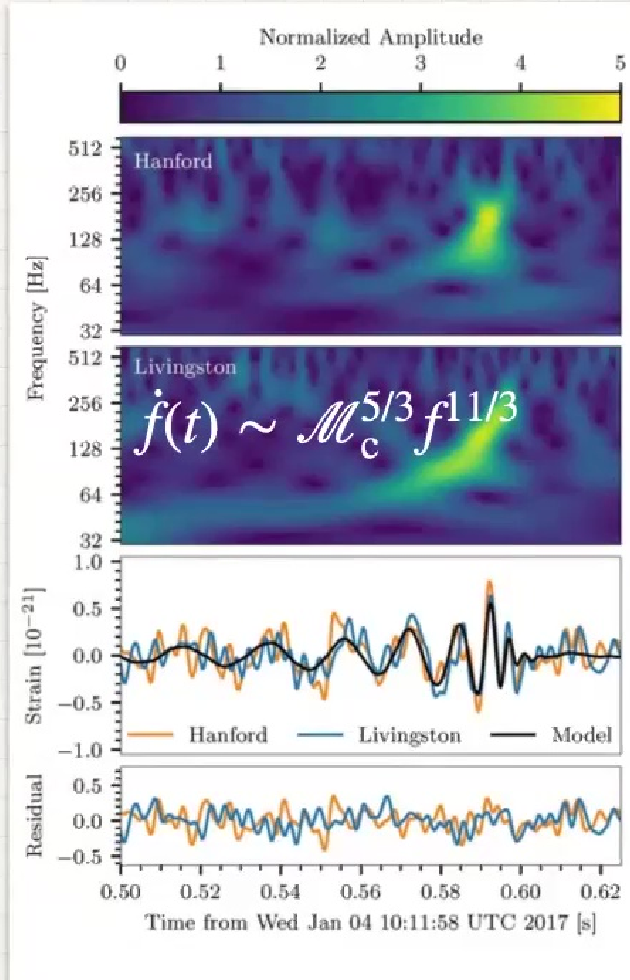
- **GWs measure the luminosity distance**

$$h_\times(t) \sim \frac{\cos\iota}{D_L(z)}\left(\mathcal{M}_c\right)^{5/3} f(t)^{2/3}\sin\Phi(t)$$

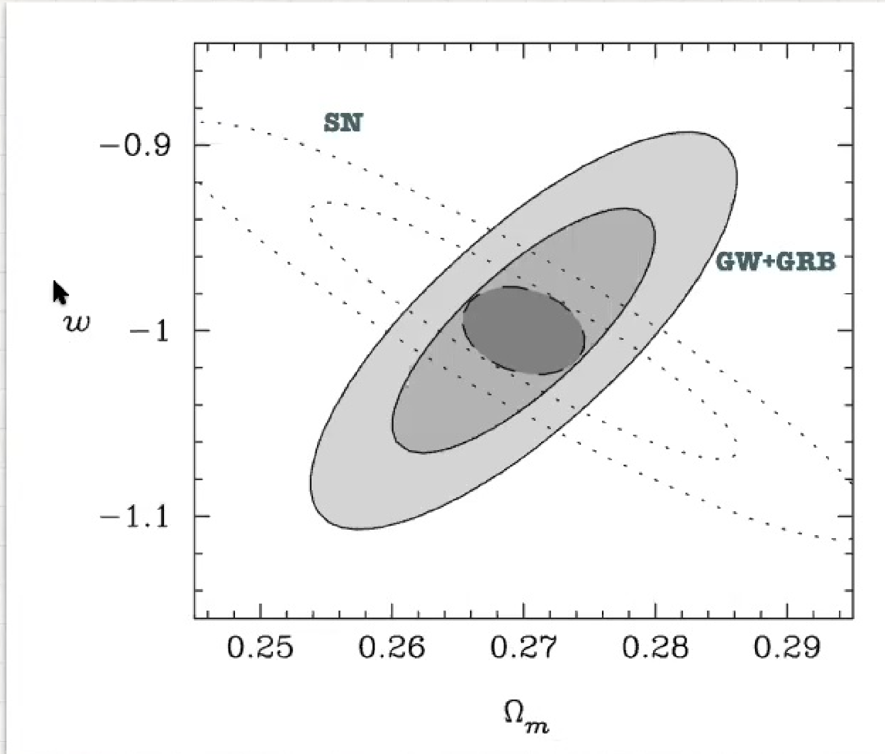
$$h_+(t) \sim \frac{1+\cos^2\iota}{D_L(z)}\left(\mathcal{M}_c\right)^{5/3} f(t)^{2/3}\cos\Phi(t)$$

