INFLATIONARY STOCHASTIC GRAVITATIONAL WAVE BACKGROUND IN LISA

LISA CONSORTIUM

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10th LISA COSWG Workshop

Stavanger 6TH June 2023

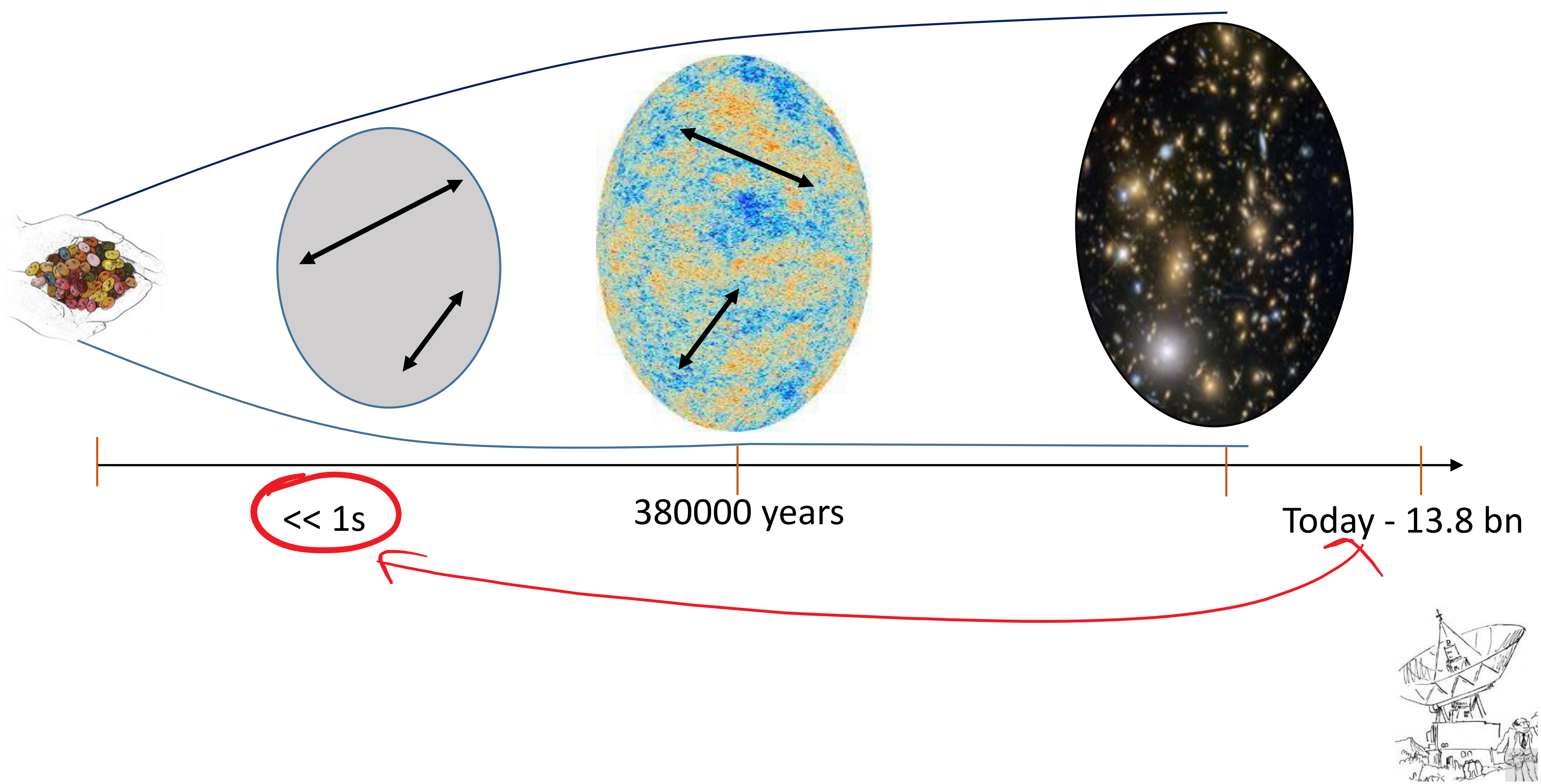
Work in Progress with CosWG LISA

ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

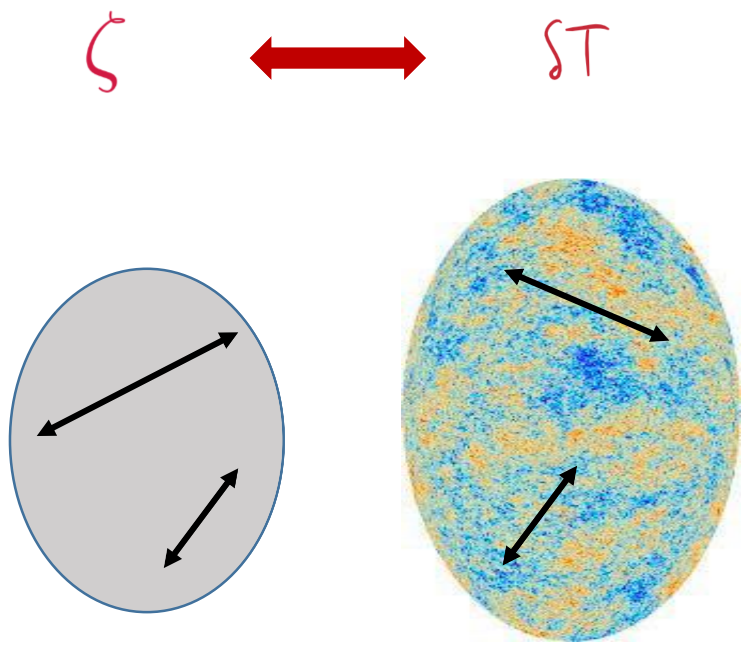
EXCELENCIA MARÍA DE MAEZTU 2020-2023

INITIAL CONDITIONS FROM INFLATION

