Gravitational Waves from Inflation and Primordial Black Holes

Marco Peloso, University of Padua

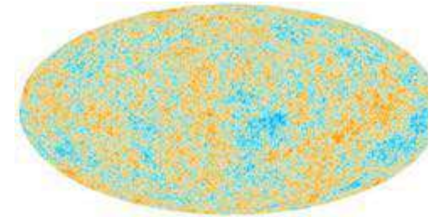
- GW from axion inflation
- GW from primordial black holes (PBH)
- Characterization of the stochastic GW background (SGWB)

Barnaby, Bartolo, Bertacca, De Luca, Domcke, Figueroa, Franciolini,

García-Bellido, Lewis, Matarrese, Nardini, Pajer, Pieroni, Racco,

Ricciardone, Riotto, Sakellariadou, Sorbo, Tasinato, Unal

GW as a probe of inflation

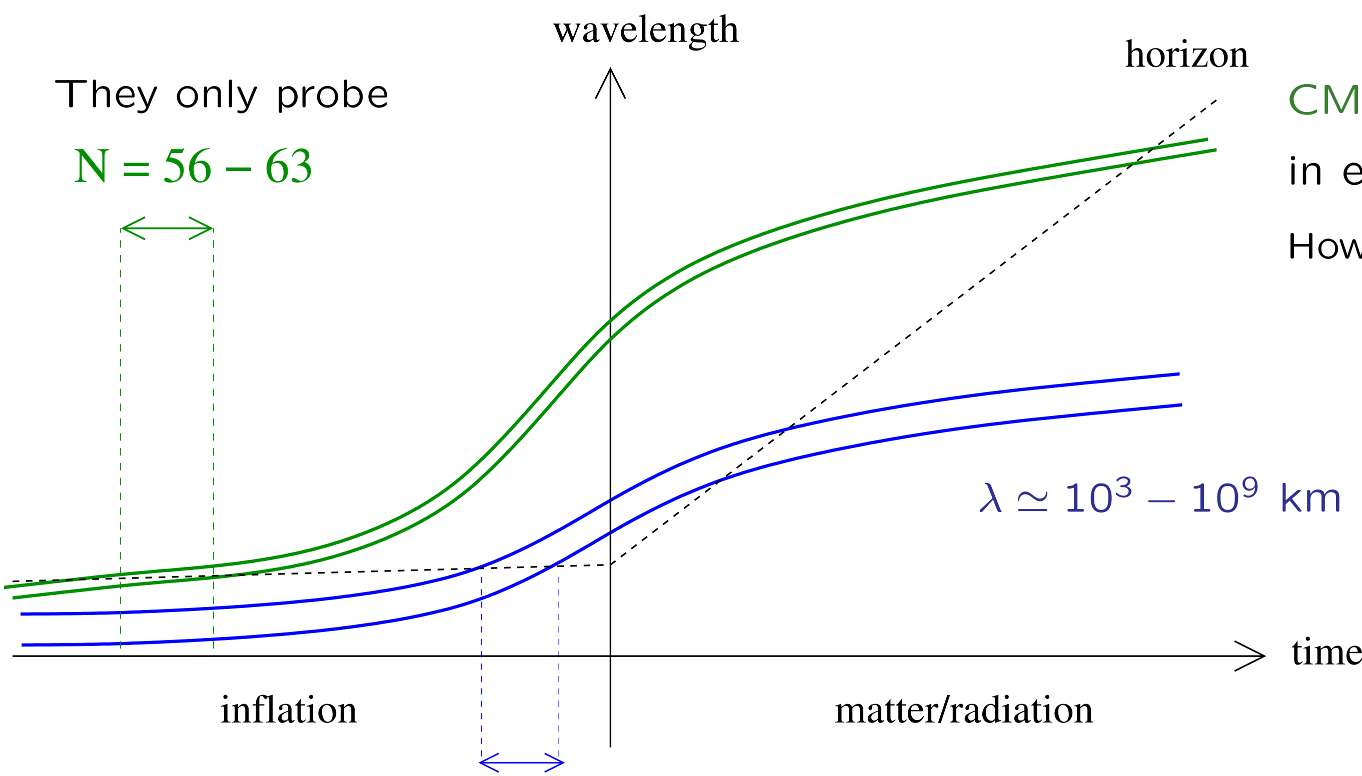


We give time in terms of e – foldings : $a \propto e^{Ht} = e^{-N}$

CMB modes produced at $N \simeq 60$ before the end of inflation, when $a \simeq e^{-60} a_{\text{end}}$

They only probe

N = 56 – 63



CMB and Large Scale Structure

in excellent agreement with inflation.

However, only probe $\lambda \simeq 10^2 - 10^5$ Mpc

$\lambda \simeq 10^3 - 10^9$ km

Smaller scales / later times

essentially unprobed

We can probe N = 15 – 28

$N = 0 \quad \leftrightarrow \quad f \simeq 10^8$ Hz

Development of GW interferometers

opens a new window on much

smaller scales

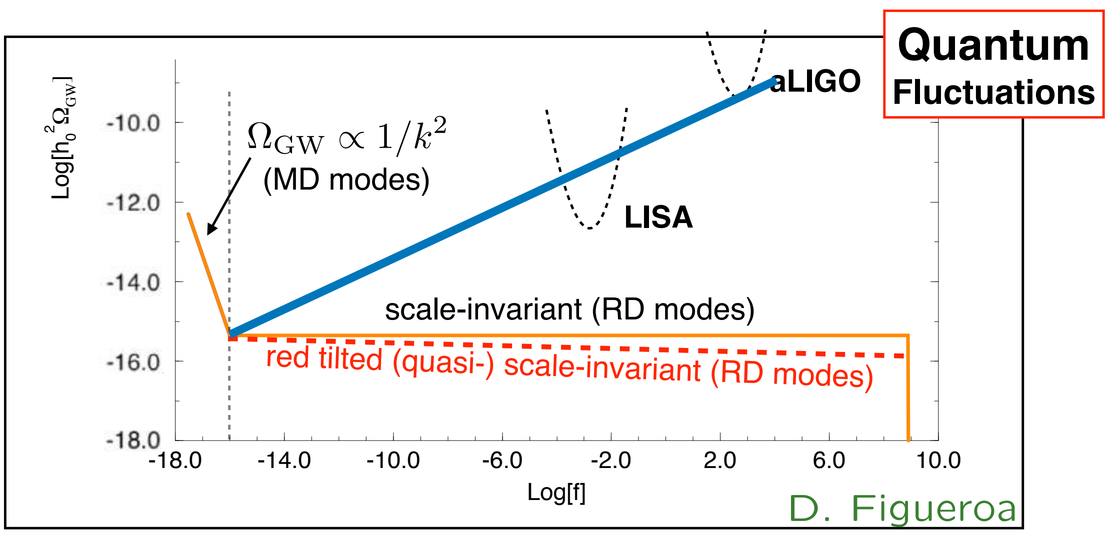
GW production during inflation

$$h''_{ij} + 2\frac{a''}{a} h_{ij} + k^2 h_{ij} = \frac{2}{M_p^2} T_{ij}^{TT}$$

Amplification of vacuum modes from inflationary expansion guaranteed signal, but too small for present and next generation detectors

Several mechanisms result in sourced GW during inflation.

Subject to the same limits as vacuum modes at CMB scales

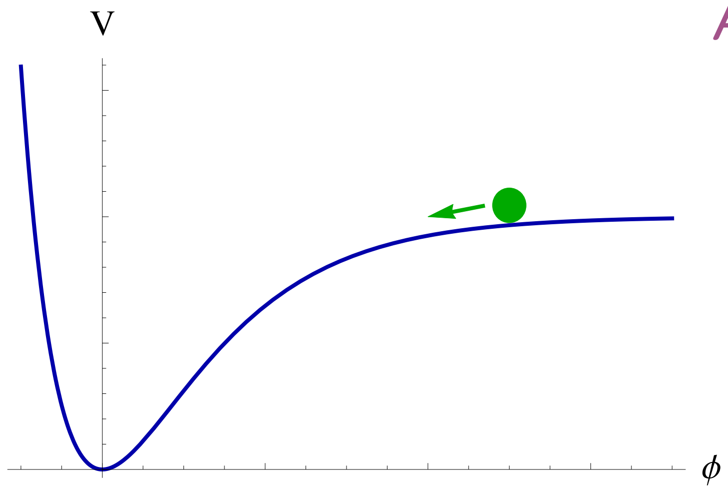


Signal must be blue to be visible at interferometers

Natural property in axion inflation

Axion inflation

Freese, Frieman, Olinto '90, . . .



