The Primordial Black Hole Dark Matter - LISA Serendipity

- PBH and PBH-DM long standing idea

Zel'dovich, Novikov '67

Hawking '71; Carr '75; Chapline '75

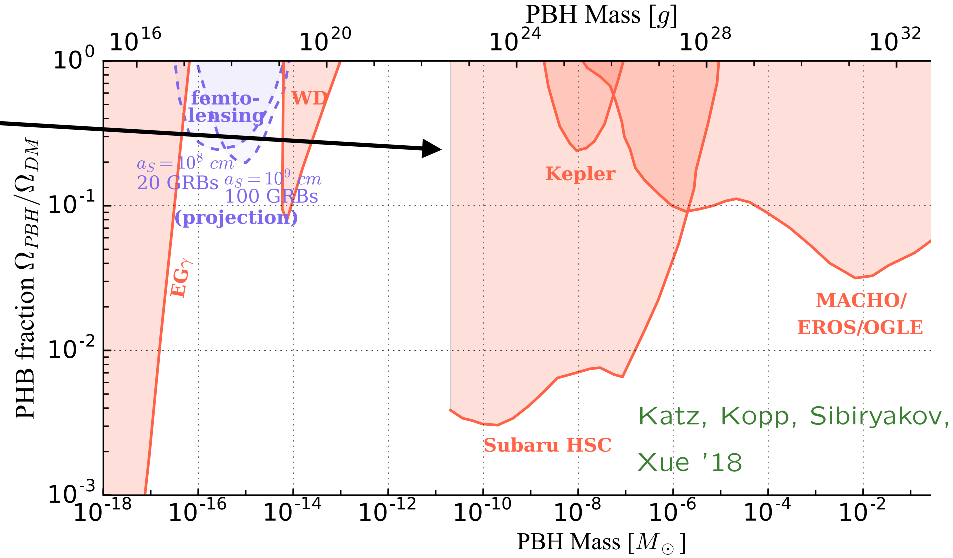
- Recent interest due to lack of detection of particle candidates, and LIGO / VIRGO events

Bird et al '16

Clesse, García-Bellido '16;

Sasaki et al '16

★ Cut due to wave effect ($R_{\text{PBH}} < \lambda_\gamma$)

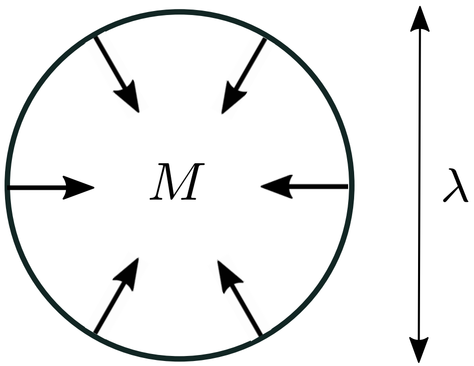


Katz, Kopp, Sibiryakov, Xue '18

★ NS capture limit not shown, as $\propto$ uncertain ρ_{dm} in globular clusters

Capela, Pshirkov, Tinyakov '13

Pani, Loeb '14



Formed by the collapse of an overdense region at horizon re-entry. 1:1 relation $M_{\text{PBH}} \leftrightarrow \lambda$

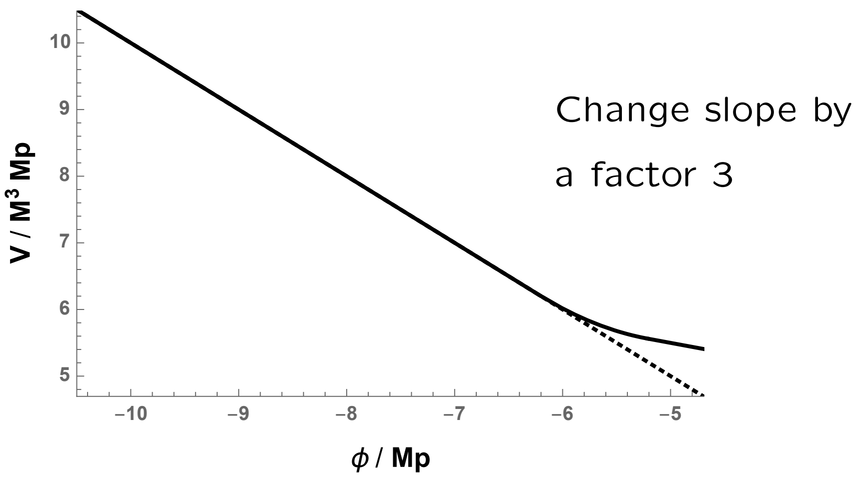
- Enhanced $\delta\rho \to$ GW. Unavoidable, nonlinear gravity. Parametrically