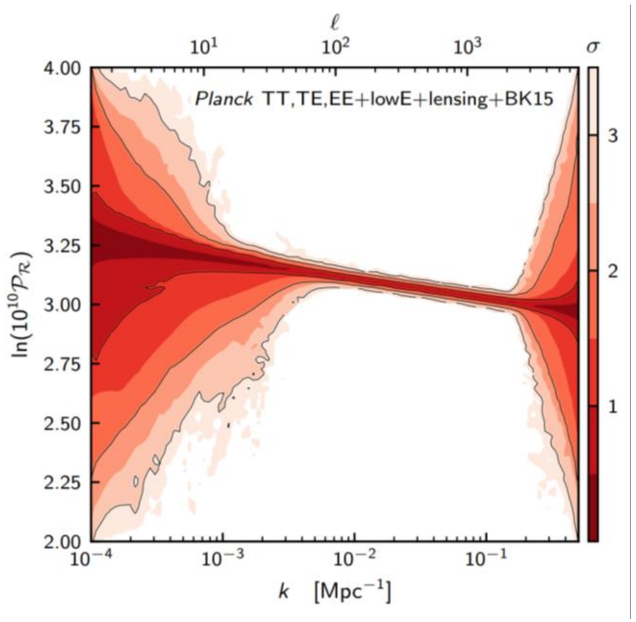
STRUCTURES IN THE UNIVERSE EMERGE FROM VACUUM QUANTUM FLUCTUATIONS



INITIAL CONDITIONS FROM INFLATION



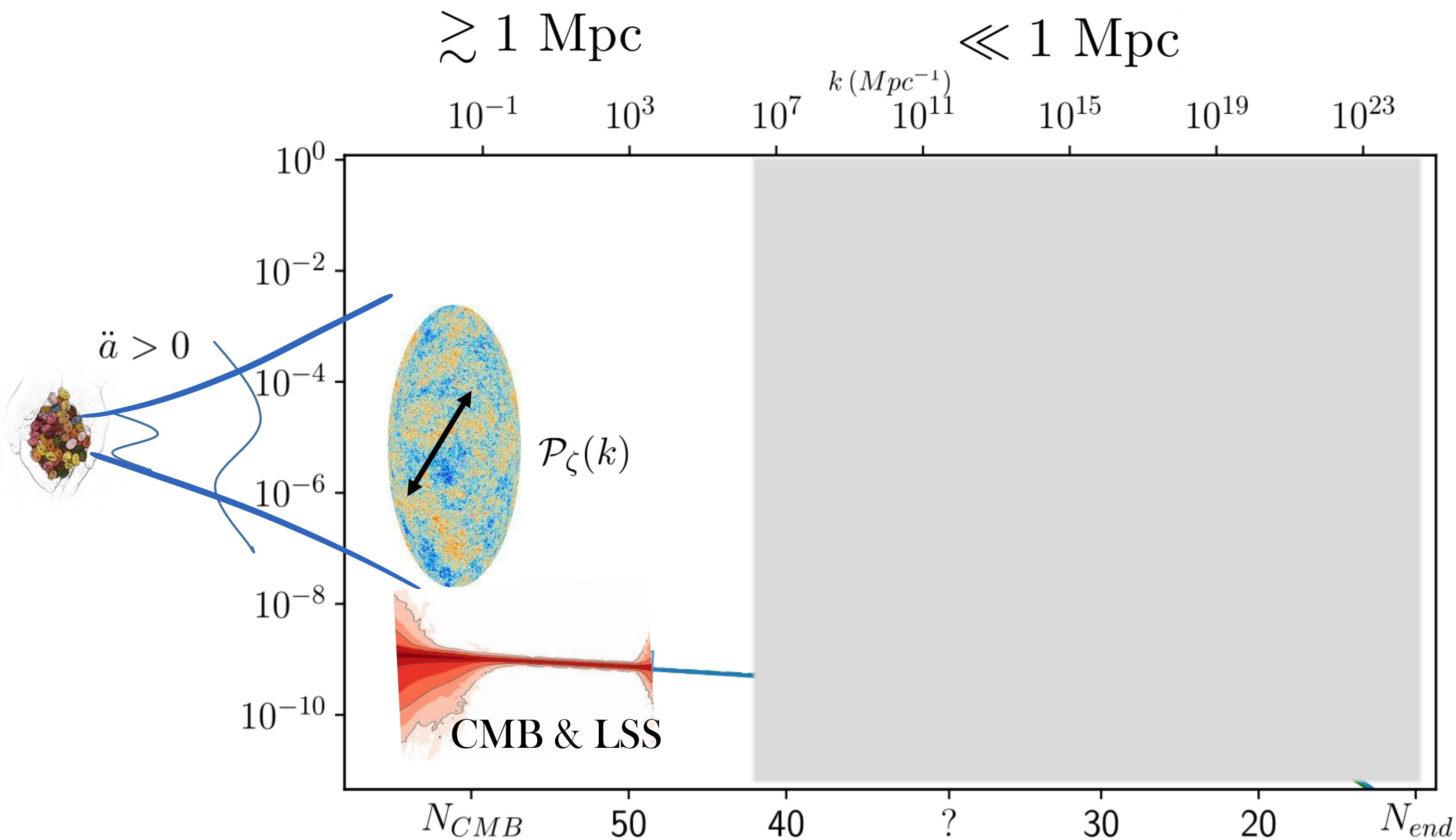
Fluctuations:
Almost scale-invariant,
Gaussian, super-Horizon…



Planck '18

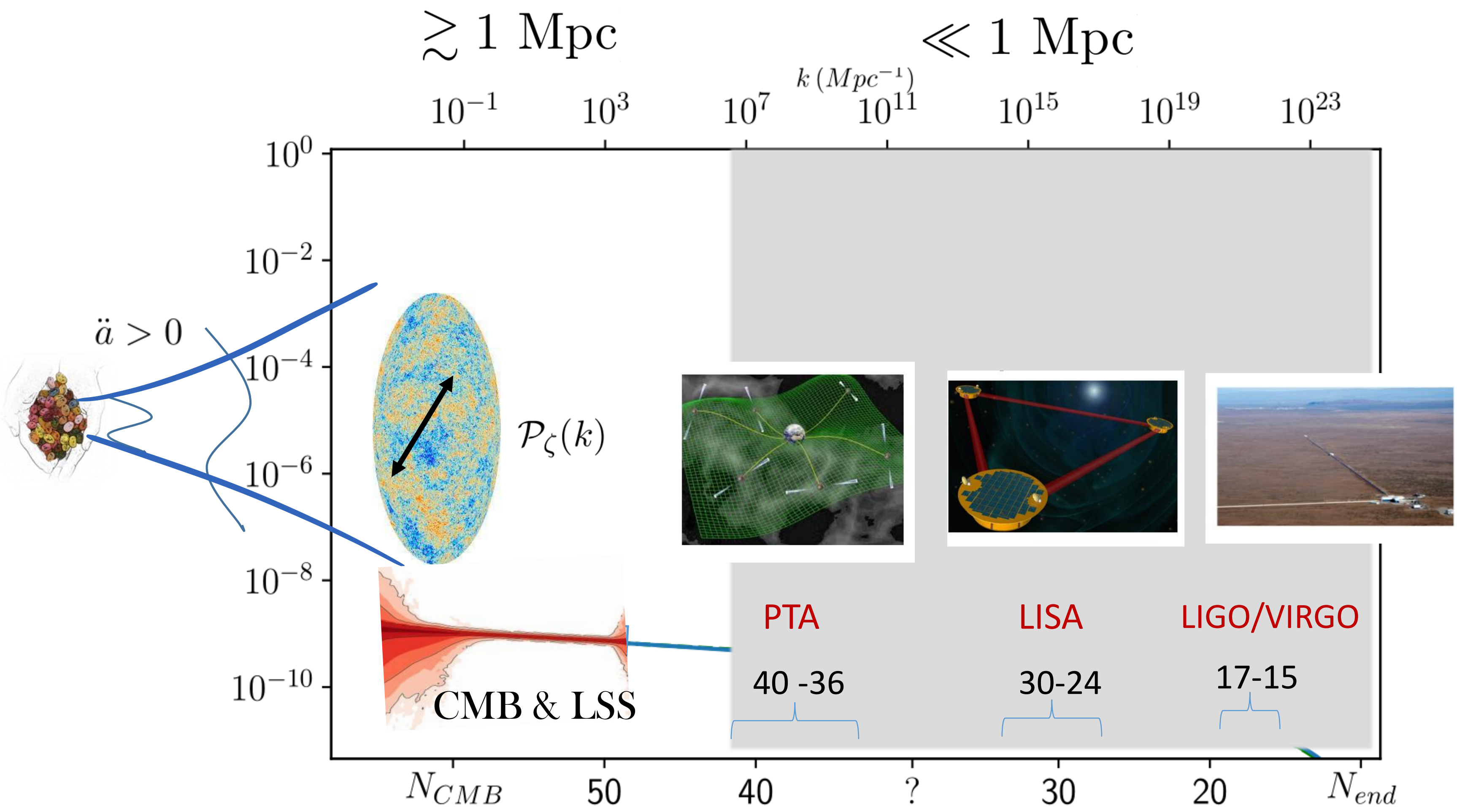
$$\langle\hat{\zeta}(\mathbf{x},\tau)\hat{\zeta}(\mathbf{x},\tau)\rangle = \int d\ln k \cdot \mathcal{P}_\zeta(k,\tau)$$