Main theoretical difficulty

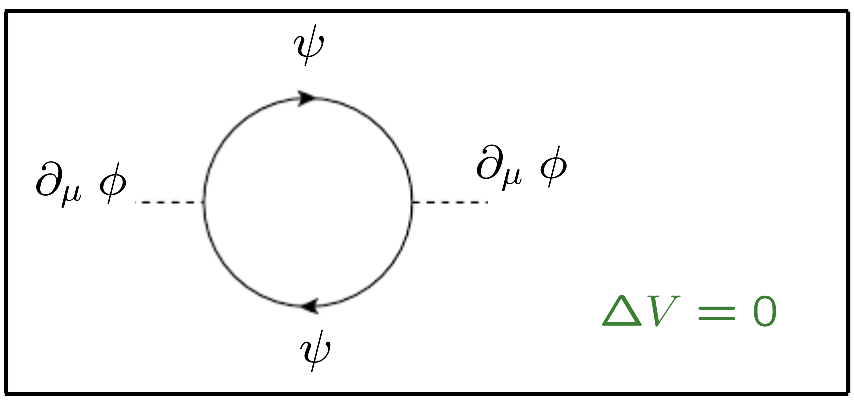
is to keep the potential flat

against radiative corrections

- Coupling to matter invariant under $\phi \to \phi +$ constant

Coupling to fermions : $\Delta\mathcal{L} = \frac{\partial_\mu \phi}{f} \bar{\psi}\gamma^5\gamma^\mu\psi$

to gauge fields : $\Delta\mathcal{L} = \frac{\phi}{f} F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv -4\frac{\partial_\mu\phi}{f}\epsilon_{\mu\nu\alpha\beta}A_\nu\partial_\alpha A_\beta$



Loops with these couplings

do not modify the potential

Vector production from $\frac{\phi}{f} F \tilde{F}$

Turner, Widrow '88
Garretson, Field, Carroll '92
Anber, Sorbo '06

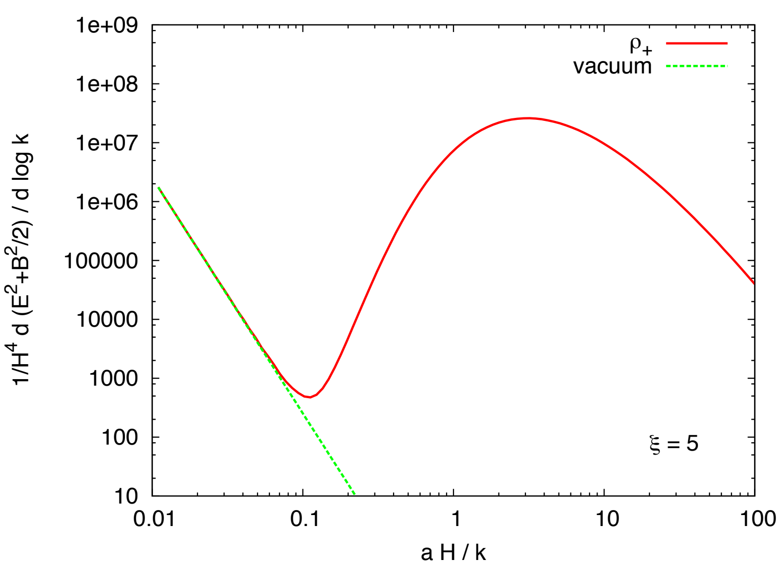
Originally studied for magnetogenesis. Here, generic U(1)

$\phi F \tilde{F}$ breaks parity, $\neq$ results for two polarizations

$$\left(\frac{\partial^2}{\partial \tau^2} + k^2 \mp \frac{a k \dot{\phi}}{f} \right) A_{\pm}(\tau, k) = 0$$

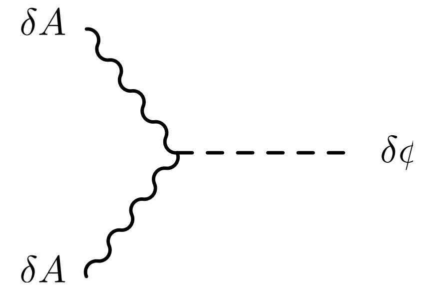
$+$ left handed
$-$ right handed

Physical ρ in one mode



- One tachyonic helicity at horizon crossing
- Then diluted by expansion
- Max amplitude $A_+ \propto e^{\dot{\phi}}$

- The produced A_+ modes source inflaton perturbations $\delta\phi$ through inverse decay. These modes are highly non-gaussian.



This imposes $f \gtrsim 10^{16}$ GeV $\left(\text{recall } \mathcal{L} \supset -\frac{\phi F \tilde{F}}{f} \right)$

Barnaby, MP '10
Planck '15

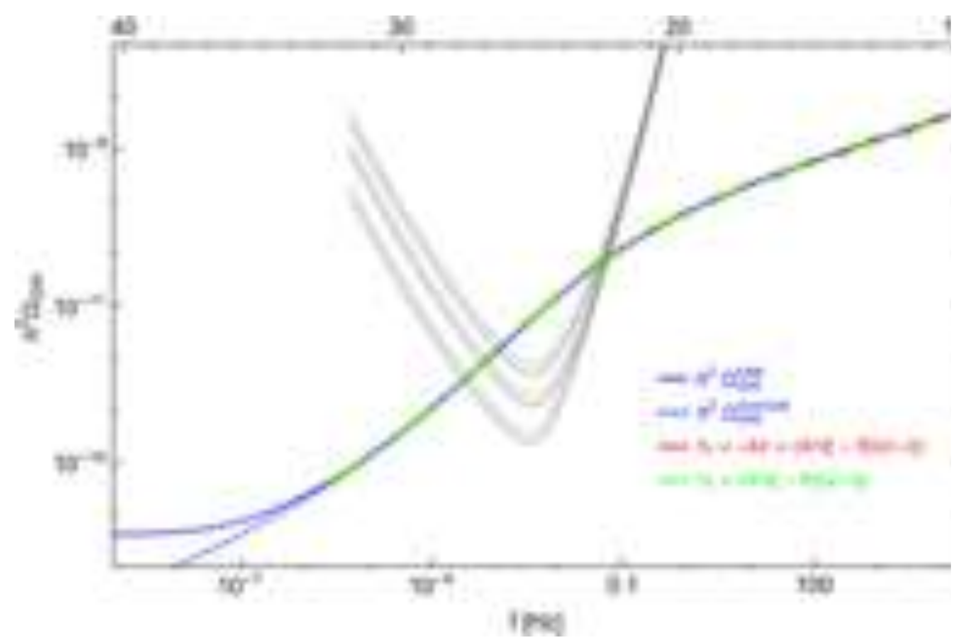
- The amplified gauge fields also produce GW, though $A_+ A_+ \to h_L$

Barnaby, MP '10
Sorbo '11

★ $\dot{\phi}$ grows during inflation (inflation ends because $\dot{\phi}$ too large) $\Rightarrow$ Blue GW and potentially visible at interferometers

Cook, Sorbo '11; Barnaby, Pajer, MP'11;
Domcke, Pieroni, Binétruy '16; ...