- **Need electromagnetic counterpart?**





GW+GRB

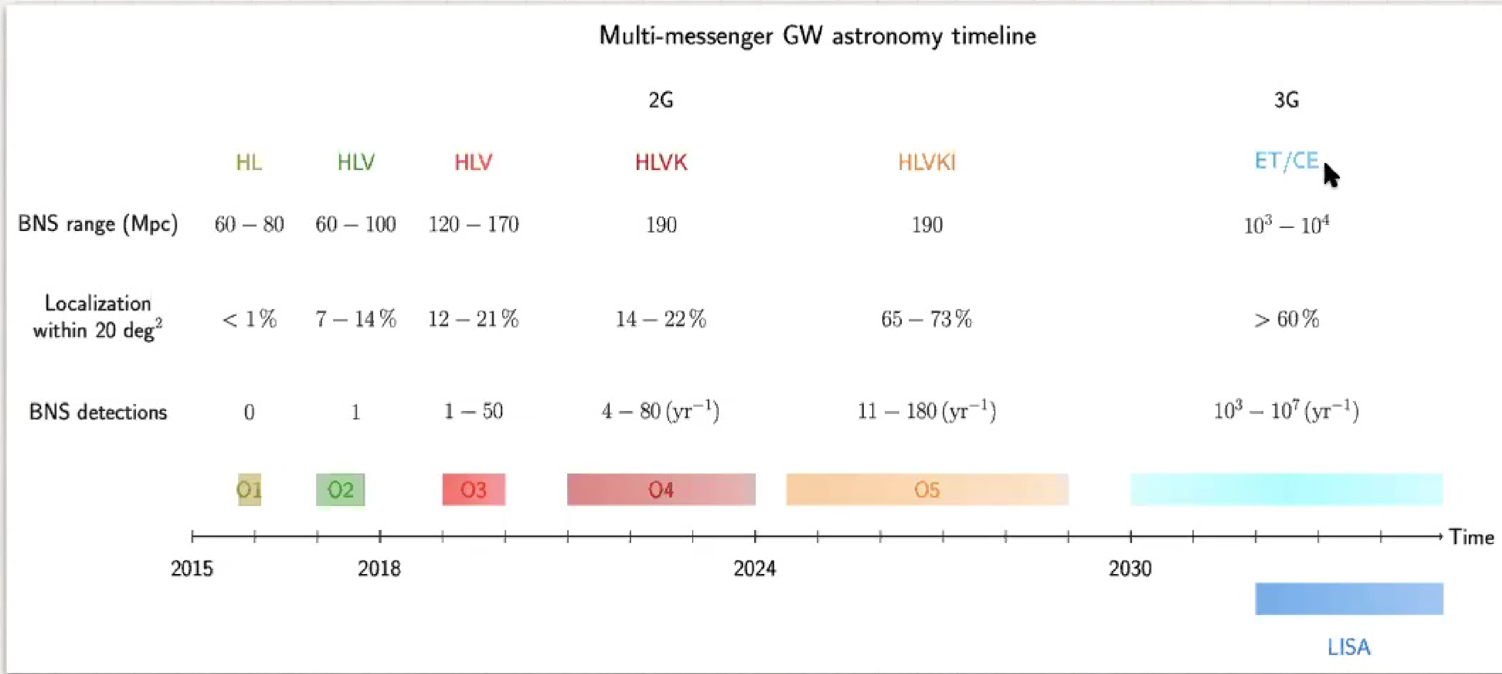


Holz, Hughes, 2005

Dalal, Holz, Hughes, Jain, 2006

Nissanke, Holz, Hughes, Dalal, Sievers, 2009

ANTICIPATED TIMELINE



Summary from Ezquiaga, Zumalacarregui, 2018

IN THIS TALK

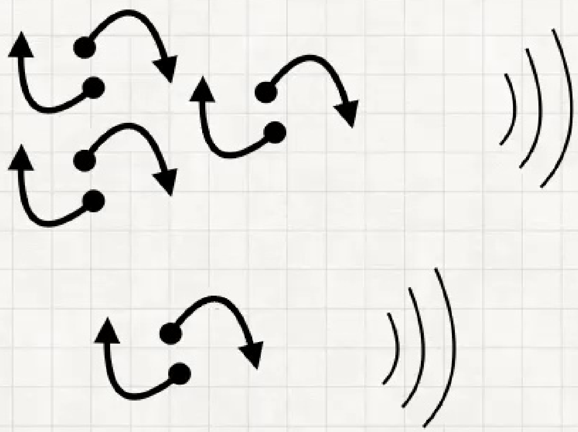
- Part 1: Clustering of black hole binaries — cosmology without electromagnetic counterparts. Testing the GW propagation in the late universe.
- Part 2: Characterizing the stochastic background.
- Part 3: The origin of black holes: Primordial or astrophysical? Merger rates and bias.
- Part 4: What can GWs teach us about the early universe? Tensor modes from matter sources — beyond the vacuum

Canas-Herrera, Contagian, Vardanyan, PRD 2020
Canas-Herrera, Contagian, Vardanyan, APJ 2021
Sasaki, Takhistov, Vardanyan, Zhang, In prep
Cai, Jiang, Sasaki, Vardanyan, Zhou, arXiv:2105.12554