SGWB FROM INFLATION AT SMALL SCALES



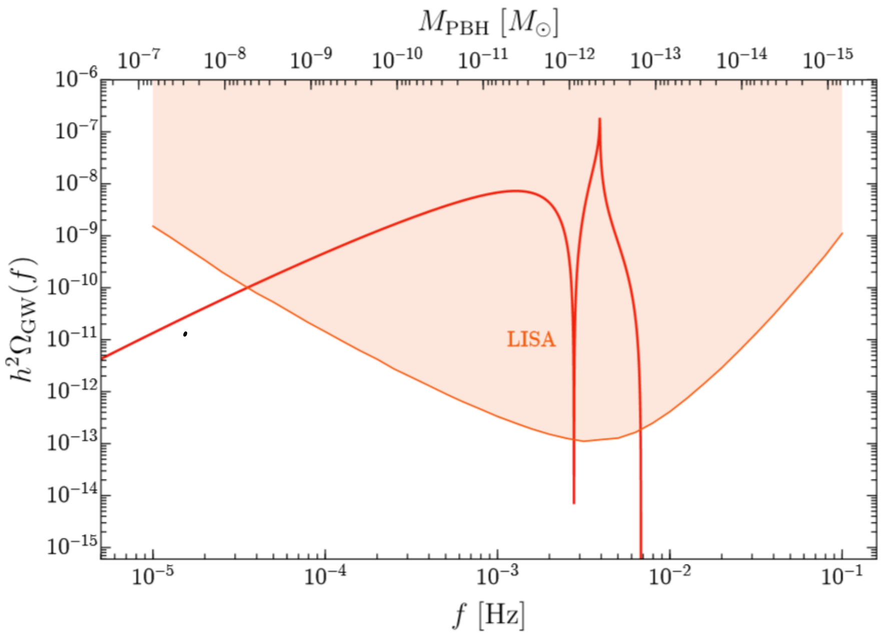
Constrained at large scales

SGWB FROM INFLATION AT SMALL SCALES

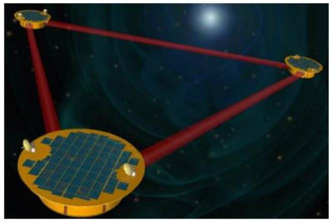


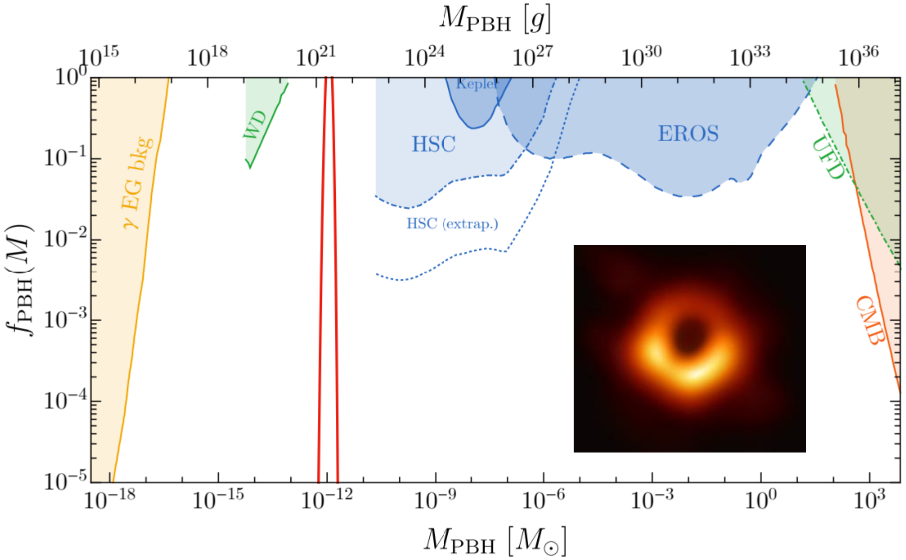
Constrained at large scales

PBH / SGWB & LISA COINCIDENCE



$$\Omega_{\rm GW}(k) \propto \int\int I(u,v)\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv)$$





LISA Serendipity
Bartolo, Franciolini, Peloso et al. '18

STOCHASTIC BACKGROUND OF GWS

- Angular size on the sky (today) of a correlated region at the time of production $\ll$ detector resolution

Caprini and Figueroa '18

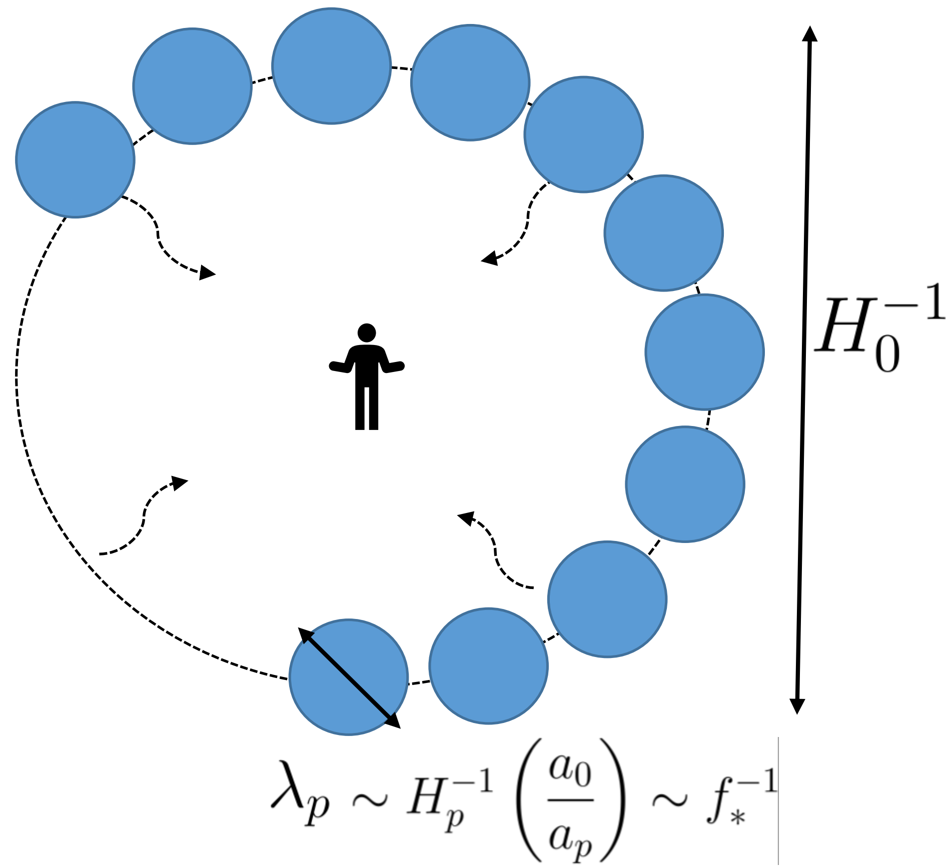
with resolution $\Theta_{\rm Res} \sim 10\,{\rm deg}$