Bartolo et al '16; LISA cosmology WG

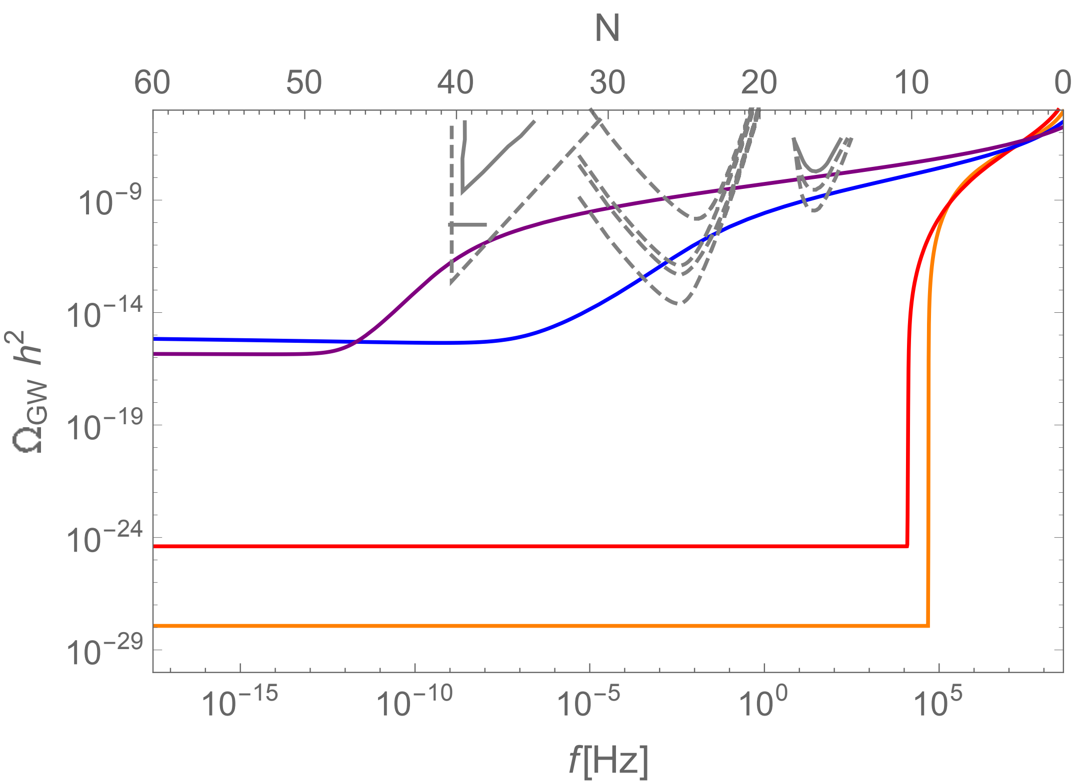


Signal is chiral $h_L \gg h_R$ and highly non-Gaussian, $\langle h^3 \rangle \sim \langle h^2 \rangle^{3/2}$

$V(\phi)$ from ~~shift symmetry~~

Due to $\propto e^{\dot{\phi}}$, signal very sensitive to the inflaton potential

Domcke, Pieroni, Binétruy '16



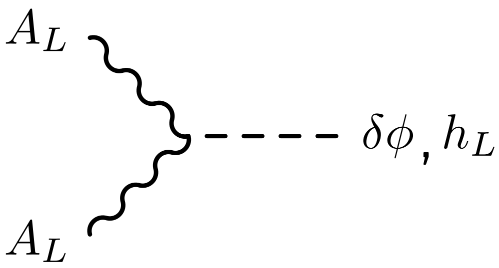
$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

$$V(\phi) = V_0 \left(1 - e^{-\sqrt{\frac{2}{3}\phi}}\right)^2$$

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{v}\right)^4\right]^2$$

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{v}\right)^3\right]^2$$

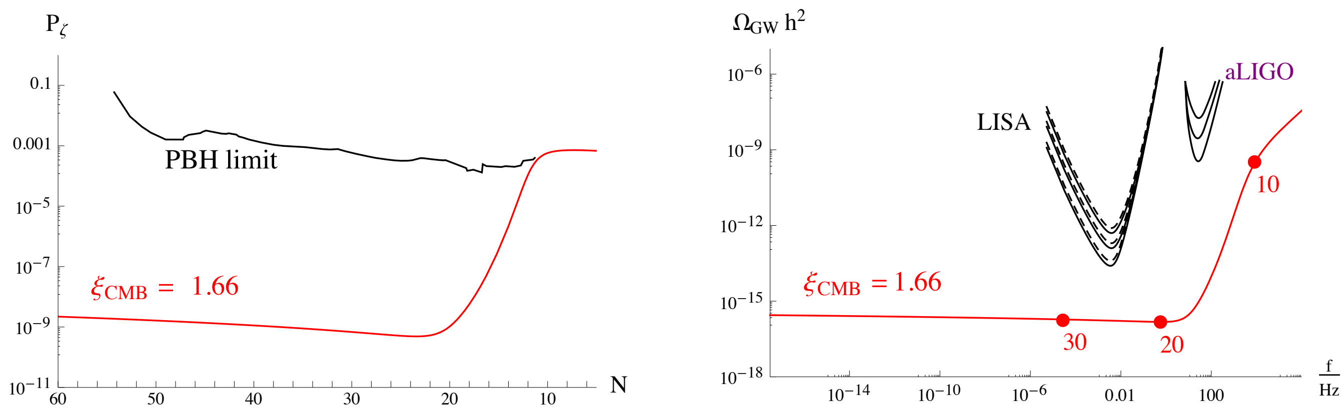
N = number of e-folds before the end of inflation when a mode is produced. Different experiments probe different ranges of $V(\phi)$



- As in all mechanisms of GW from inflation, the key difficulty is to produce observable GW without overproducing density perturbations

- For a monomial $V(\phi)$, PBH bounds prevent GW from being observable at aLIGO and LISA

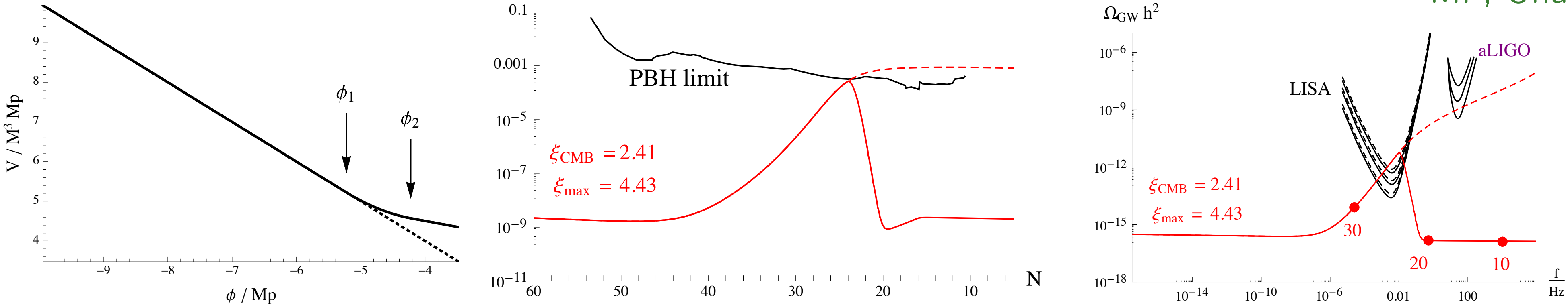
Linde, Mooij, Pajer '13



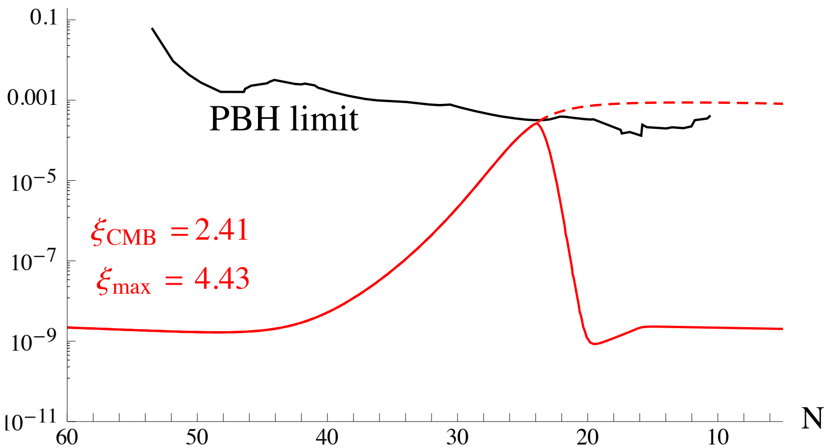
$$N \sim 15 - \ln\left(\frac{f}{100\,\text{Hz}}\right)$$

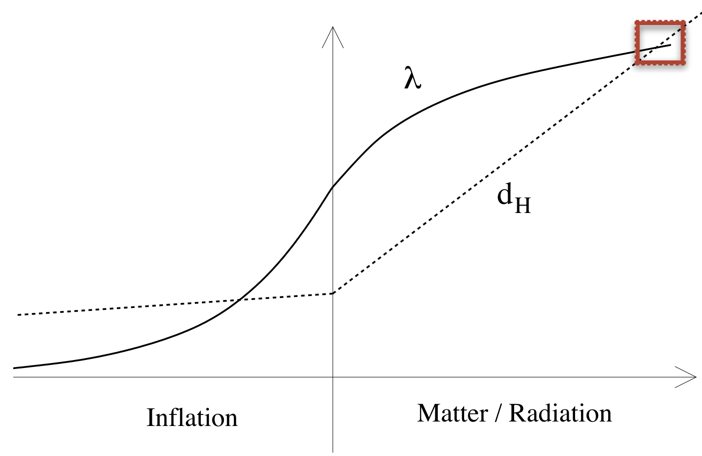
- Due to $\propto e^{\dot{\phi}}$, significant differences from a minor change of V