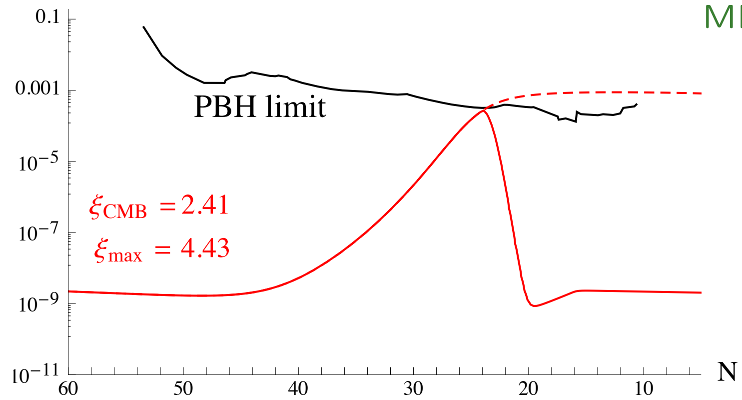
$$f_{\text{GW}} \sim \frac{1}{\lambda} \sim 3\,\text{mHz} \sqrt{\frac{10^{-12}\,M_\odot}{M}}$$

- Requires suitable mechanism to increase selected modes during inflation
- Ex: in axion inflation, $\phi(t) \to \delta A$ through $\phi F \tilde{F}$, with amplitude $\propto \exp\left(\dot{\phi}\right)$

  Then $\delta A + \delta A \to \delta\rho$ very sensitive to $\dot{\phi}$.

García-Bellido, MP, Unal '16





- Possible generation within standard model, by Higgs instability; quantum fluctuations push H to region where $\lambda < 0$; stable $V_T(H)$ at reheating

Espinosa, Racco, Riotto '17

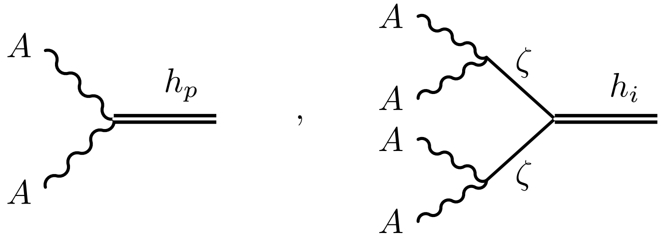
- Near-inflection point from RGE running in Higgs inflation

Ezquiaga, García-Bellido, Morales '17

- Many works exploting $P_\zeta \propto \frac{1}{\epsilon}$. References in García-Bellido '17

GW produced
1) during inflation, by the same source that produced $\delta\rho$
2) by $\delta\rho$ at horizon re-entry after inflation