$$\Longrightarrow \quad z \lesssim 17$$

- Characteristic frequency associated to the time of production/experiment

- $h_{ij} \longleftrightarrow$ <u>STOCHASTIC VARIABLE</u>

$$\Omega_{\rm GW}(k) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln k}$$

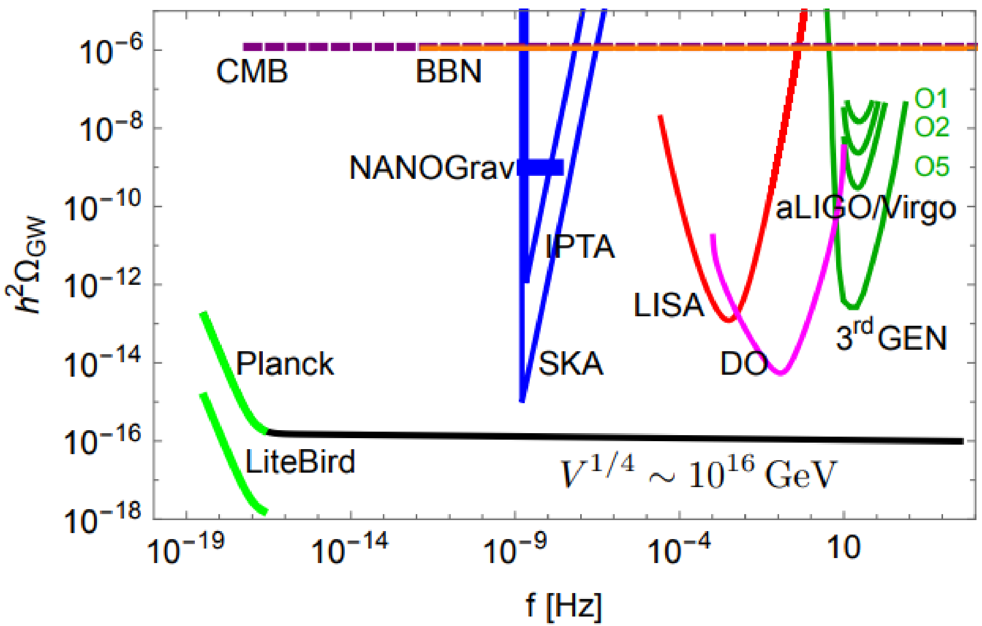


SGWB FROM INFLATION:

the Holy Grail of Theoretical cosmology

Standard: enhancement of the vacuum fluctuations due to the inflationary exp. Expansion

$$\Box h_{ij} = 0$$



$$\frac{2}{\pi}\frac{H^2}{M_{\rm pl}^2}$$

$$n_T \simeq -2\epsilon$$

Too tiny to be seen directly in future GW detector !

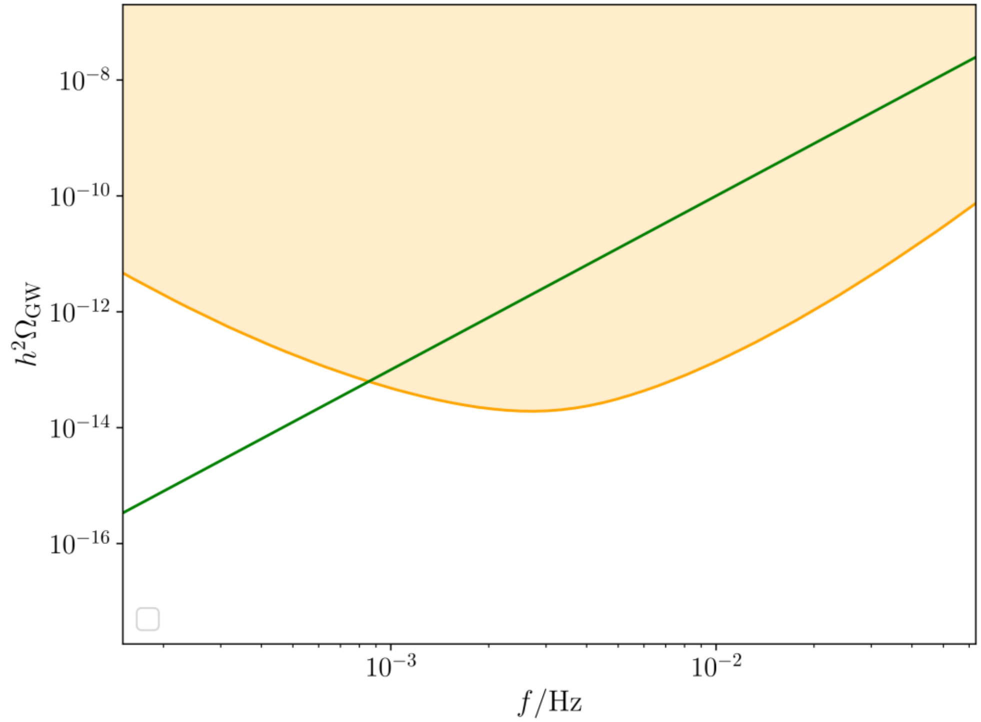
STOCHASTIC BACKGROUND OF GWS

TEMPLATE DATABANK

THE INFLATIONARY MENU

POWER LAW

$$h^2\Omega_{\rm GW}^{\rm PL}(f,\vec{p}) = 10^{\alpha_*}\left(\frac{f}{f_*}\right)^{n_t}$$



- Anything far from production
- Axion inflation

$$\mathcal{L} \supset \frac{\phi F_{\mu\nu}\tilde{F}^{\mu\nu}}{4 f_\phi}$$

$$n_t(\dot{\phi}_*/f_\phi, \epsilon_*, \eta_*)$$

N. Barnaby, M. Peloso '10
L. Sorbo '11

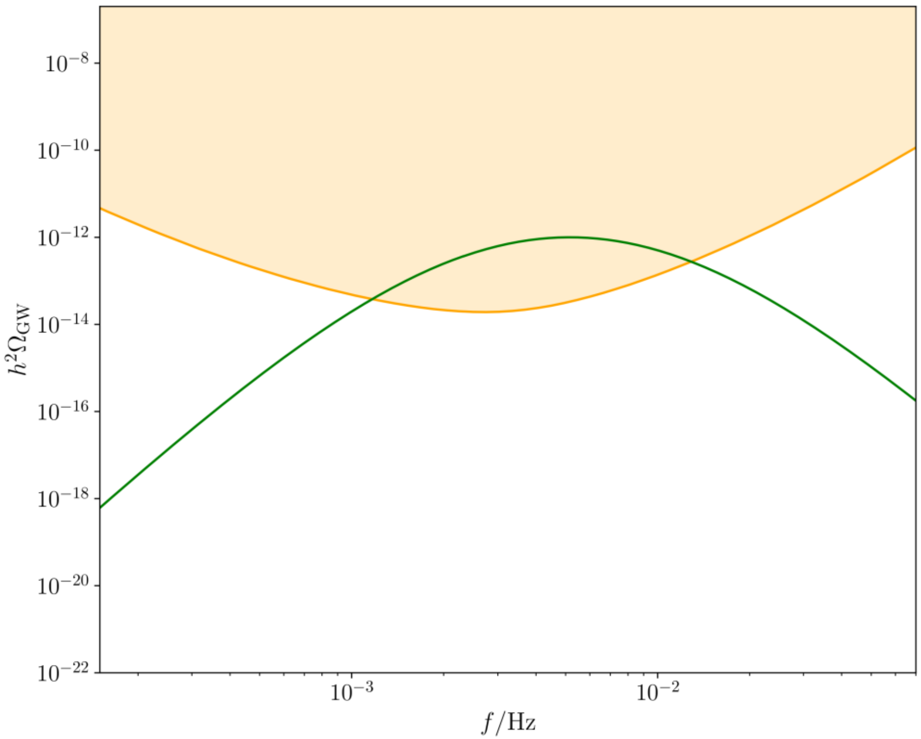
- Massive spin-2 field, time dependent sound speed

$$n_t \simeq \frac{2}{3}\frac{m_h^2}{H_*^2} \qquad n_t \simeq |s_2|(2\nu - 1)$$

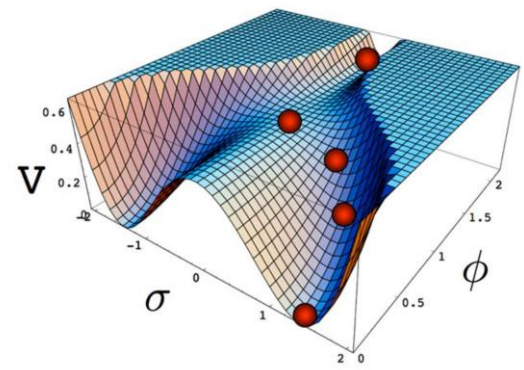
N. Bartolo et al. '16, D. Cannone '15,
L. Iacconi '20, E. Dimastrogiovanni '21