Garcia-Bellido
MP, Unal '16

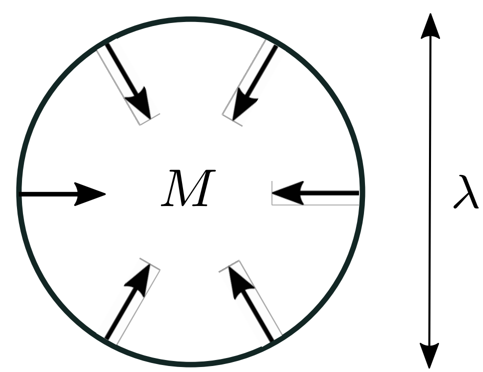


- Mechanism for a peaked distribution of PBH





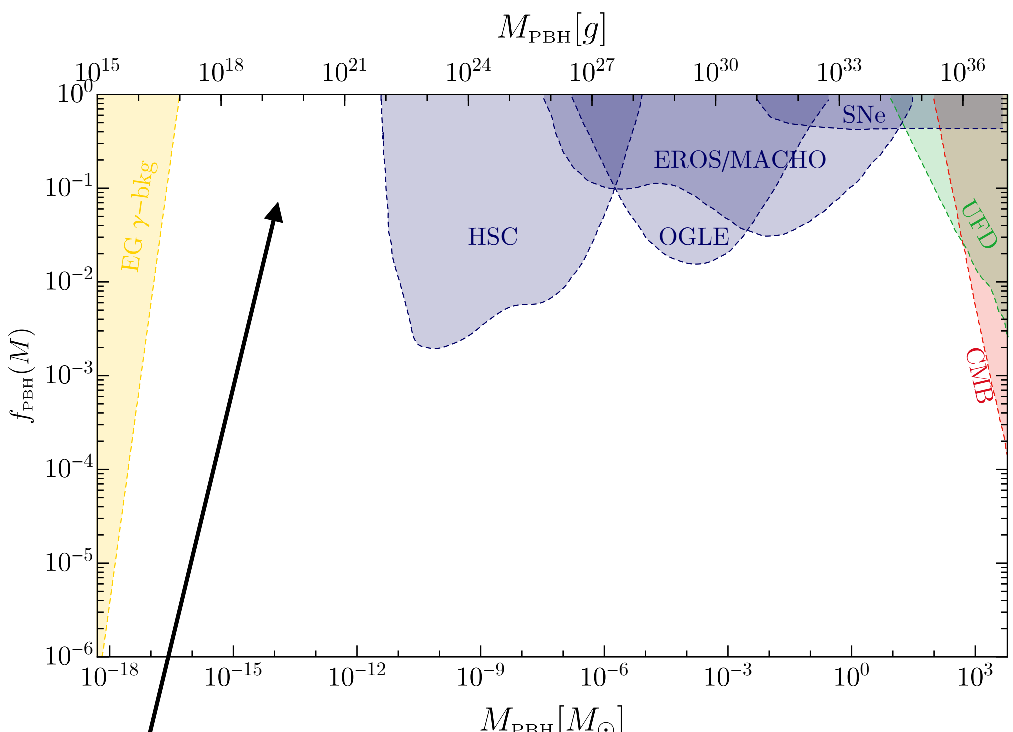
If sufficiently large, at horizon re-entry, the perturbation collapses to form a Primordial Black Hole (PBH)



A significant fraction of the mass in the horizon collapses into the PBH. So, parametrically, $\lambda \leftrightarrow M_{\rm PBH}$

PBH dark matter

- 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
- 2 windows, one at $\sim 10^{-12} M_\odot$, and (possibly) one at $\sim 10-100 M_\odot$



Credit: G. Franciolini, update of Carr, Kuhnel, Sandstad '16 and Inomata et al '17

Cut on HSC and on limits from femtolensing of γ-ray bursts. Schwarzschild radius$_{\rm PBH} < \lambda_\gamma$

Katz, Kopp, Sibiryakov, Xue '18

Limits from capture from NS and WD not shown due to uncertainty in DM astrophysical abundance, and on nuclear physics

Capela, Pshirkov, Tinyakov '13

Montero-Camacho, Fang, Vasquez, Silva. Hirata '19

PBH $\leftarrow$ enhanched $\delta\rho$ $\rightarrow$ GW

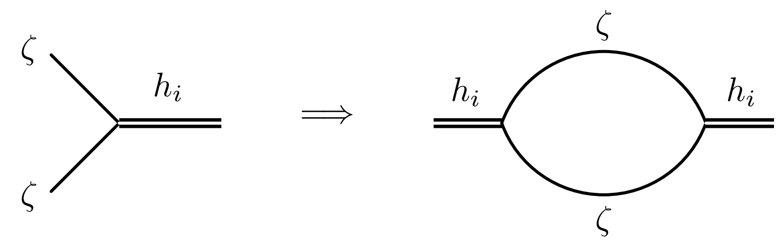
- Whenever $\delta\rho$ present GW produced

  1) during inflation, by the same source that produced $\delta\rho$

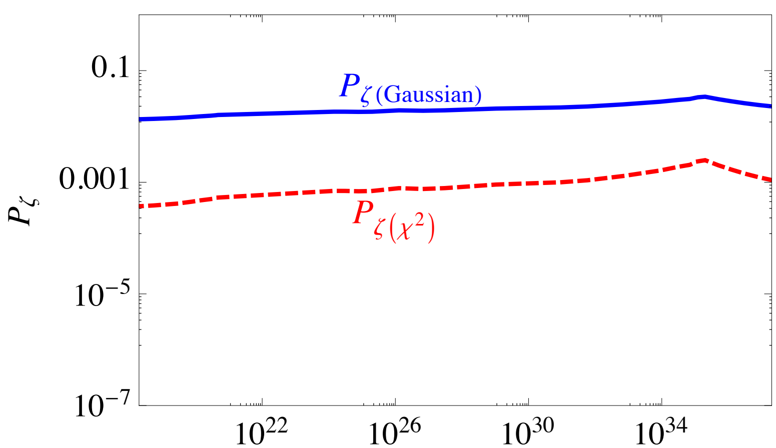
  2) by $\delta\rho$ at horizon re-entry after inflation

- Mechanism 2 is unavoidable and model-independent

  Standard gravitational interaction:



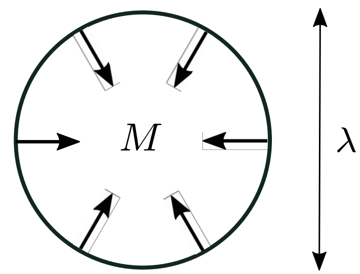
- Technical (but important !) point. Power spectrum $\left\langle \delta\rho^2 \right\rangle$ controls the amount of GW. Full statistics of $\delta\rho$ relevant for PBH abundance.



Stronger constraint on $P_{\delta\rho}$ sourced in axion infaltion (non-gaussian statistics)

$\Rightarrow$ Fewer GW

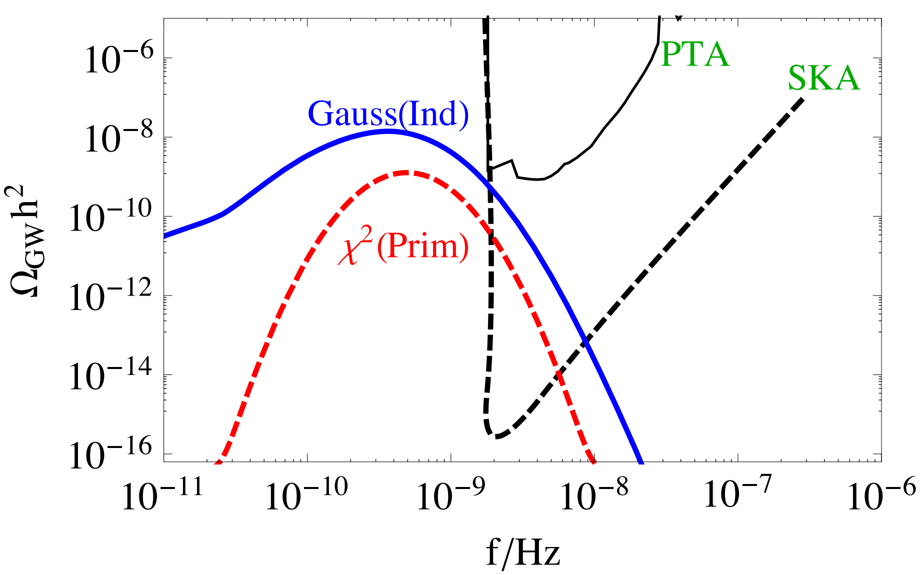
$$f_{\mathrm{GW}} \sim \frac{1}{\lambda} \sim 3\,\mathrm{mHz}\sqrt{\frac{10^{-12}\,M_\odot}{M}}$$