For instance, in axion inflation,

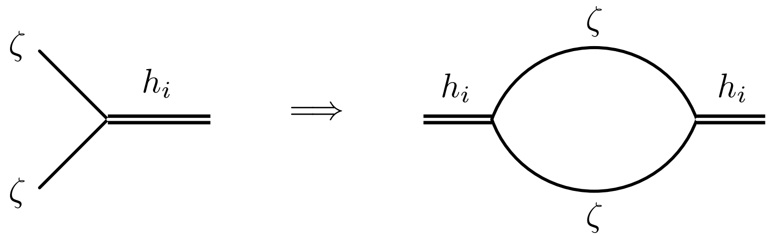


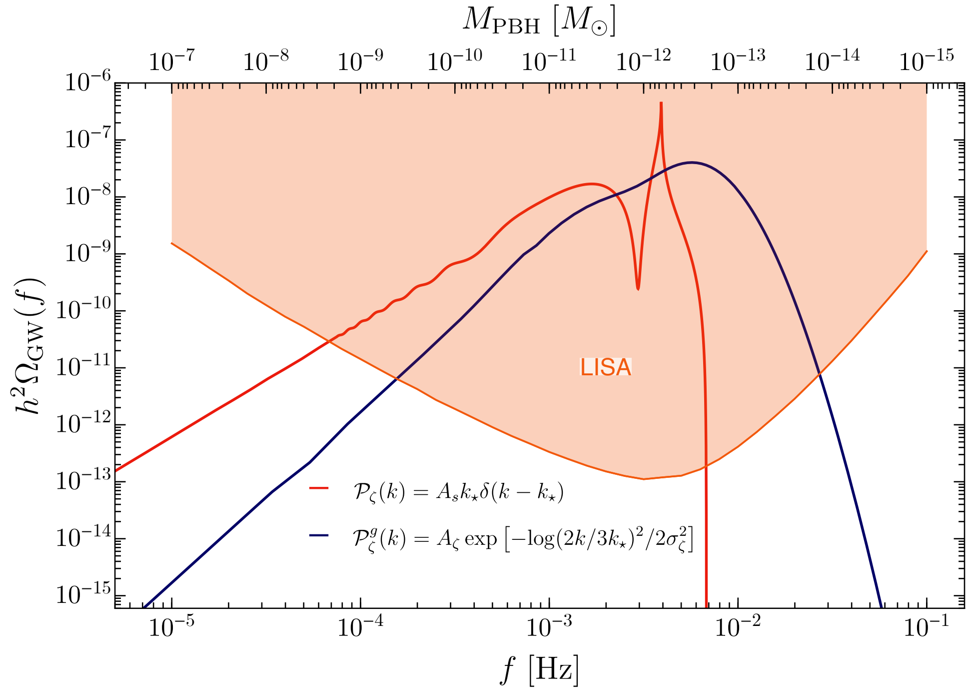
García-Bellido, MP, Unal '17

- Let us focus on mechanism (2) which is model independent

Actual bump in several models $P_\zeta = A_\zeta \exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{k}{k_c}\right)\right]$

Dirac delta approximation $P_\zeta = A_\zeta\, k_*\, \delta\,(k - k_*)$





Beside the scale-dependence, how can we distinguish them from an astrophysical background ?

Non-Gaussianity of the SGWB

(to be quantified!)

- $\sum$ incoherent astrophysical sources $\rightarrow$ Gaussian background

  Measure of large scale coherence, ex. from inflation or long cosmic strings

- Simplest quantity $\left\langle h^3 \right\rangle$, that vanishes for a Gaussian background

★ Current efforts on $\left\langle \text{signal}^2 \right\rangle \rightarrow$ strain $\propto \Omega_{\rm GW}(f)$, $\rho_{\rm GW} = \frac{M_p^2}{4} \left\langle \dot{h}_{ij} \dot{h}_{ij} \right\rangle$

★ Analogously $\left\langle \text{signal}^3 \right\rangle \rightarrow \left\langle h^3 \right\rangle$

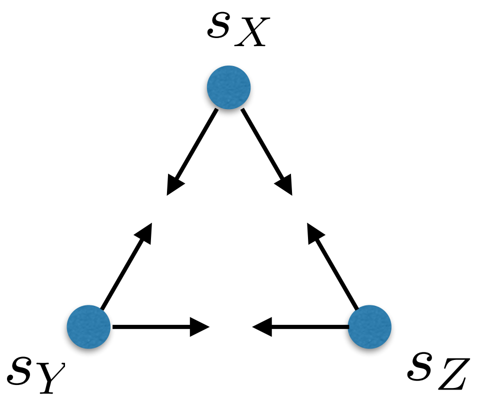
Power spectrum $\left\langle h_\lambda\left(\vec{k}\right) h_{\lambda'}\left(\vec{k}'\right)\right\rangle = \frac{P_\lambda(k)}{4\pi k^3} \delta_{\lambda,\lambda'} \delta^{(3)}\left(\vec{k}+\vec{k}'\right)$