BROKEN POWER LAW

$$h^2\Omega_{\rm GW}(f,\vec{p}) = h^2\Omega_* \frac{\left(\frac{f}{f_*}\right)^{n_{t,1}}}{\left[\frac{1}{2}\left(1+\frac{f}{f_*}\right)\right]^{n_{t,1}-n_{t,2}}}$$



- **Hybrid mild waterfall phase**



S. Clesse, J. Garcia-Bellido '15

- **Non-standard thermal history**

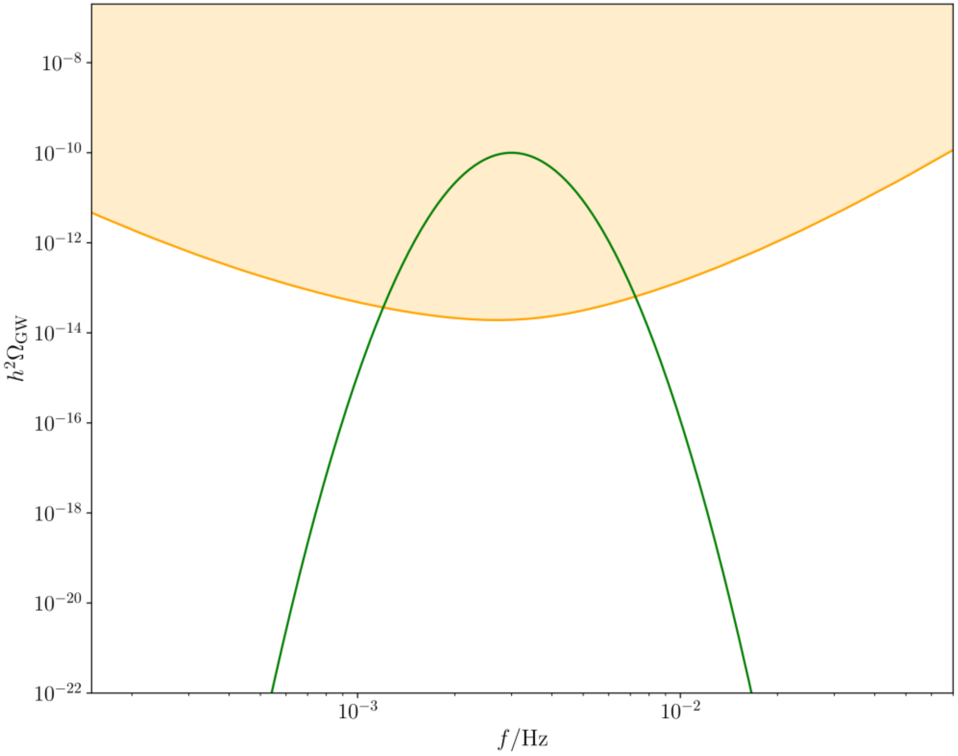
  Matter Domination / Kination...

$$n_{t,1} = n_{T,\rm prim} + 2(3w_1 - 1)/(3w_1 + 1)$$

$$n_{t,2} = n_{T,\rm prim} + 2(3w_2 - 1)/(3w_2 + 1)$$

GAUSSIAN BUMP

$$h^2\Omega_{\rm GW}^{\rm GBp}(f,\vec{p}) = 10^{\alpha_*}\exp\left[-\frac{1}{2\times 10^{2\Delta}}\,\log_{10}^2\left(\frac{f}{f_*}\right)\right]$$

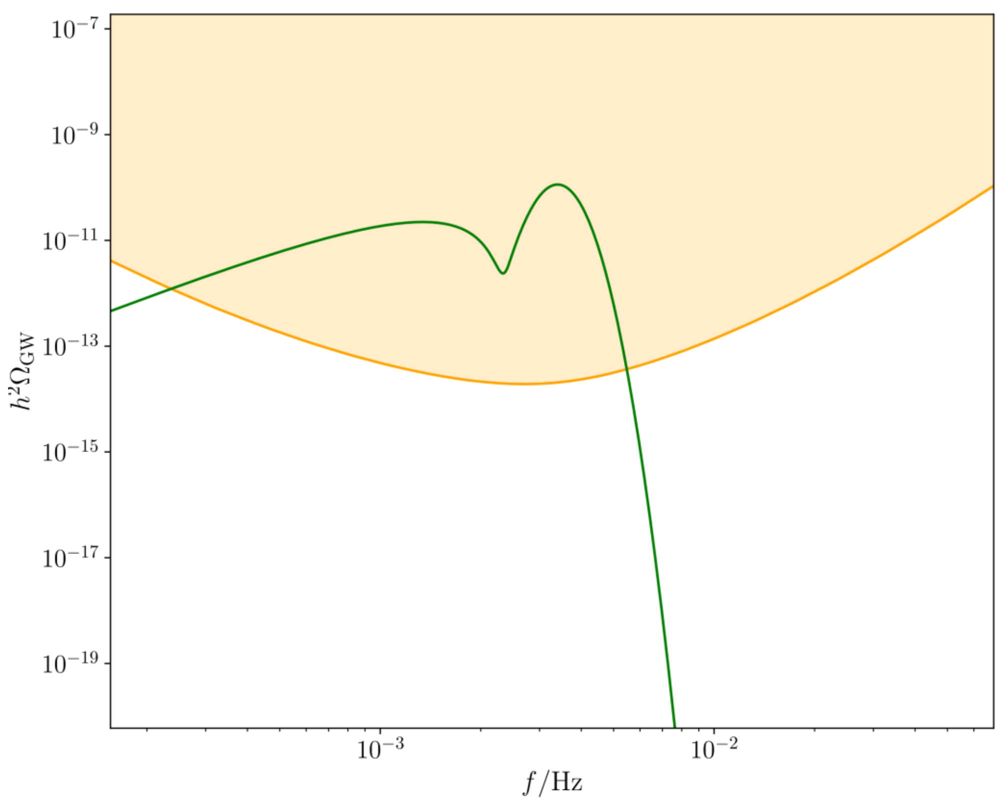


- Producing phenomenon persisting during inflation
- Axion spectator

R. Namba et al. '16
P. Campeti et al. '22
...
...

DOUBLE PEAK

$$\Omega_{\rm GW}(f) = \beta\,\Omega_* \left(\frac{f}{\kappa_1 f_*}\right)^{\alpha} \left(\frac{\sqrt{\frac{2}{3}} - \frac{f}{f_*}}{\sqrt{\frac{2}{3}} - \kappa_1}\right)^{\frac{\alpha}{\kappa_1}\left(\sqrt{\frac{2}{3}}-\kappa_1\right)} \theta\left(\sqrt{\frac{2}{3}} - \frac{f}{f_*}\right)$$
$$+\,\Omega_* \exp\left[-\frac{1}{2\rho^2}\ln^2\left(\frac{f}{\kappa_2 f_*}\right)\right]\left\{1 + {\rm Erf}\left[-\zeta \ln\left(\frac{f}{\kappa_2 f_*}\right)\right]\right\}$$



Scalar-induced GWs

Acquaviva et al. '02; Mollerach, Harari, Matarrese '03; Ananda, Clarkson, Wands '06;

Log-normal Pzeta (resonance etc..)