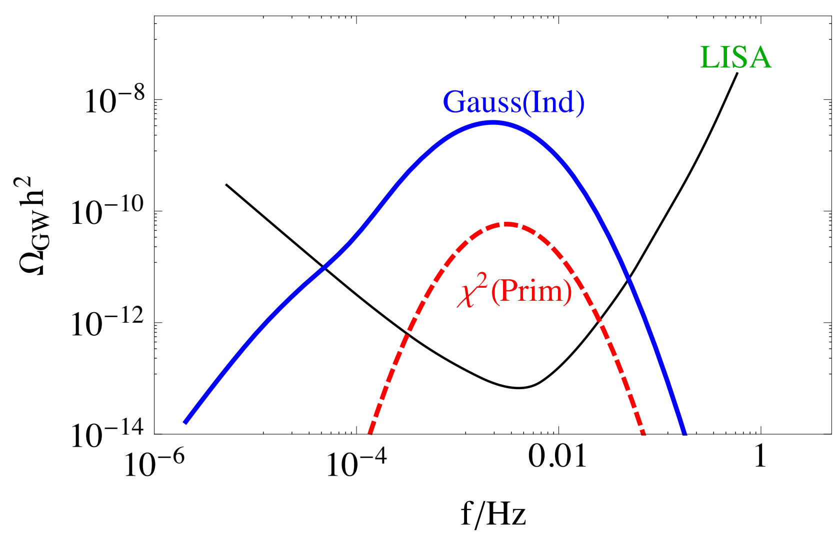


$M \sim 10\,M_\odot \quad \Rightarrow \quad f_{\mathrm{GW}} \sim \mathrm{nHz}$ PTA!

$M \sim 10^{-12}\,M_\odot \quad \Rightarrow \quad f_{\mathrm{GW}} \sim \mathrm{mHz}$ LISA!

García-Bellido, MP, Unal ’17





From axion inflation

Gaussian $\delta\rho$

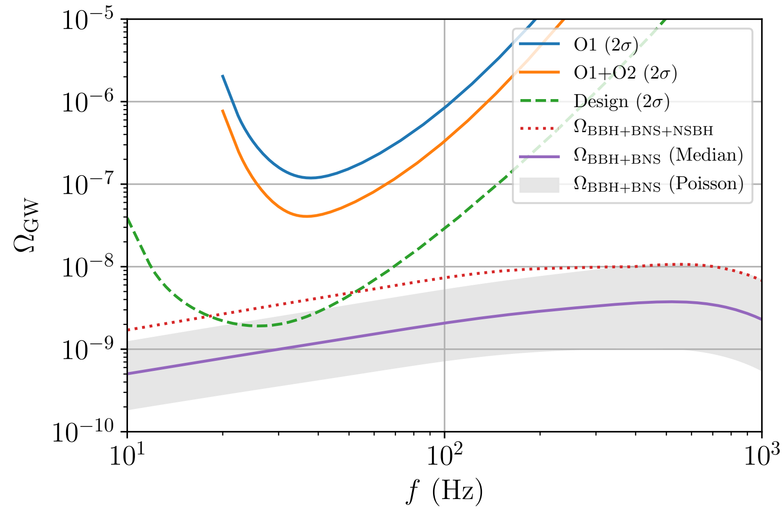
Measurement of the SGWB

SGWB from cosmological sources superimposed with astrophysical one.

Potential observables to disentangle them

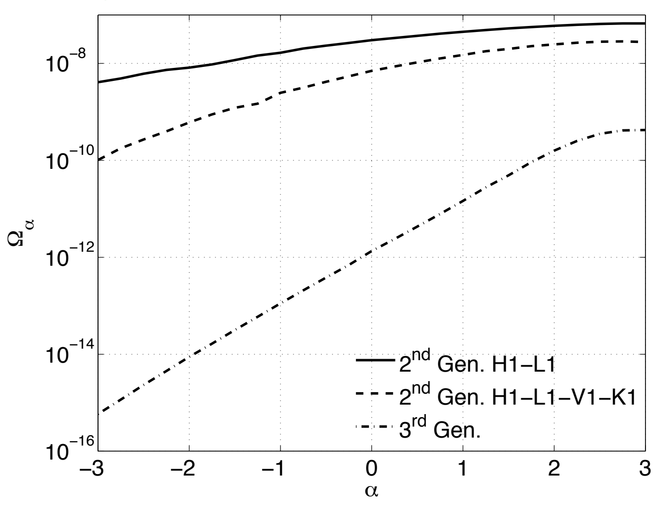
- Spectral shape $\Omega_{\rm GW}(f)$
- Net Polarization $\Omega_{{\rm GW},\lambda}$
- Statistics $\left\langle \Omega_{\rm GW}^n \right\rangle$
- Directionality $\Omega_{\rm GW}(\vec{x})$

Current LIGO bounds



Measurement of GW polarization

Crowder, Namba, Mandic, Mukohyama, MP '12



Assume $\Omega_{\rm GW,L} = \Omega_\alpha \left(\frac{f}{100\,{\rm Hz}} \right)^\alpha$ and $\Omega_{\rm GW,R} = 0$

Amplitude needed to detect $\Omega_{\rm GW}$

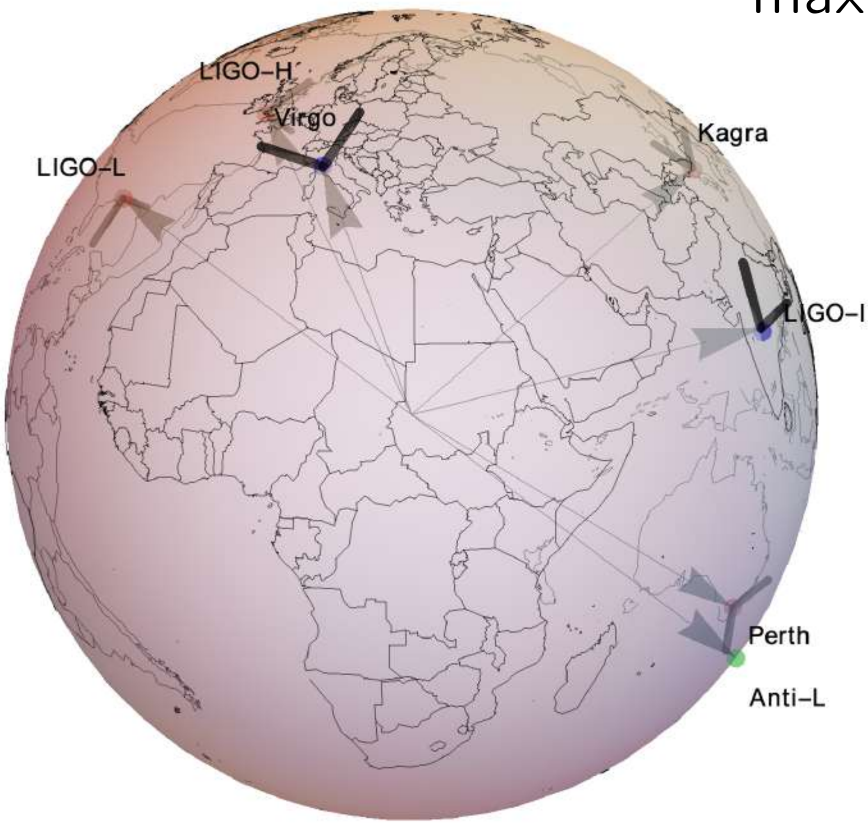
and exclude $\Omega_{\rm GW,R} = \Omega_{\rm GW,L}$ at 2σ