Bispectrum $\left\langle h_{\lambda_1}\left(\vec{k}_1\right) h_{\lambda_2}\left(\vec{k}_2\right) h_{\lambda_3}\left(\vec{k}_3\right)\right\rangle = B_{\lambda_1,\lambda_2,\lambda_3}(k_1, k_2, k_3)\, \delta^{(3)}\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)$

★ P "diagonal" in momentum and helicity. Two functions of k

★ Scale and shape $(k_2/k_1, k_3/k_1)$ dependence in B; mixing of $\neq$ helicities

Highly informative, since $\neq$ models predict $\neq$ B

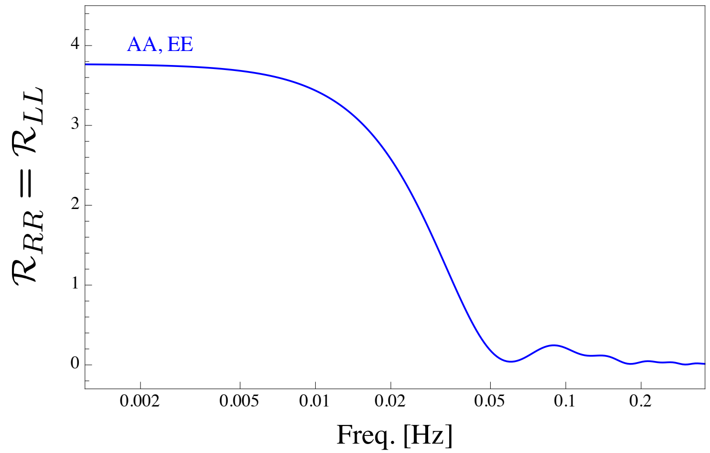


$s_{X,Y,Z}$ have correlated noise

Noise-orthogonal combinations Adams, Cornish '10

$$S_A = \frac{1}{3}(2s_X - s_Y - s_Z) \qquad S_E = \frac{1}{\sqrt{3}}(s_Z - s_Y)$$