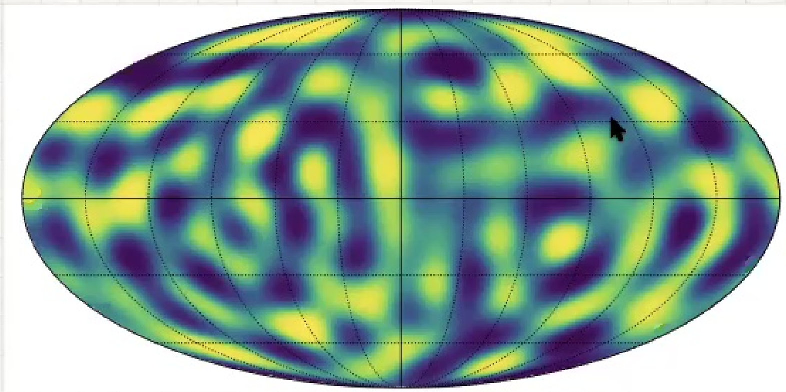
Part 1: Resolved GW sources

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

Analysis code: GitHub.com/valerivardanyan/GW-Cosmo

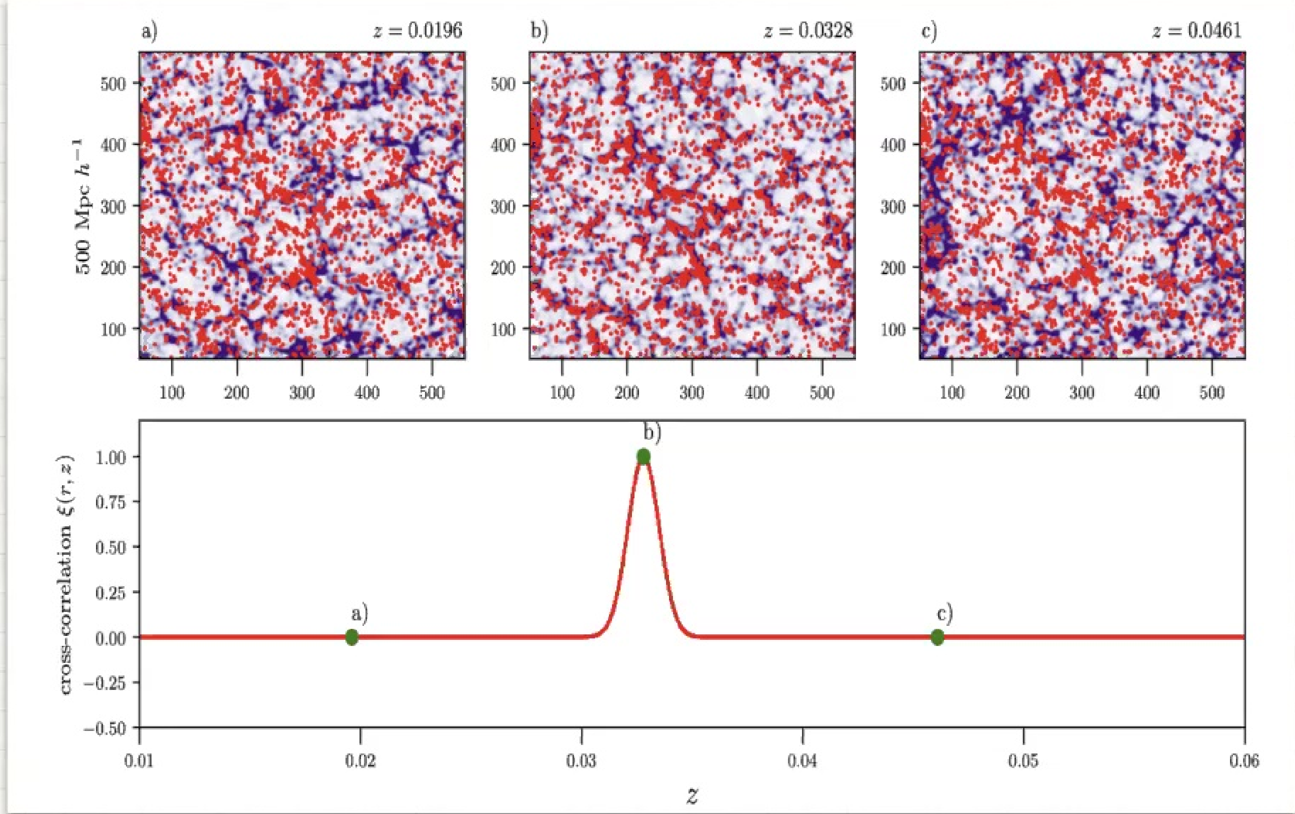


Clustering of resolved compact object binaries



The resulting observable is the projected number count.

Redshift estimation



Oguri, 2016

Bera, Rana, More, Bose, 2020

Mukherjee, Wandelt, Nissanke, Silvestri, 2020

Tomographic cross-corrs: what are they good for?

$$h_{ij}'' + \left[2 + \boxed{\alpha_M(\eta)}\right] \mathscr{H} h_{ij}' + \left[\boxed{\left(1 + \alpha_{\mathrm{T}}(\eta)\right)} k^2 + \boxed{m_{\mathrm{T}}^2(\eta)}\right] h_{ij} = \boxed{\Pi_{ij}}$$

Dumping of GWs | **GW speed** | **Massive gravitons** | **Anisotropic stress from matter**

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Connection to large-scale structure

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

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

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

$$\nabla^2\Psi \sim \mu(\eta, k)\rho\delta$$

$$\nabla^2\left(\Psi + \Phi\right) \sim \Sigma(\eta, k)\rho\delta$$

$$\eta \equiv \frac{\Phi}{\Psi} = 2\frac{\Sigma(\eta, k)}{\mu(\eta, k)} - 1$$

$\eta \neq 1 \rightarrow \alpha_{\rm M} \neq 0$ **or** $\alpha_{\rm T} \neq 0$

Saltas, Sawicki, Amendola, Kunz, 2014

Tomographic cross-corrs: what are they good for?

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

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

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

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

Common parametrization

Belgacem, Dirian, Foffa, Maggiore, 2018

Power spectra

$$C_{\rm GW}(\ell) = \int_0^\infty dz\, \frac{H(z)}{\chi^2(z)} W^2_{\rm GW}(z) b^2_{\rm gw}(z) P\left(\frac{\ell+1/2}{\chi(z)}, z\right)$$

$$C_{\rm gal}(\ell) = \int_0^\infty dz\, \frac{H(z)}{\chi(z)^2} W^2_{\rm gal}(z) b^2_{\rm gal}(z) P\left(\frac{\ell+1/2}{\chi(z)}, z\right)$$

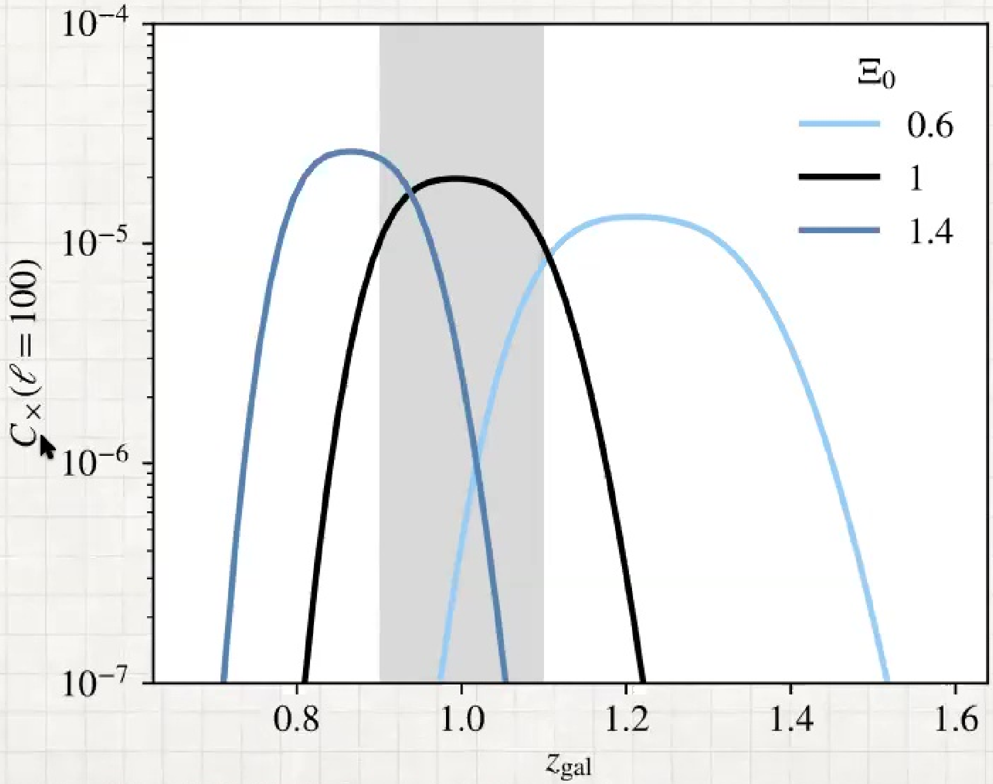
$$C^{ij}_{\times}(\ell) = \int_0^\infty \mathrm{d}z \frac{H(z)}{\chi^2(z)} W^i_{\rm GW}(z) W^j_{\rm gal}(z) \times b_{\rm gw}(z) b_{\rm gal}(z) P\left(\frac{\ell+1/2}{\chi(z)}, z\right)$$

$$\mathrm{Cov}\left[C^{ij}(\ell) C^{mn}(\ell')\right] = \frac{\delta_{\ell\ell'}}{(2\ell+1) f_{\rm sky}} \times \left(\tilde{C}^{im}\tilde{C}^{jn} + \tilde{C}^{in}\tilde{C}^{jm}\right)$$

$$\tilde{C}^{im}(\ell) = C^{im}(\ell) + \frac{\delta_{im}}{\bar{n}}$$

Tomographic cross-corrs: what are they good for?