$$\mathcal{P}_\zeta(k) \simeq \mathcal{P}_\zeta(k)^{\rm ln} = \mathcal{A}_s \exp\left[-\frac{1}{2\Delta^2}\ln^2\left(\frac{k}{k_*}\right)\right]$$

e.g. Cai et al '18

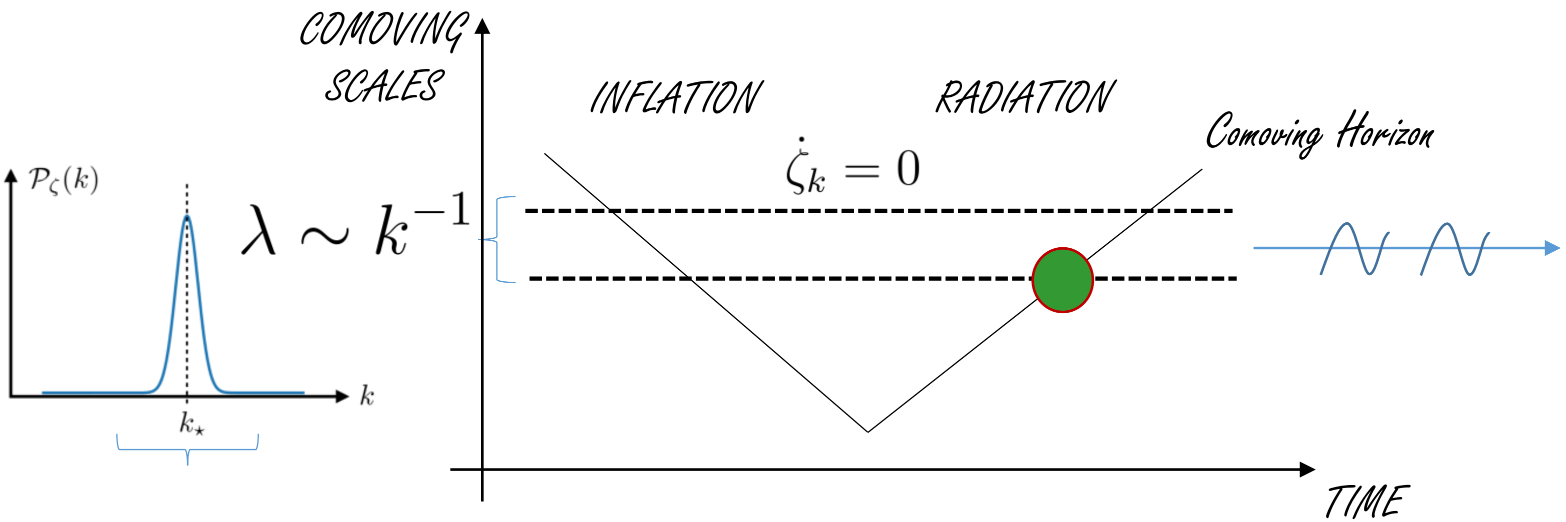
Broken Power law Pzeta (Ultra-slow-roll..)

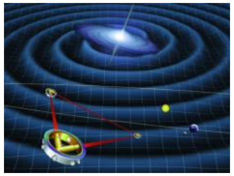
$$\mathcal{P}_\zeta(k) \simeq \mathcal{P}_\zeta(k)^{\rm bpl} = \frac{\mathcal{A}_s(p_1+p_2)}{\left[p_2\left(\frac{k}{k_*}\right)^{-p_1} + p_1\left(\frac{k}{k_*}\right)^{p_2}\right]}$$

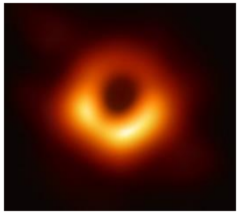
SCALAR INDUCED (post-inflationary) SGWB

SCALAR PERTURBATIONS ACT AS A TENSOR SOURCE

$$\boxed{\Box h_{ij} = S_{ij}^{TT}} \sim (\partial\zeta)^2$$

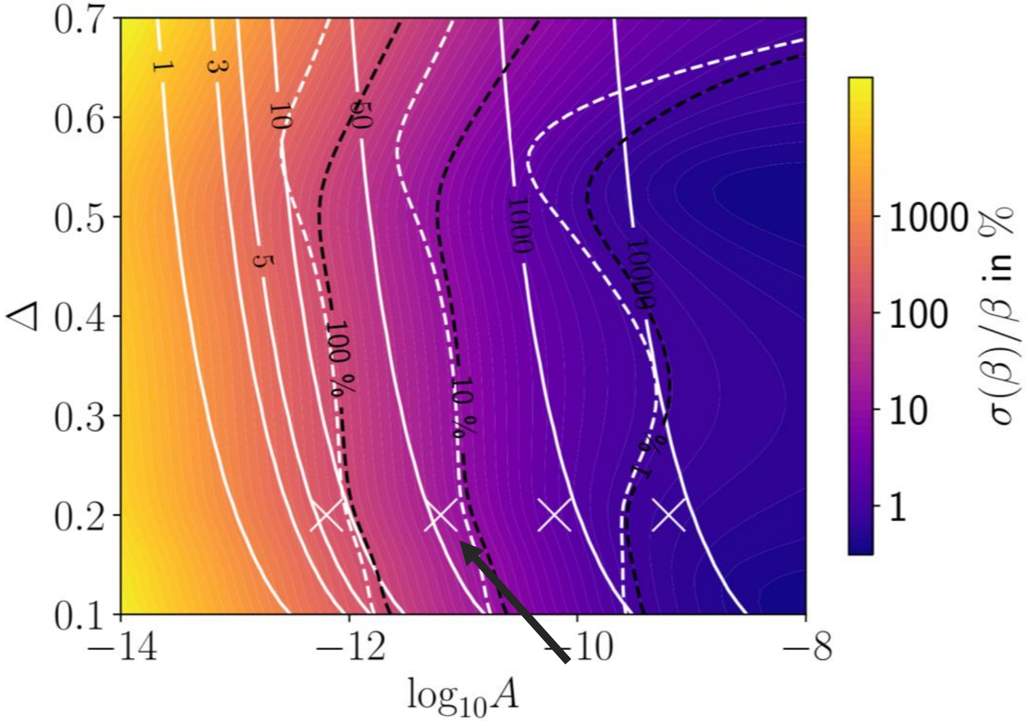


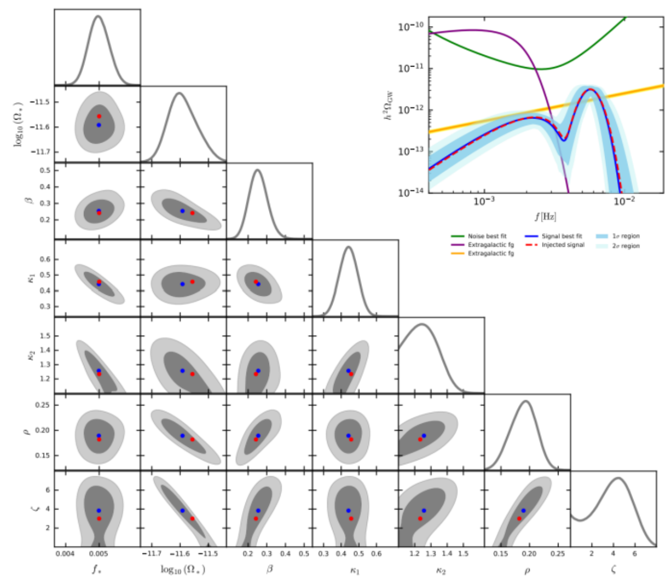




$$\boxed{\Omega_{\rm GW}(k) = \int\int \mathcal{T}(u,v)\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv)}$$