Schematically, $\langle s^n \rangle = \mathcal{R} \star \langle h^n \rangle$

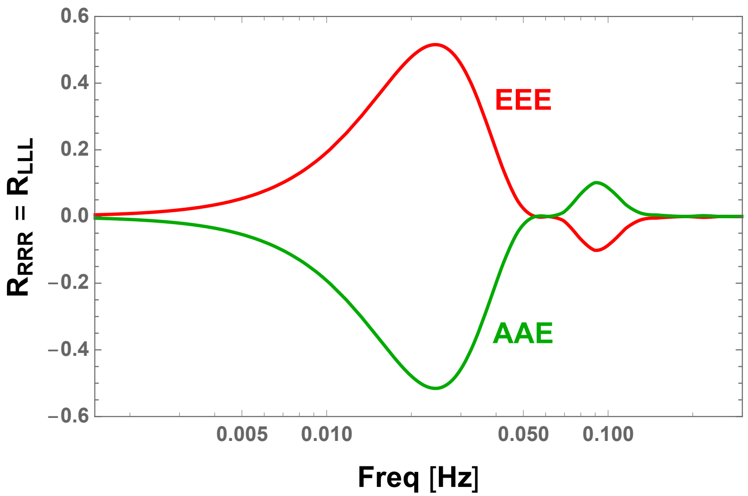


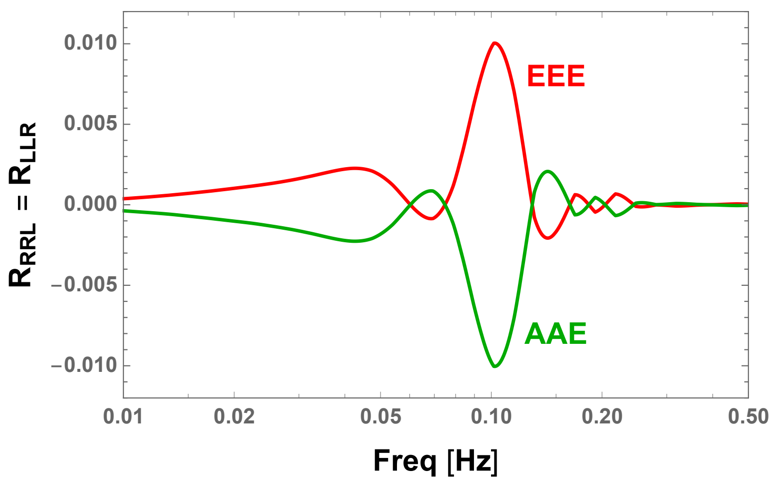
Two-point response function well studied