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

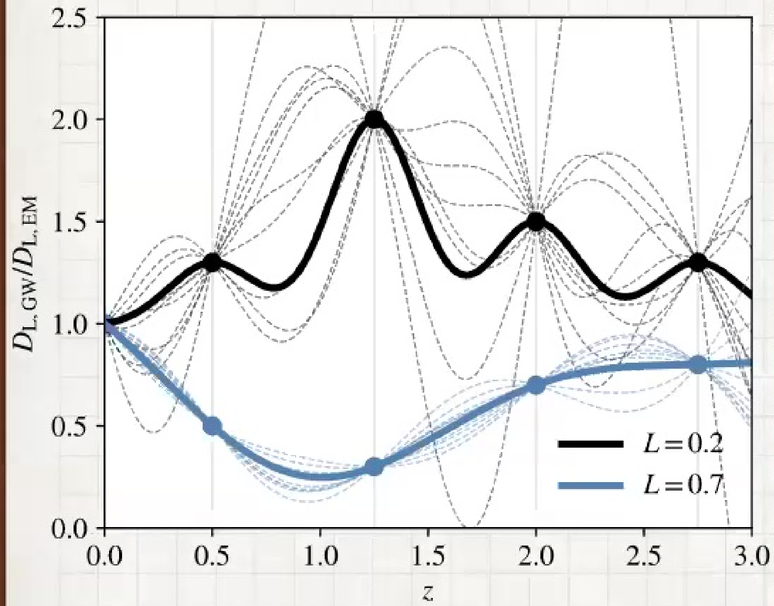


Mukherjee, Wandelt, Silk, 2012.15316 for a related analysis

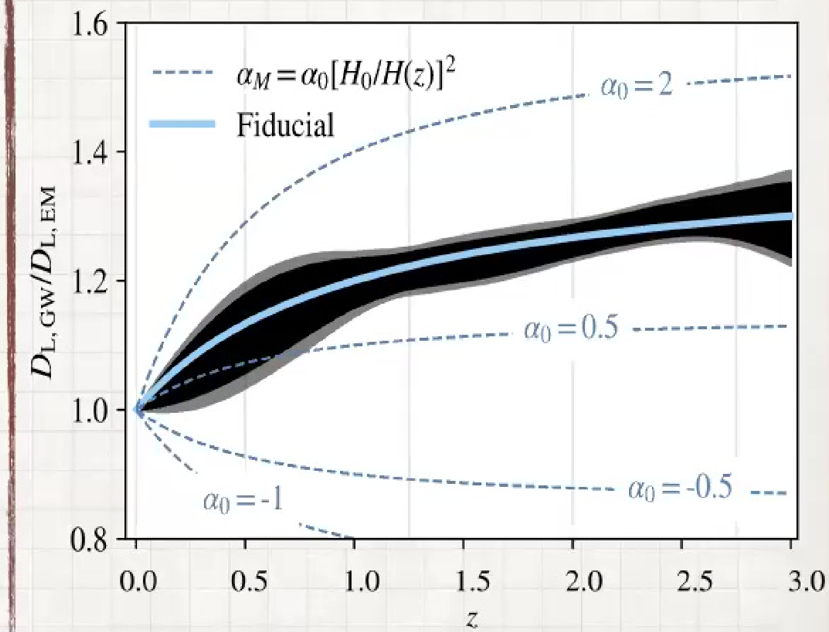
Gaussian process reconstruction

Not very general

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



Reconstruct the shape model independently



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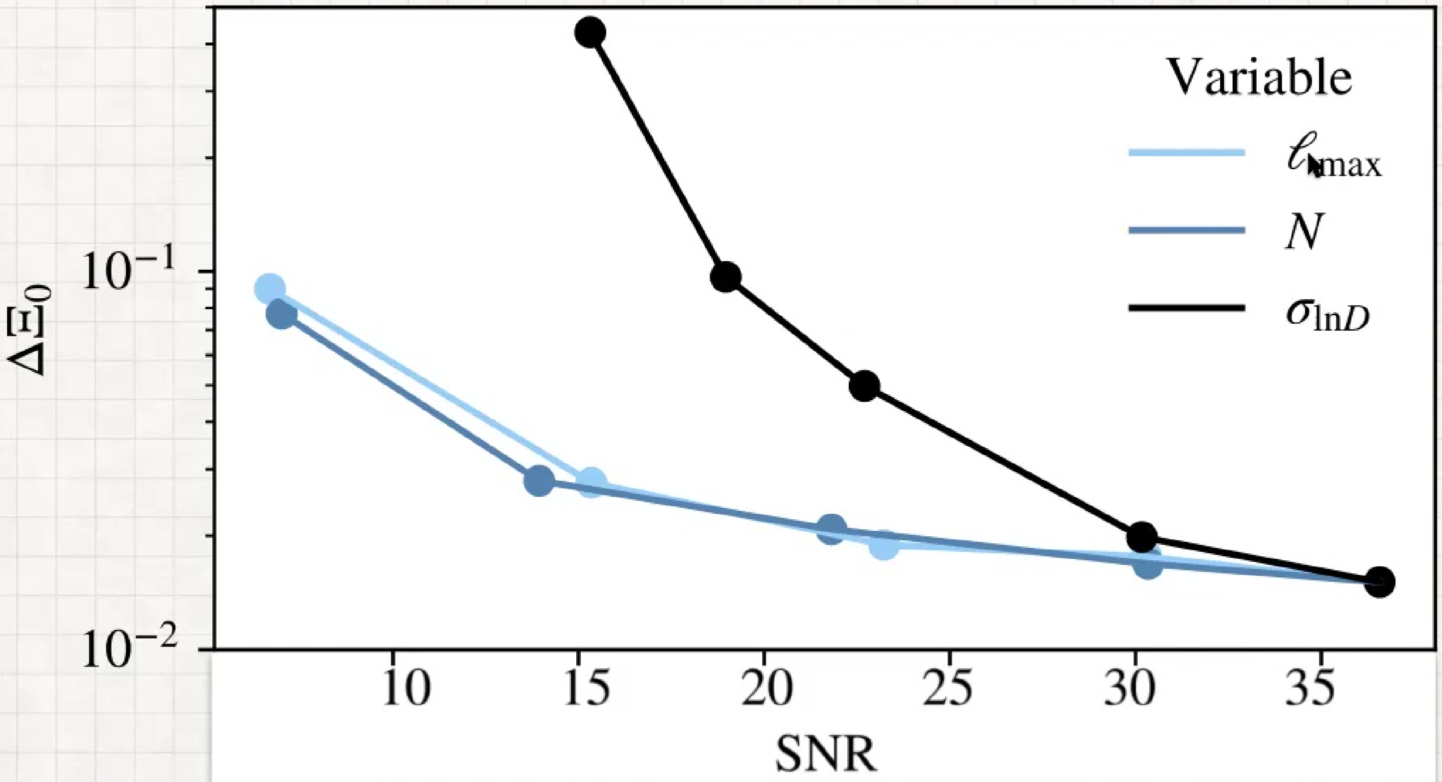
Observational strategy