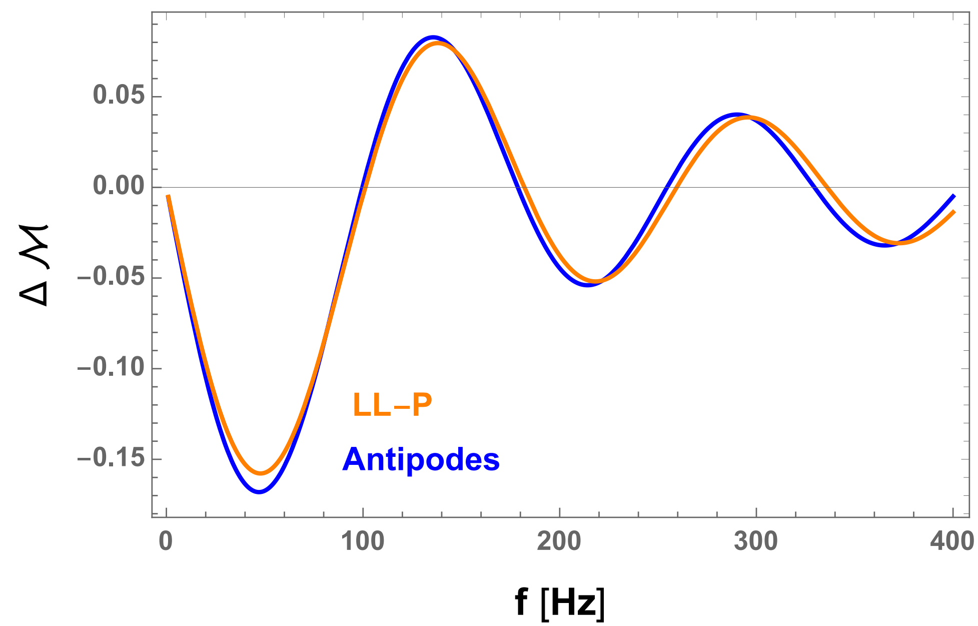
One more motivation for an Australian detector !

$$\left\langle \frac{\Delta t_{\text{detector i}}}{t} \frac{\Delta t_{\text{detector j}}}{t} \right\rangle = \int \frac{df}{f} \left[\mathcal{M}_{ij,R}(f)\; P_{\text{GW,R}}(f) + \mathcal{M}_{ij,L}(f)\; P_{\text{GW,L}}(f) \right]$$

$\Delta\mathcal{M} = \mathcal{M}_R - \mathcal{M}_L$ measure of chirality

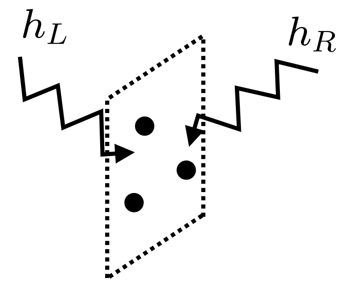
maximized for anti-podal detectors



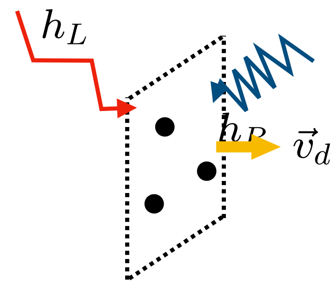


Measurement of GW polarization at LISA / ET

Two GWs related by a mirror symmetry produce the same response in a planar detector. Cannot detect net circular polarization of an isotropic SGWB



Isotropy in any case broken by peculiar motion of the solar system. Assumption, $v_d \simeq 10^{-3}$ as CMB

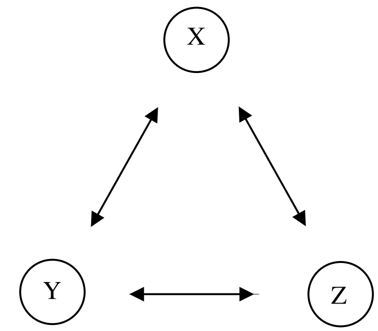


$$\text{SNR}_{\text{LISA}} \simeq \frac{v_d}{10^{-3}} \frac{\Omega_{\text{GW,R}} - \Omega_{\text{GW,L}}}{1.2 \cdot 10^{-11}} \sqrt{\frac{T}{3\,\text{years}}}$$

Domcke, García-Bellido, MP, Pieroni Ricciardone, Sorbo, Tasinato '19

(one order of magnitude greater than estimate in Seto '06)

Measurement at LISA: $X, Y, Z \equiv$ time delays at the vertices

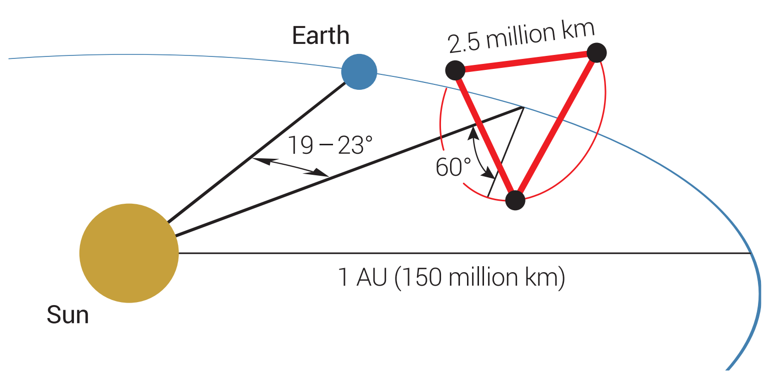


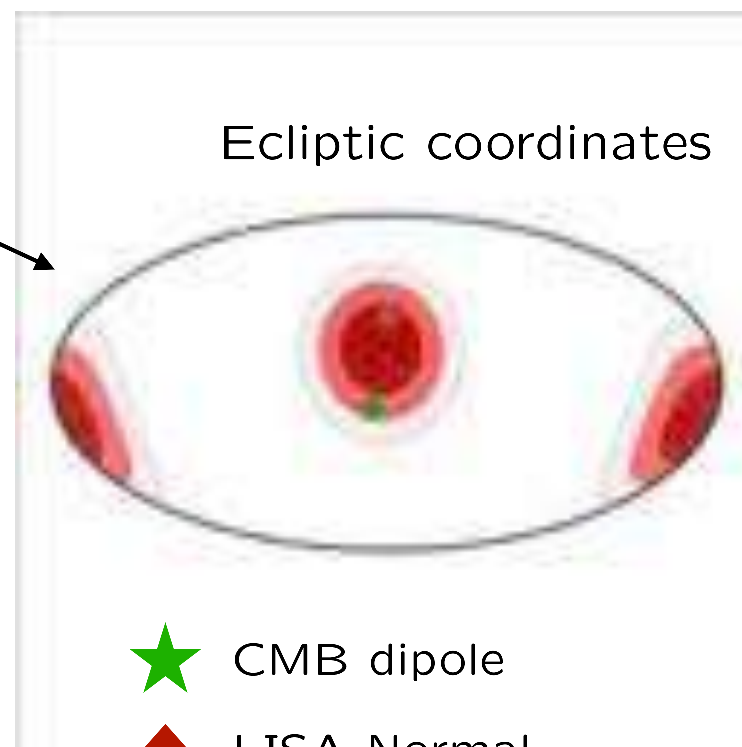
Correlation $\left\langle (2X - Y - Z) * (Z - Y) \right\rangle$ vanishes if $P_R = P_L$

Detector response function : $\left\langle \text{signal}^2 \right\rangle \sim \mathcal{R}_\lambda (k) \langle h_\lambda (k)\, h_\lambda (k) \rangle$

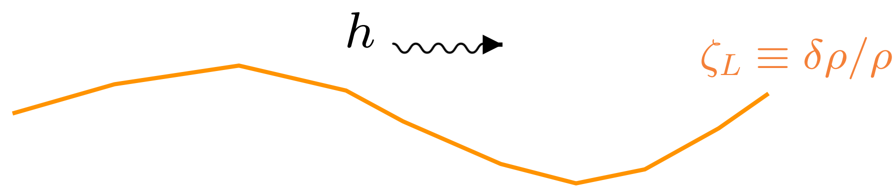
$\mathcal{R}_\lambda$, has opposite sign for the two helicities, and $\propto$ cosine of the angle between the direction of the dipole and the normal to the LISA plane

$$\mathcal{R}_\lambda = \int d\,(\text{angles on the sky})\ \lambda \times F\,[\theta,\, \phi]$$





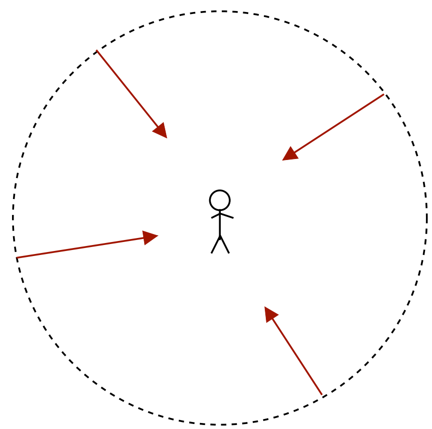
Non-G, angular anisotropies, and a probe of the large scale structure of the Universe