$\mathcal{R}_{LL} = \mathcal{R}_{RR}$ since planar instrument

$\mathcal{R}^{AA} = \mathcal{R}^{EE}$

Three-point response function. Bartolo et al '18





$\mathcal{R}_{RRR} = \mathcal{R}_{LLL}$

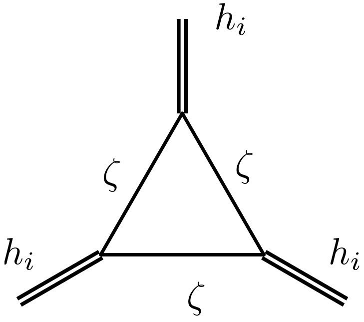
$\mathcal{R}_{RRL} = \mathcal{R}_{LRR}$

$\mathcal{R}^{AAE} = -\mathcal{R}^{EEE}$

$\mathcal{R}^{AAA} = \mathcal{R}^{AEE} = 0$

The bispectrum of sourced GW

Bartolo, De Luca, Franciolini, MP, Racco, Riotto '18

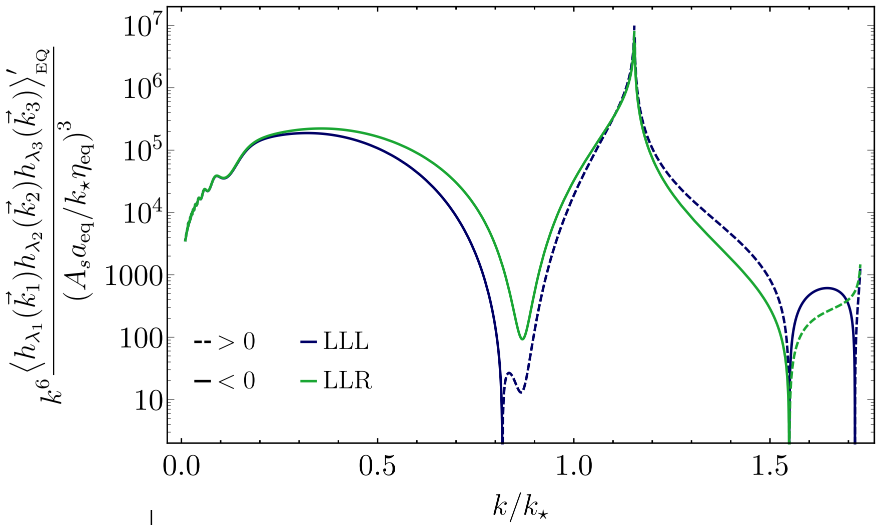


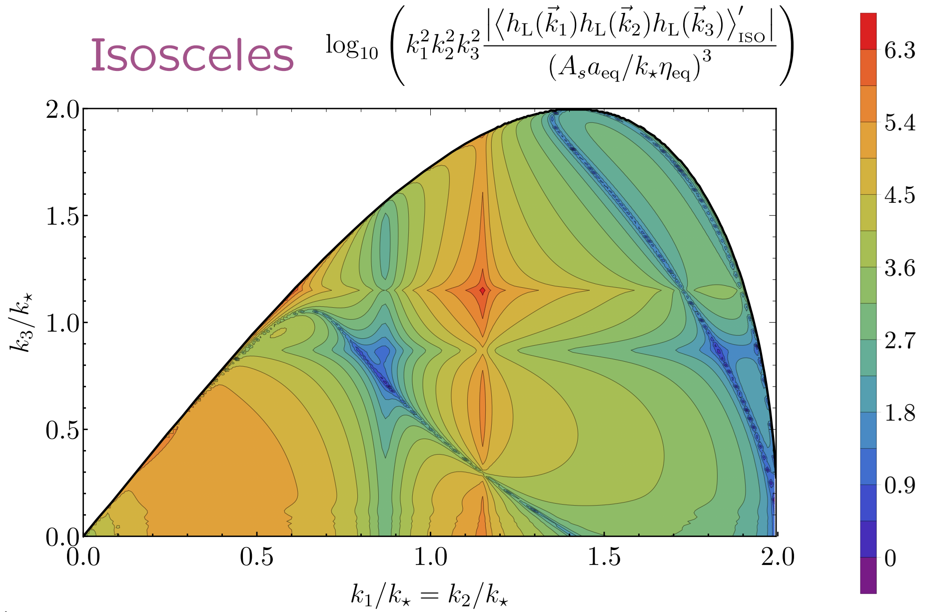
Peaked at equilateral configurations, with $k_1 = k_2 = k_3 \simeq k_{\text{peak},\zeta}$