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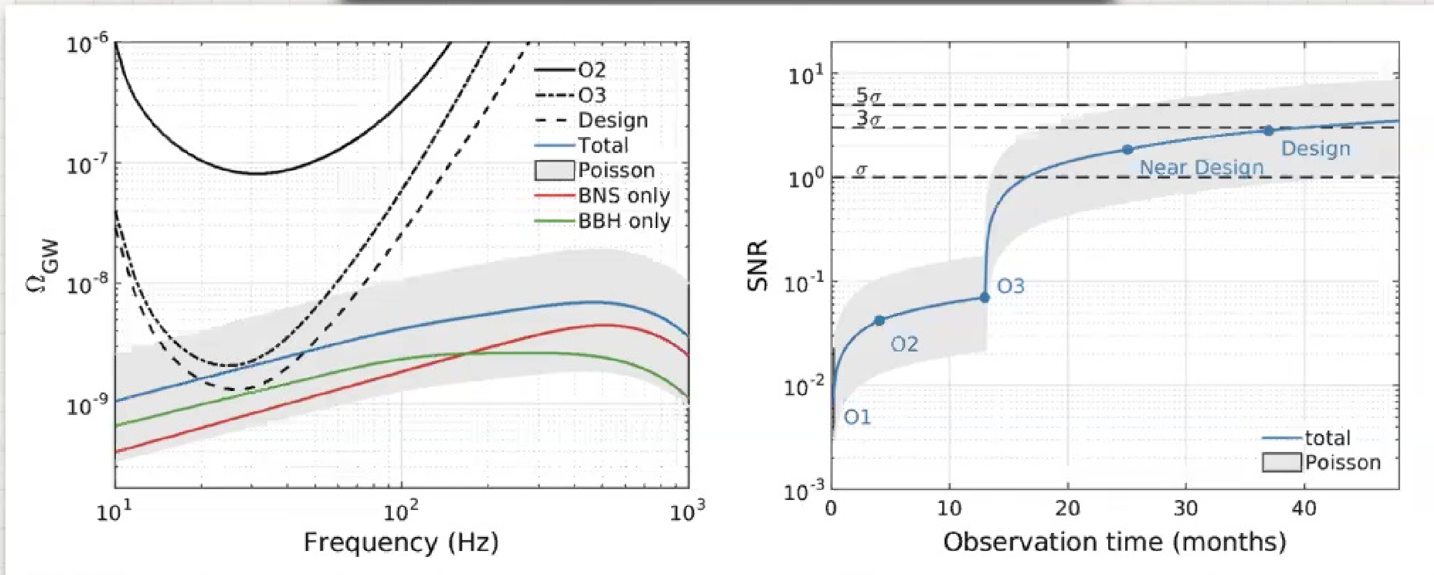
Part 2: Astrophysical GW background

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

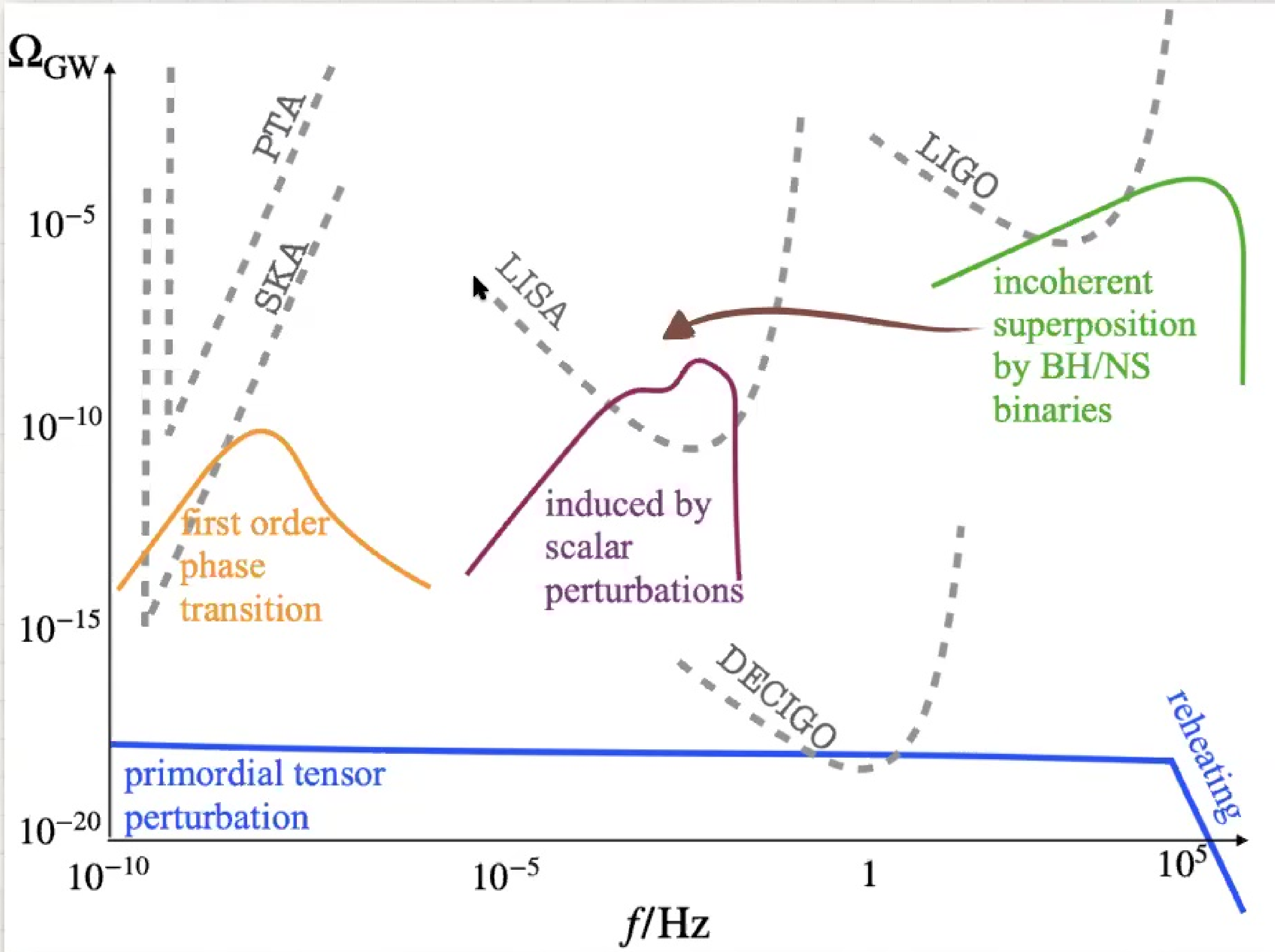
Analysis code: GitHub.com/valerivardanyan/GW-GC-CrossCorr