Production mechanism & propagation imprint anisotropies, $\rho_{\text{GW}}\left(\vec{x}\right) \propto \dot{h}_{ij}\dot{h}_{ij}$

- Treatment as CMB Alba, Maldacena '15; Contaldi '16; Cusin, Pitrou, Uzan '17; Jenkins, Sakellariadou '18; Bartolo, Bertacca, Matarrese, MP, Ricciardone, Riotto, Tasinato '19

$$\rho_{\text{GW}} = \sum_{\ell m} a_{\ell m}^{\text{GW}} \, Y_{\ell m}$$



$$\langle a_{\ell m} \, a^*_{\ell' m'} \rangle = C_\ell \, \delta_{\ell \ell'} \, \delta_{m m'}$$

Angular power spectrum

$$\langle a_{\ell_1 m_1} \, a_{\ell_2 m_2} \, a_{\ell_3 m_3} \rangle \propto b_{\ell_1 \ell_2 \ell_3}$$

Bispectrum (non-G) ⟵ This is $\langle \rho^3_{\text{GW}} \rangle$

$\langle h^3 \rangle$ not observable

Anisotopies from the production mechanism

Bartolo et al '19

$$\frac{C_{\ell,in}(f)}{4\pi} = \int \frac{dk}{k} P_{\text{in}}(f,\, k)\; j_\ell^2(k\, t_0)$$

$f \sim$ mHz observed GW frequency

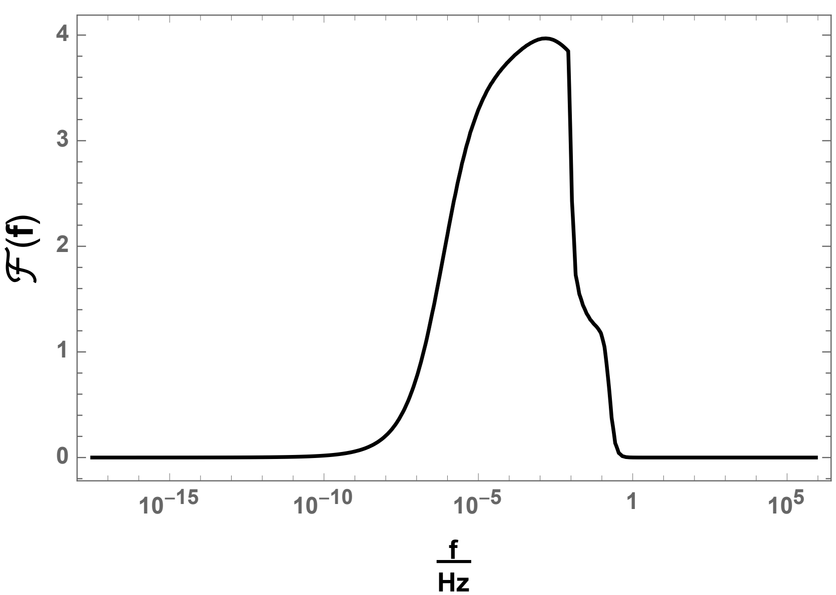
$k \sim H_0 \sim (10\,\text{billion yrs})^{-1}$ scale of anisotropie

$k \leftrightarrow \frac{1}{|\delta \vec{x}|} \leftrightarrow \ell$

Power in initial condition. Can depend on f - different from CMB, where

C_ℓ do not depend on f (initial thermal state)

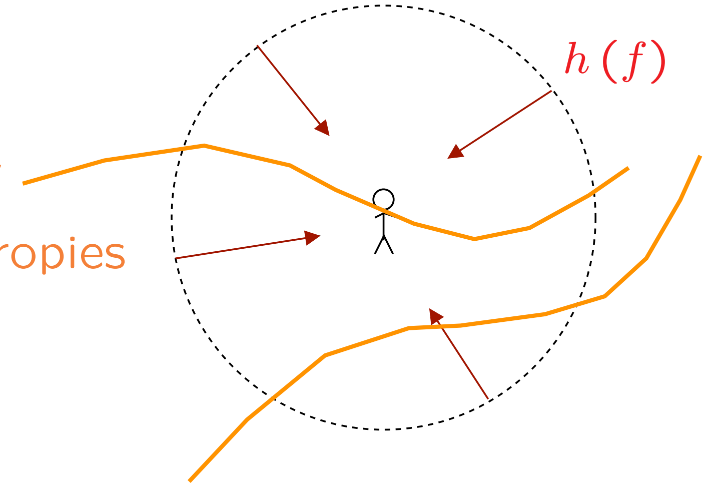
For instance, in axion inflation $\dot{\phi}(t) + \delta\dot{\phi}(t,\, \vec{x}) \;\rightarrow\; P_{\text{GW}} + \delta P_{\text{GW}}$



$$\frac{\delta\rho_{\text{GW}}(f,\, k)}{\rho_{\text{GW}}} \propto \mathcal{F}(f)\; \delta\dot{\phi}(k)$$

$\rightarrow C_\ell(f)$

Anisotopies from the propagation



$$\frac{C_{\ell,S} + C_{\ell,T}}{4\pi} = \int \frac{dk}{k} \left[P_\zeta(k)\, \mathcal{T}_{\text{scalar}} + P_h(k)\, \mathcal{T}_{\text{tensor}} \right]$$

Bispectrum from 2nd order interactions. Already a first order, due to propagation, induced by the non-Gaussianity of $\delta\rho$. At large scales

$$b_{\ell_1,\ell_2\ell_3} \simeq 2\, f_{\text{NL}} \left[C_{\ell_1} C_{\ell_2} + C_{\ell_1} C_{\ell_3} + C_{\ell_2} C_{\ell_3} \right]$$

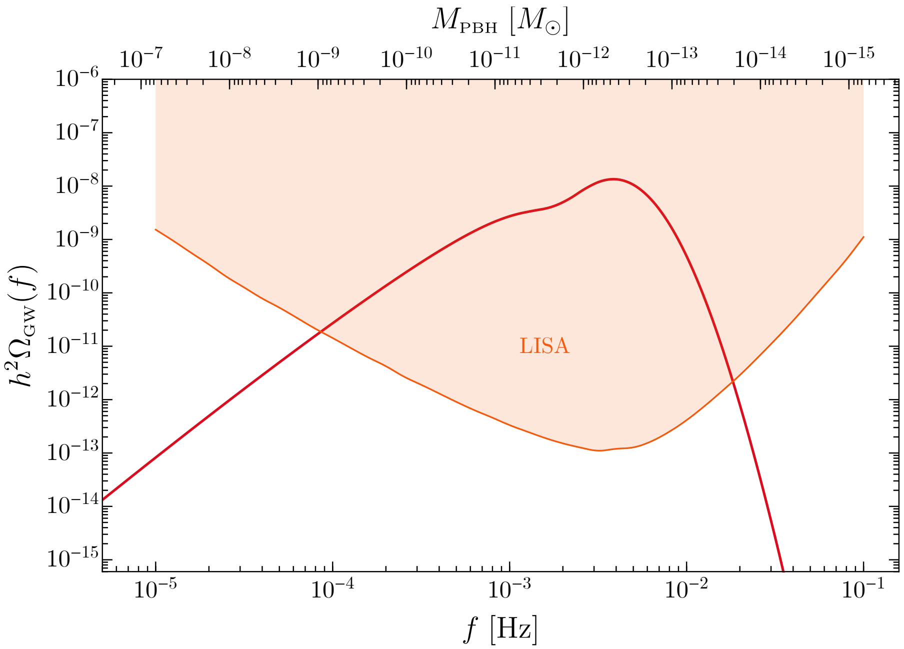
"local" scalar NG,

$$\delta\rho \sim \delta\rho_{\text{g}} + f_{\text{NL}}\, \delta\rho_g^2$$

New probe of large scale anisotropies (like CMB photons)

Anisotropies & non-G at the production - GW in models with PBH

Bartolo et al '19



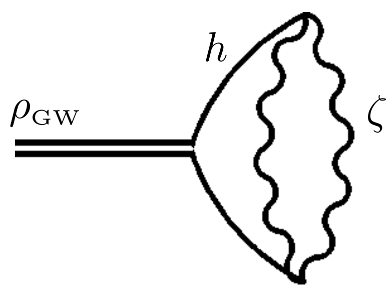
Very large GW signal @LISA

in models of PBH-DM.