DOUBLE PEAK FISHER FORECAST



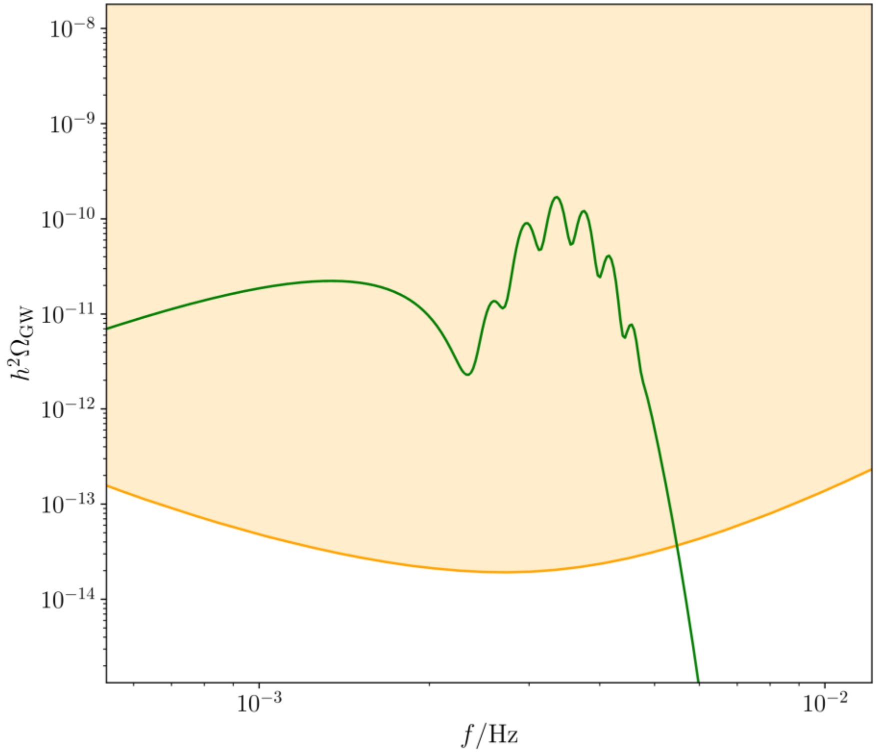


Direct link with 'Fundamental physics' is hard to achieve

Exra layer of complexity wtr to **phase transition**, see E.Madge talk

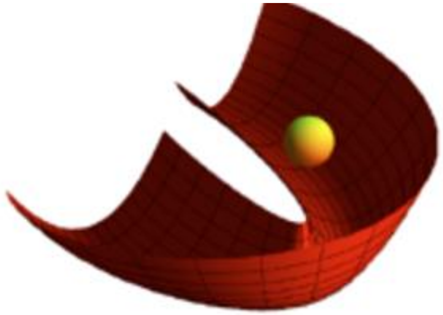
LINEAR OSCILLATIONS

$$h^2\Omega_{\rm GW}^{\rm LO}(f,\vec{p}) = \left[1 + \mathcal{A}_{\rm lin}\cos\left(\omega_{\rm lin} f + \theta_{\rm lin}\right)\right] h^2\Omega_{\rm GW}^{\rm env}(f,\vec{p}_{\rm env})$$



Sharp feature – Localized Event

(Step in the potential / 2-stage / turn in field-space etc..)

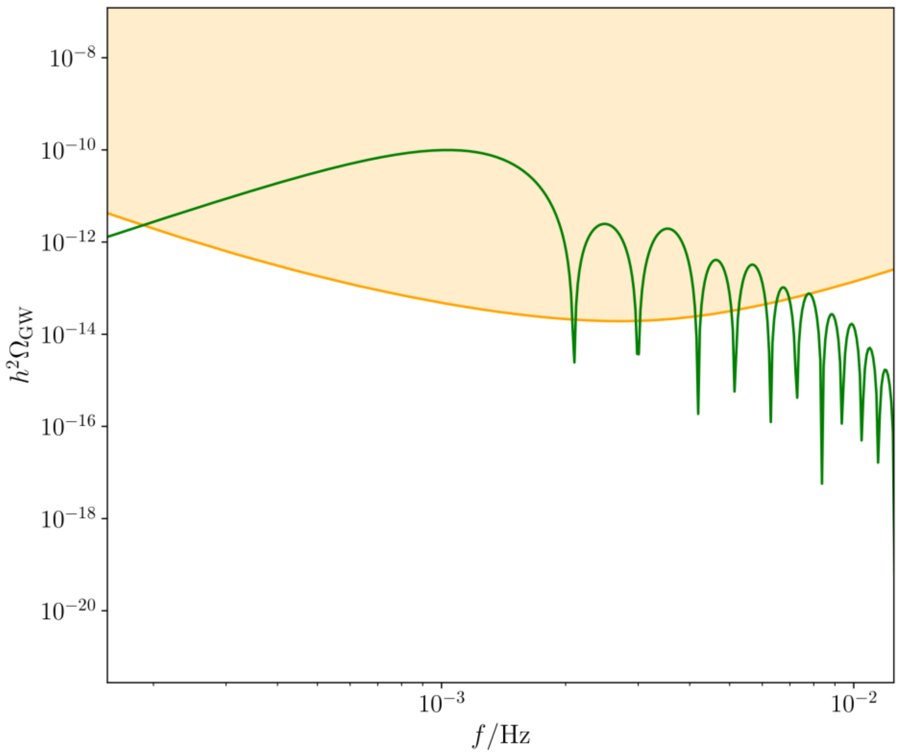


$$\omega_{\rm lin} \sim 2c_s^{-1}/\bar{f}$$

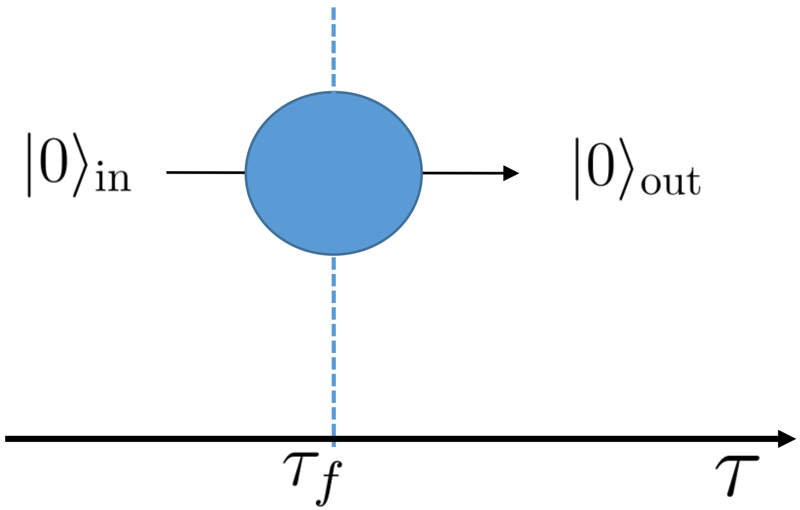
J. Fumagalli, S.Renaux-Petel, L.Witkowski '20,
M. Braglia, X. Chen, D.K. Hazra '20
I. Dalianis et al. '21

EXCITED STATES

$$h^2\Omega_{\rm GW}^{\rm DB}(f,\vec{p}) = \frac{10^{\log_{10}\Omega_*}}{0.0065}\frac{1}{(\omega f)^3}\left(1-\frac{(\omega f)^2}{16\gamma^2}\right)^2\cdot\left(\sin(\omega f/2)-4\frac{(1-\cos(\omega f/2))}{\omega f}\right)^2$$