Equilateral

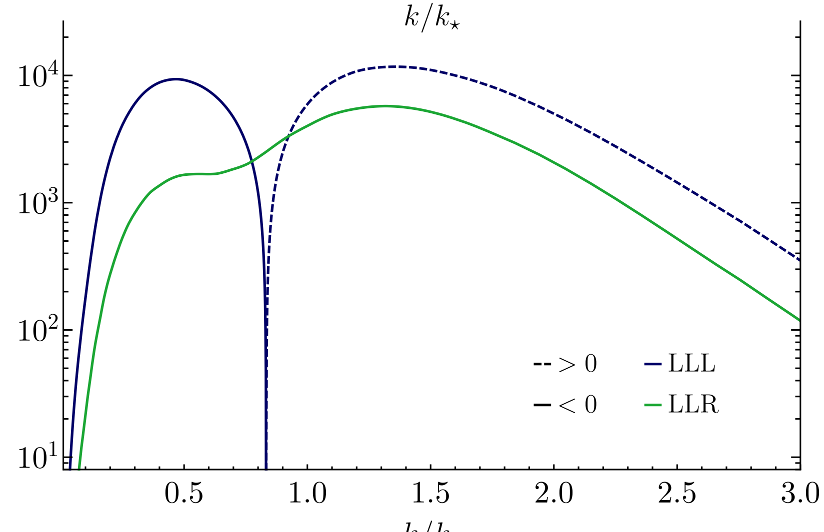
Isosceles

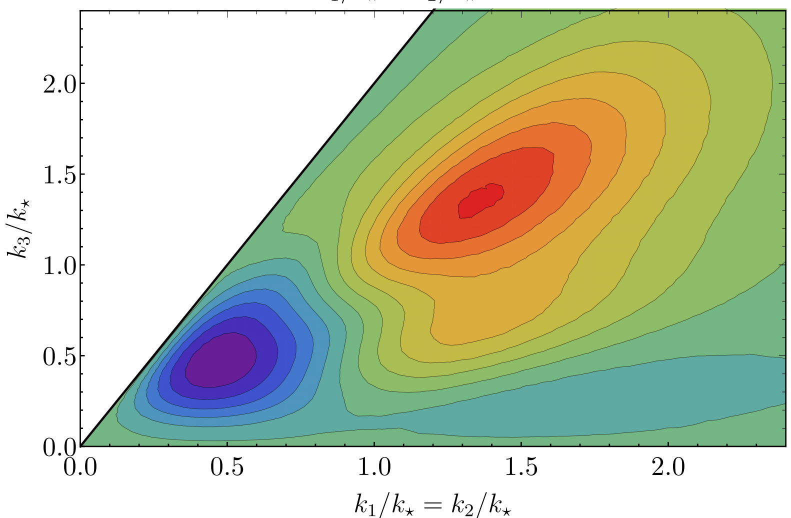
Dirac δ





Gaussian bump



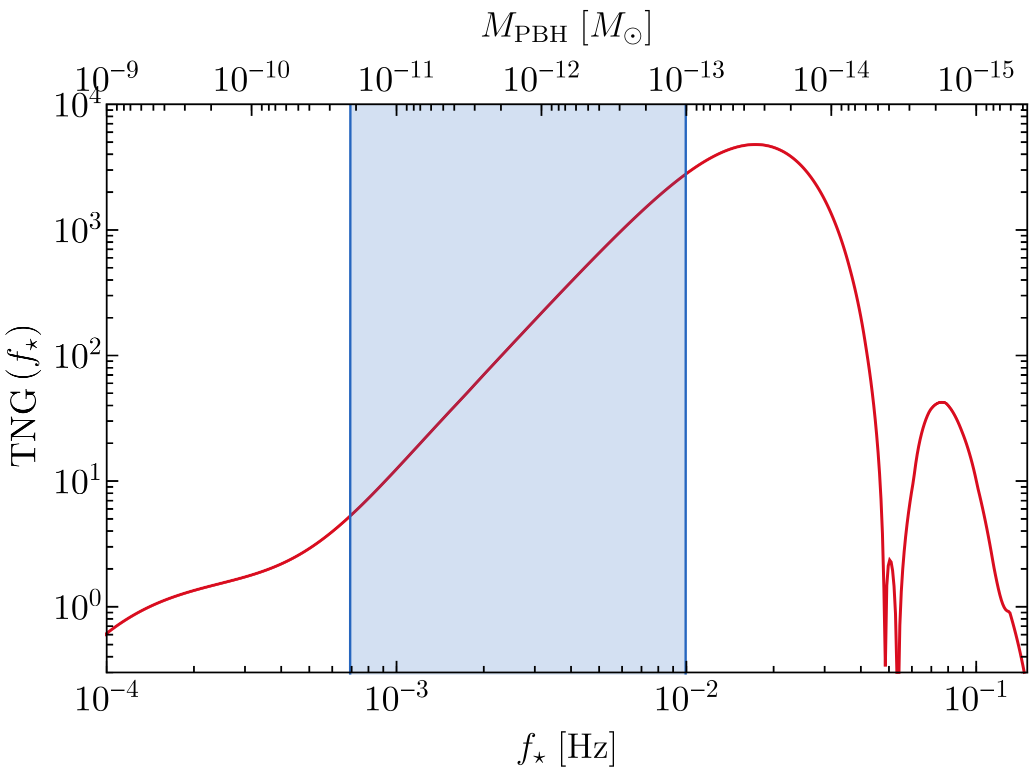


Can we see this ?

Construct an estimator $\hat{\mathcal{F}} \equiv \sum_{ijk} \int \mathrm{d}F_1\, \mathrm{d}F_2\, \mathrm{d}F_3 W^{ijk}(F_1,\, F_2,\, F_3)\, \tilde{s}_i(F_1)\, \tilde{s}_j(F_2)\, \tilde{s}_k(F_3)$

(sum of measurements over channels and frequencies)

Test of non – Gaussianity : $TNG = \frac{\langle \hat{F} \rangle}{\sqrt{\langle \hat{F}^2 \rangle_{\mathrm{PS}}}} \propto \frac{\langle \mathrm{signal}^3 \rangle}{\left(\langle \mathrm{signal}^2 \rangle\right)^{3/2}}$



Typical measured bispectrum in one realization of Gaussian background (signal $\gg$ noise)

Larger significance when peak bispectrum
$\equiv$ peak response function

Expect significant evidence if PBH - DM !