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



LIGO/VIRGO Collaboration

Multitude of sources



Modelling the signal

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

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

$$\Omega_{\rm GW}(\hat{r}) = \int dr\, r^2 \boxed{\mathscr{K}(r)}\, \bar{n}(r) \left(\delta_{\rm GW}(\vec{r}) + 1\right)$$

Astrophysical kernel

Modelling the signal

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

Astrophysical kernel

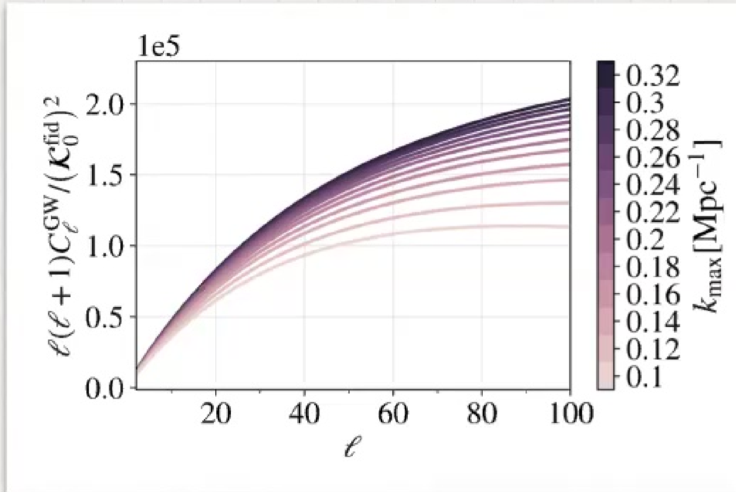
From real space to angular correlations

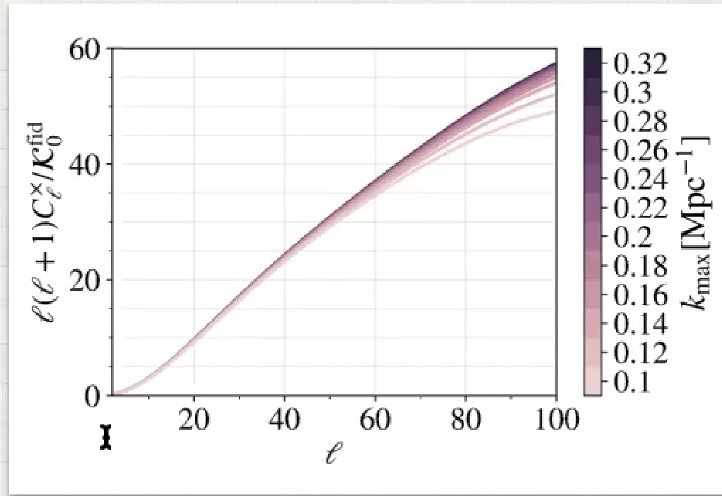
$$C_\ell^{\mathrm{GW}} = 4\pi \int_{k_{\min}}^{k_{\max}} \frac{dk}{k} \,|\, \delta\Omega_\ell \,|^2\, \mathcal{P}(k) + B_\ell^{\mathrm{GW}}$$

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

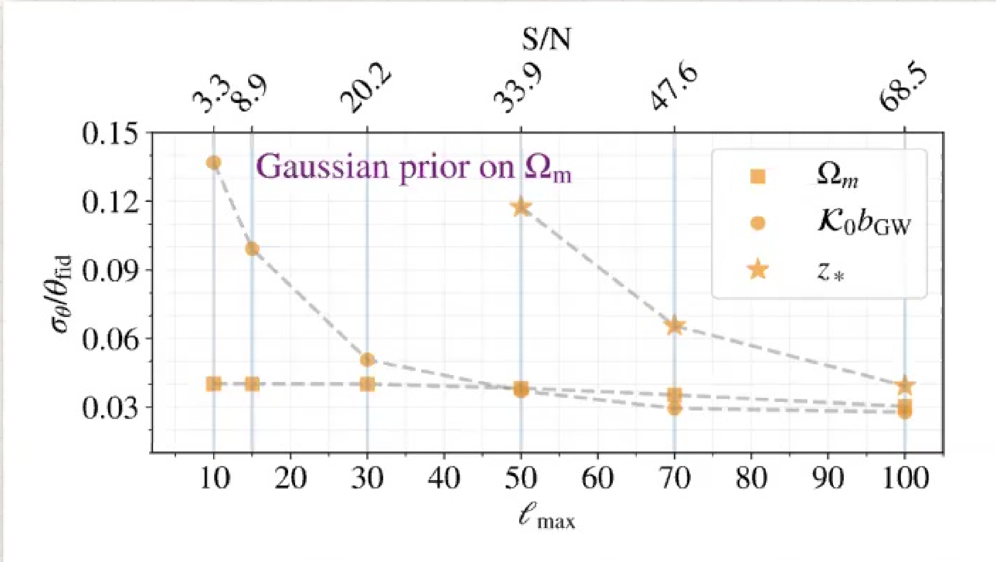
No relativistic corrections for now!

Sensitivity on non-linearities



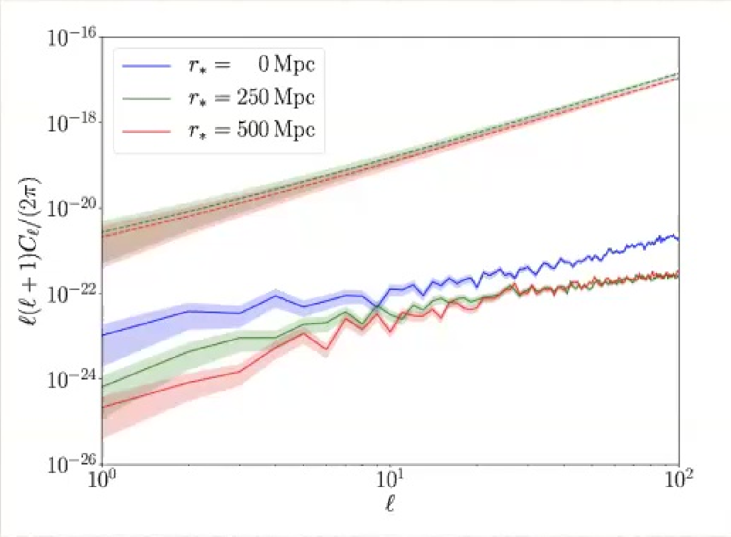


What to expect?