Dynamically generated excited state

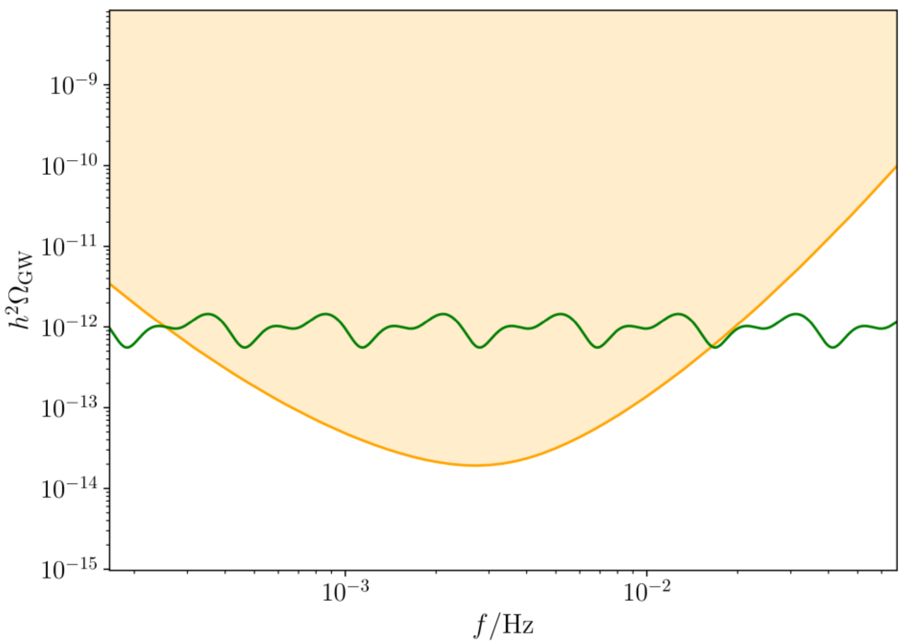


$$\omega \sim 2/\bar{f}$$

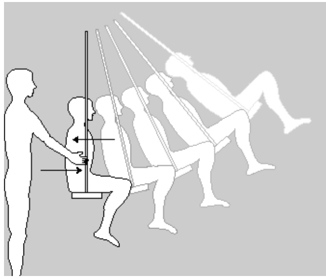
J. Fumagalli, et al. '21,
Z. Peng et al '21
K. Inomata '21

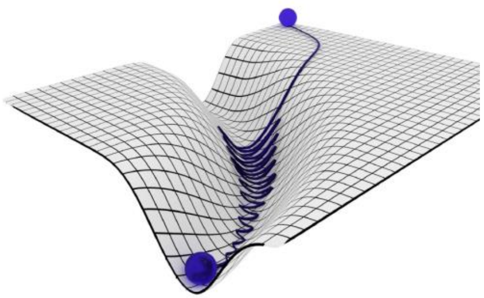
RESONANT LOGARITHMIC OSCILLATIONS

$$h^2\Omega_{\rm GW}^{\rm RO}(f,\vec{p}) = \Big[1+\mathcal{A}_1(A_{\rm log},\omega_{\rm log})\cos\left(\omega_{\rm log}\ln(f/{\rm Hz})+\theta_{\rm log,1}\right) + \mathcal{A}_2(A_{\rm log},\omega_{\rm log})\cos\left(2\omega_{\rm log}\ln(f/{\rm Hz})+\theta_{\rm log,2}\right)\Big] h^2\Omega_{\rm GW}^{\rm env}(f,\vec{p}_{\rm env})$$



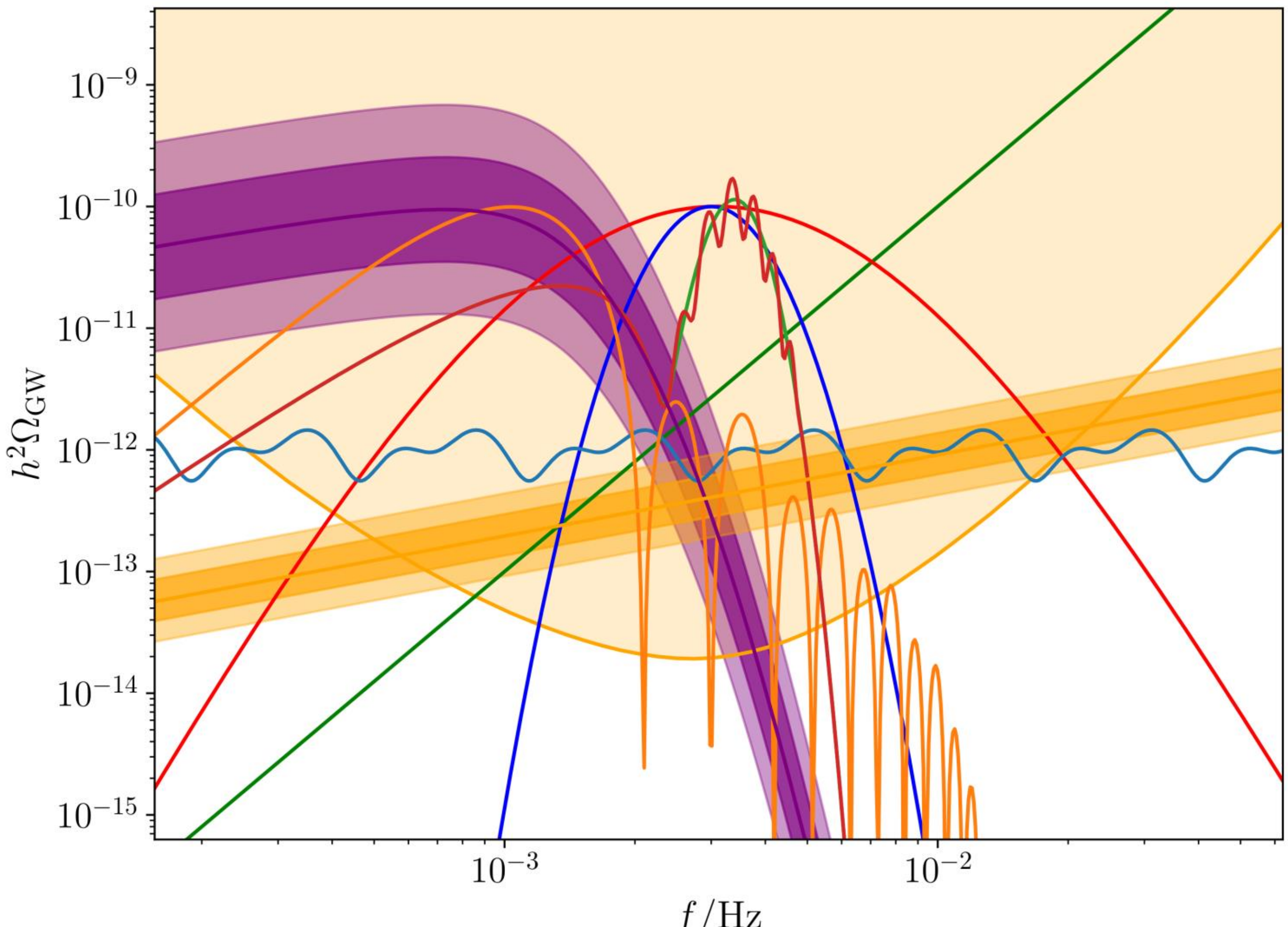
Resonant Features– Oscillations of BkG (Ex. Monodromy inflation, double turn, in-out horizon..)





J.Fumagalli et al. '21, Battacharya, Zavala '22, N. Mavromotos, V. Spanos, I. Stamou '22 ..

ALL TOGETHER



CONCLUSIONS

- Stochastic gravitational wave background has the potential to unveil new physics not reachable by any other means

- It provides a new window to test inflation at small scales.
  Reasons to go beyond the vanilla inflationary scenarios lead to
  features in the SGWB

- Building a template databank: The List is not exhaustive (and will never be)

- Often not a direct link between fundamental parameters and spectral shapes
  - Simple → Degeneracy
  - Complicated → Weak link

- Effort in making the connection with fundamental physics explicit
- Effort in identifying pattern which belongs '**only**' to inflation