Is is isotropic ? Is it Gaussian?

$$\zeta + \zeta \to h$$

$$\rho_{\rm GW} \sim \left\langle \dot{h}^2 \right\rangle \sim \left\langle \zeta^4 \right\rangle$$



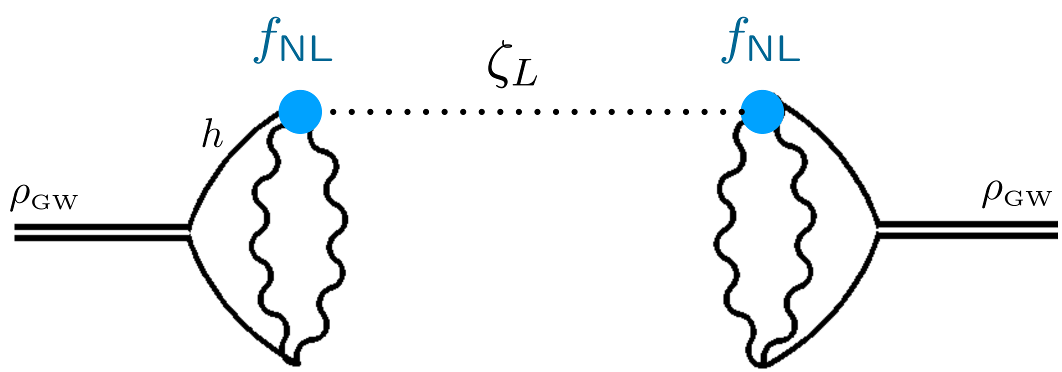
ζ is a short-scale mode, that

generates GW of $f \sim$ mHz today

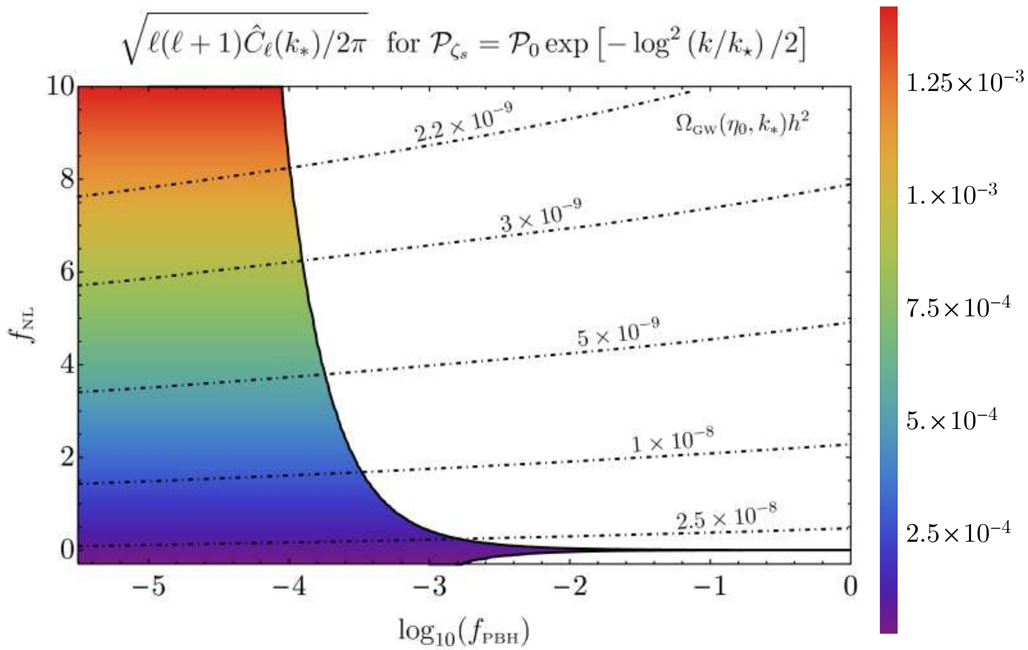
In presence of scalar non-G,

a long mode ζ_L modulates

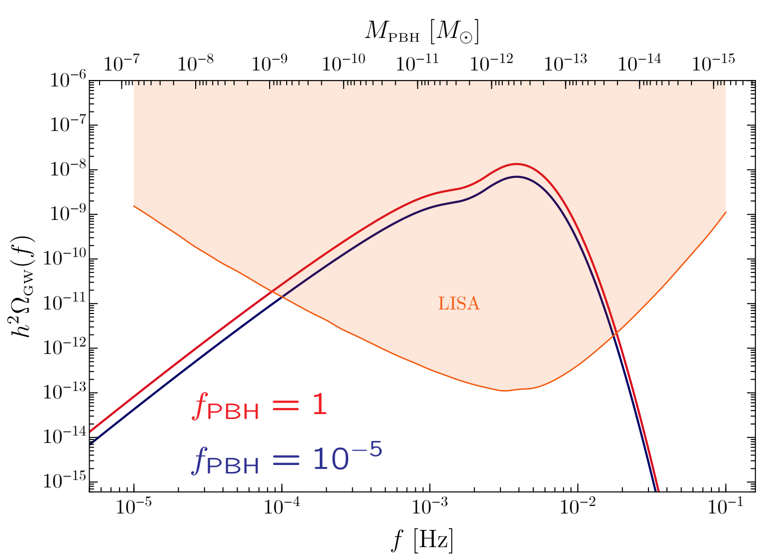
the power of ζ on small scales,



- Greater scalar $f_{\rm NL}$ leads to greater anisotropies and non-G of GW.
- $-11.1 \leq f_{\rm NL} \leq 9.3$, at 95% C.L. Planck '19
- Isocurvature constraints impose a tighter limit on $f_{\rm NL}$ for PBH-DM



Observing a bump at LISA, with significant anisotropy and non-G indicates that the PBH constitute only a small fraction of the DM

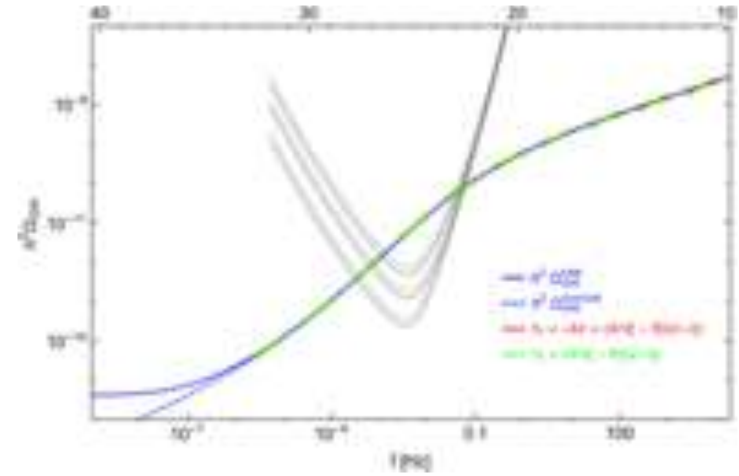


Slight change of P_ζ $\rightarrow$ large change of $f_{\rm PBH}$ / slight change in $\Omega_{\rm GW}$.

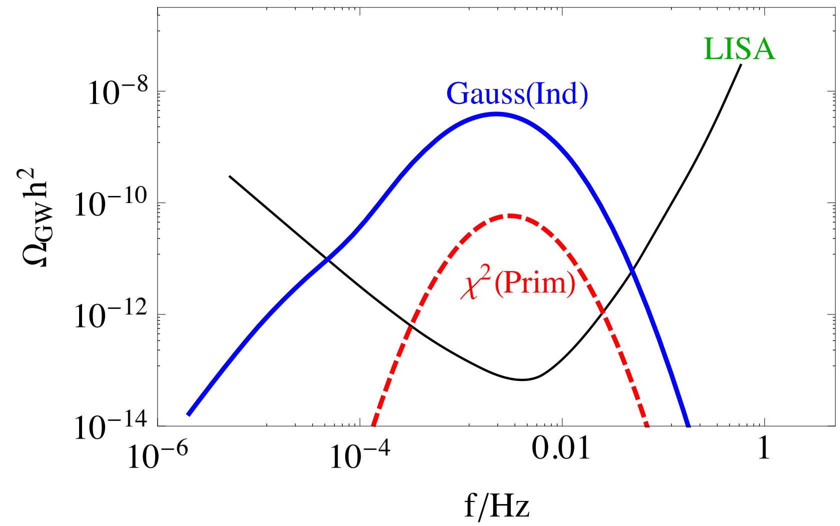
Anisotropies can differentiate between these two cases.

Conclusions

- Signal from inflation only if blue



- Probe of PBH (possibly, PBH DM)



- SGWB characterization