- **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

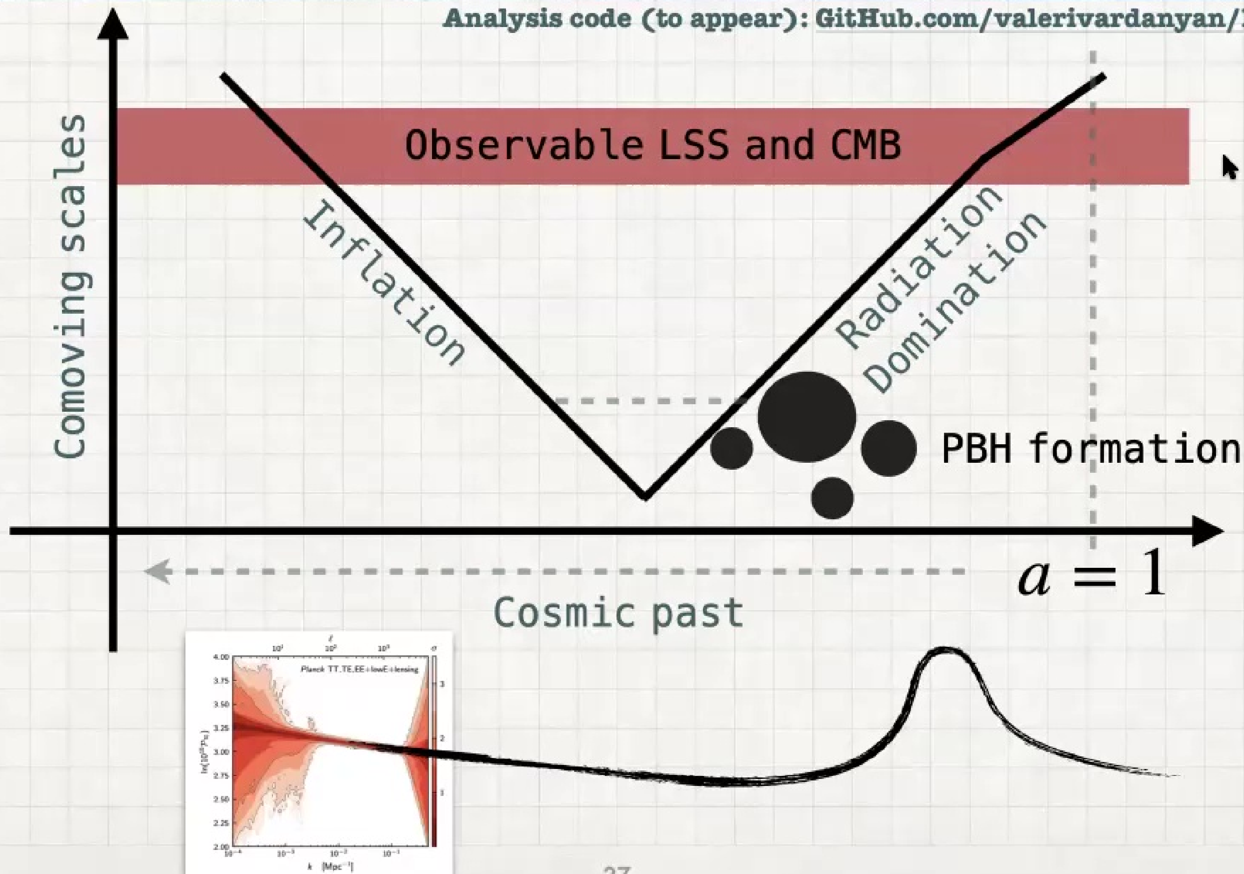
$$\mathrm{Var}C_\ell^\times = \frac{\left(C_\ell^{\mathrm{GW}} + B_\ell^{\mathrm{GW}}\right)\left(C_\ell^{\mathrm{GC}} + B_\ell^{\mathrm{GC}}\right) + \left(C_\ell^\times + B_\ell^\times\right)^2}{2\ell+1}$$

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

Analysis code (to appear): GitHub.com/valerivardanyan/PBH-NS



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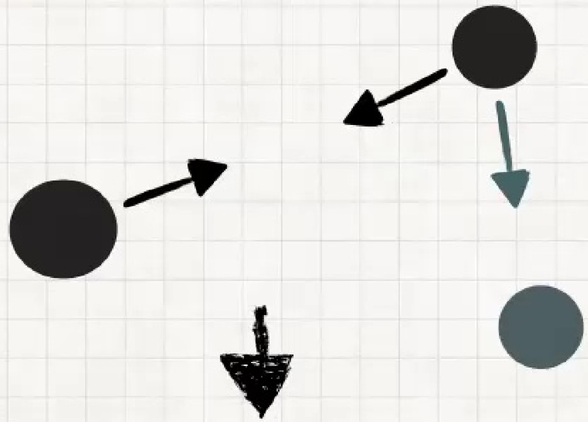
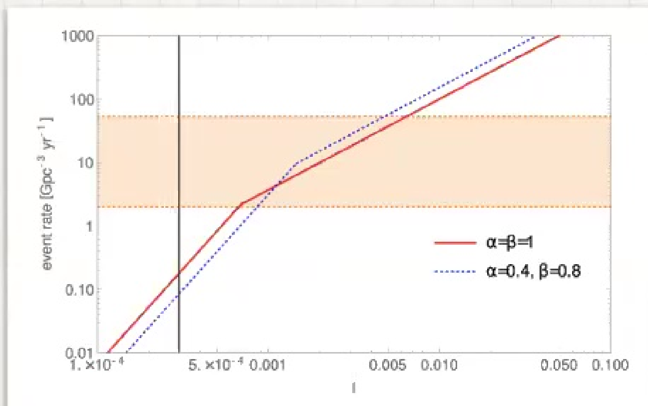
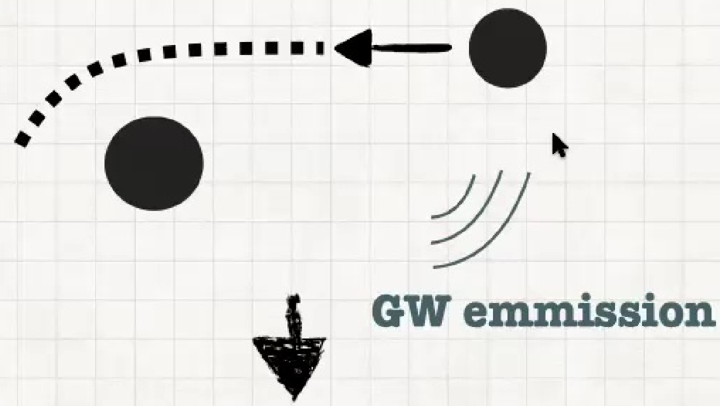
Part 3: PBH mergers



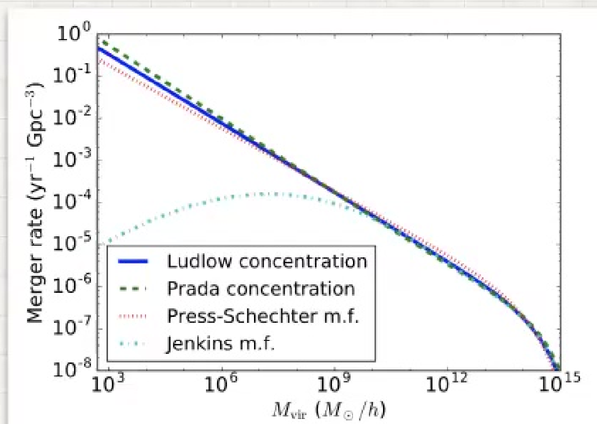
PBH binary



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



PBH binary



Bird et al, 2016

PBH-Neutron star binaries?

FACT SHEET

GW200105 GW200115

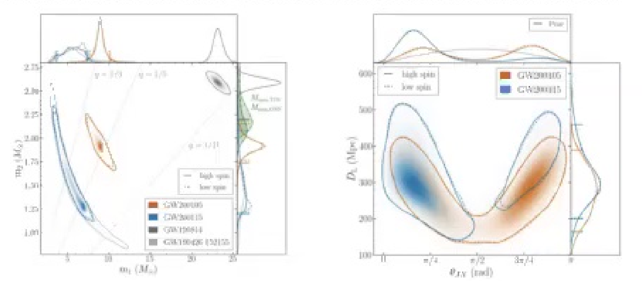
First observation of neutron star-black hole (NSBH) binaries

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

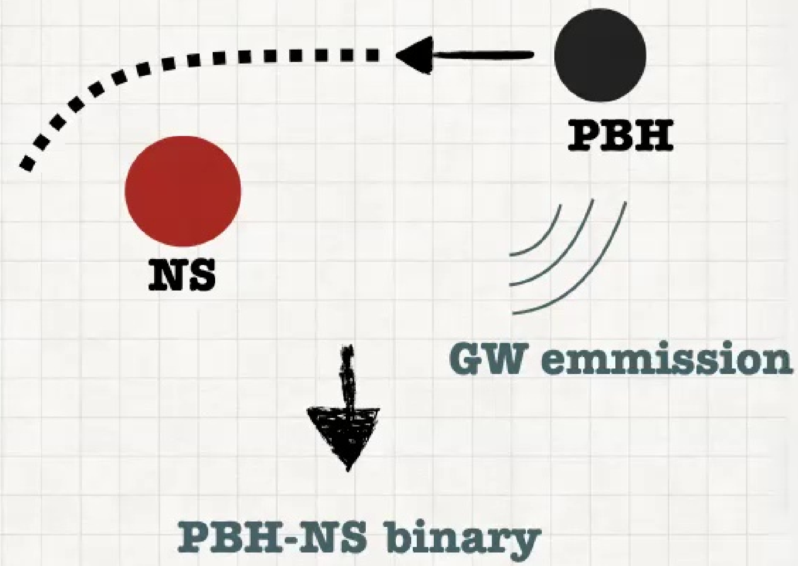
	GW200105	GW200115
observed by	LIGO Livingston and Virgo	LIGO Livingston & Hanford and Virgo
date, time	5 Jan 2020, 16:24:26 UTC	15 Jan 2020, 04:23:10 UTC
likely distance	170 to 390 Mpc	200 to 450 Mpc
source redshift	0.04 to 0.08	0.05 to 0.10
signal-to-noise ratio	13.9	11.6
false alarm rate	< 1 in 2.8 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 $yr^{-1}\,Gpc^{-3}$

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

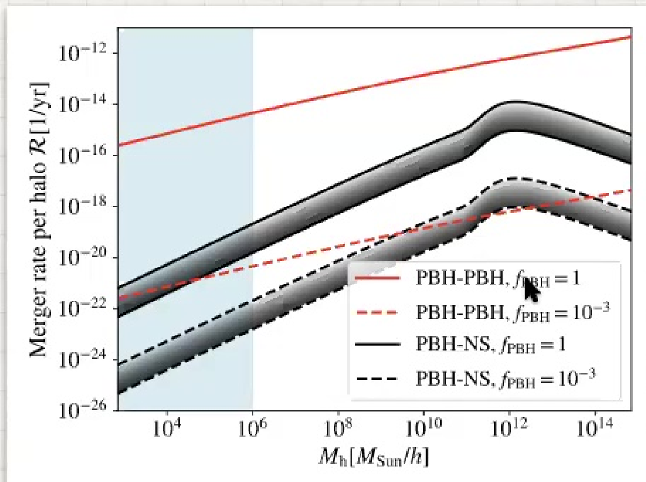


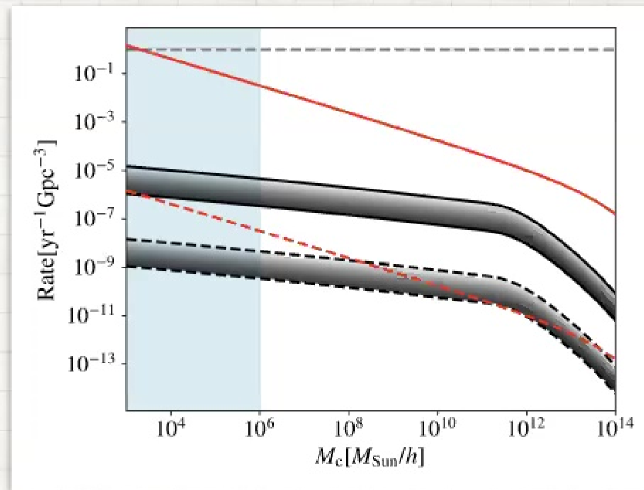
Credits: B.S. Sathyaprakash, Penn State and Cardiff University



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

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