PBH bounds on scalar-induced GWs in the PTA band

Valerie Domcke
CERN

@ MITP workshop on PTAs
14.-18.08.2023

based on
2302.07901
with Virgile Dandoy and
Fabrizio Rompineve

CERN

probes of scalar power spectrum

CMB: $P_\zeta(k) \simeq 10^{-9} \quad @ \; k \sim 0.05 \text{ Mpc}^{-1}$

at smaller scales much weaker constrained:

- scalar induced GWs (SIGWs) $\zeta + \zeta \to h$

$$f = k/(2\pi) \sim 10^{-9} \text{ Hz } (k \text{ pc})$$

- primordial black holes (PBHs) $\zeta \sim \delta\rho \to \text{PBH}$

$$M_H = \frac{4}{3}\pi H^{-3}\rho = 4\pi M_P^2 H^{-1} \simeq 20 M_\odot \, (k \text{ pc})^{-2}$$

see also Fabrizio‘s talk yesterday

large scalar perturbations at pc scale (re-entered 15 – 20 e-fold after CMB)
→ GWs at PTA scales and PBHs around ~ solar mass

scalar induced GWs

model for scalar power spectrum

$$P_\zeta(k) = \frac{A_\zeta}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

k_* peak position
A_ζ amplitude
Δ width

SIGWs: Espinosa, Racco, Riotto `18, Kohri, Terada `18

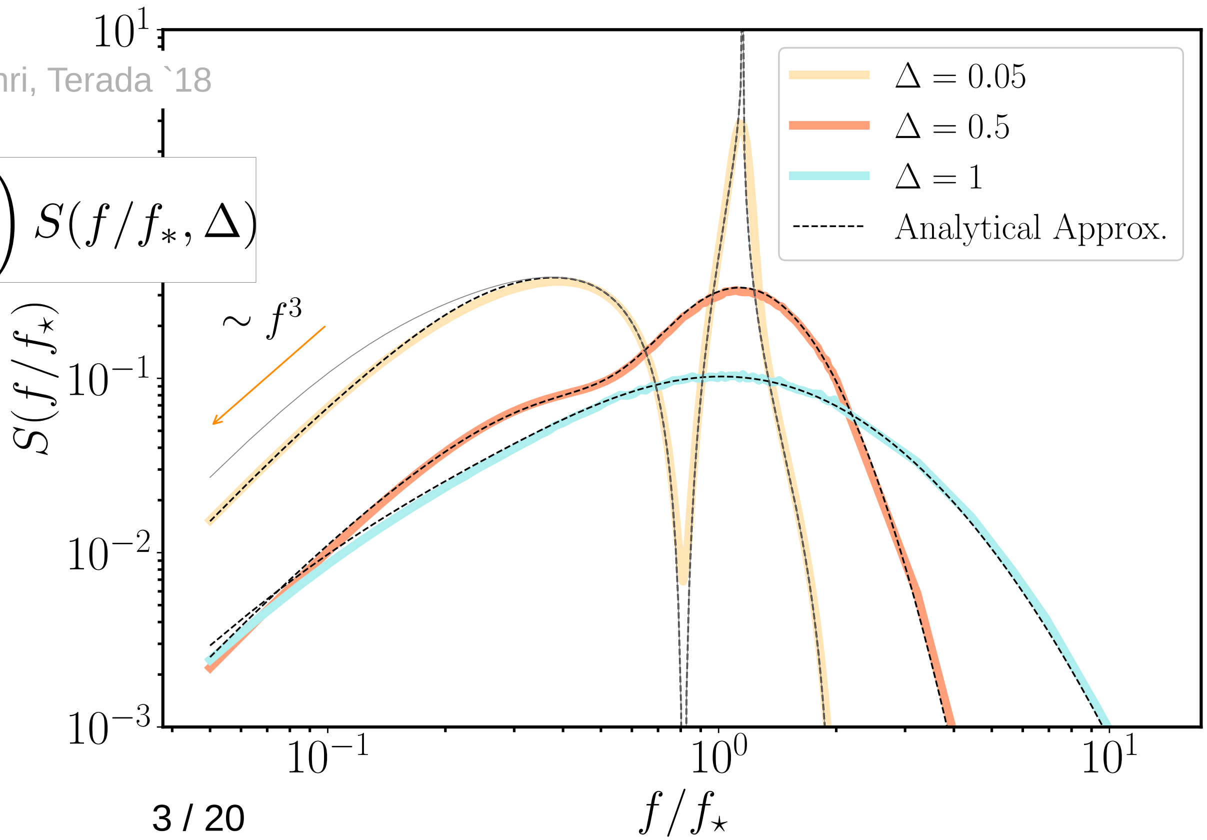
$$\Omega_{\rm gw} h^2 = 10^{-9} \left(\frac{A_\zeta}{0.01}\right)^2 \left(\frac{\Omega_r h^2}{10^{-5}}\right) S(f/f_*, \Delta)$$

resonance for narrow peak

Ananda, Clarkson, Wands `06

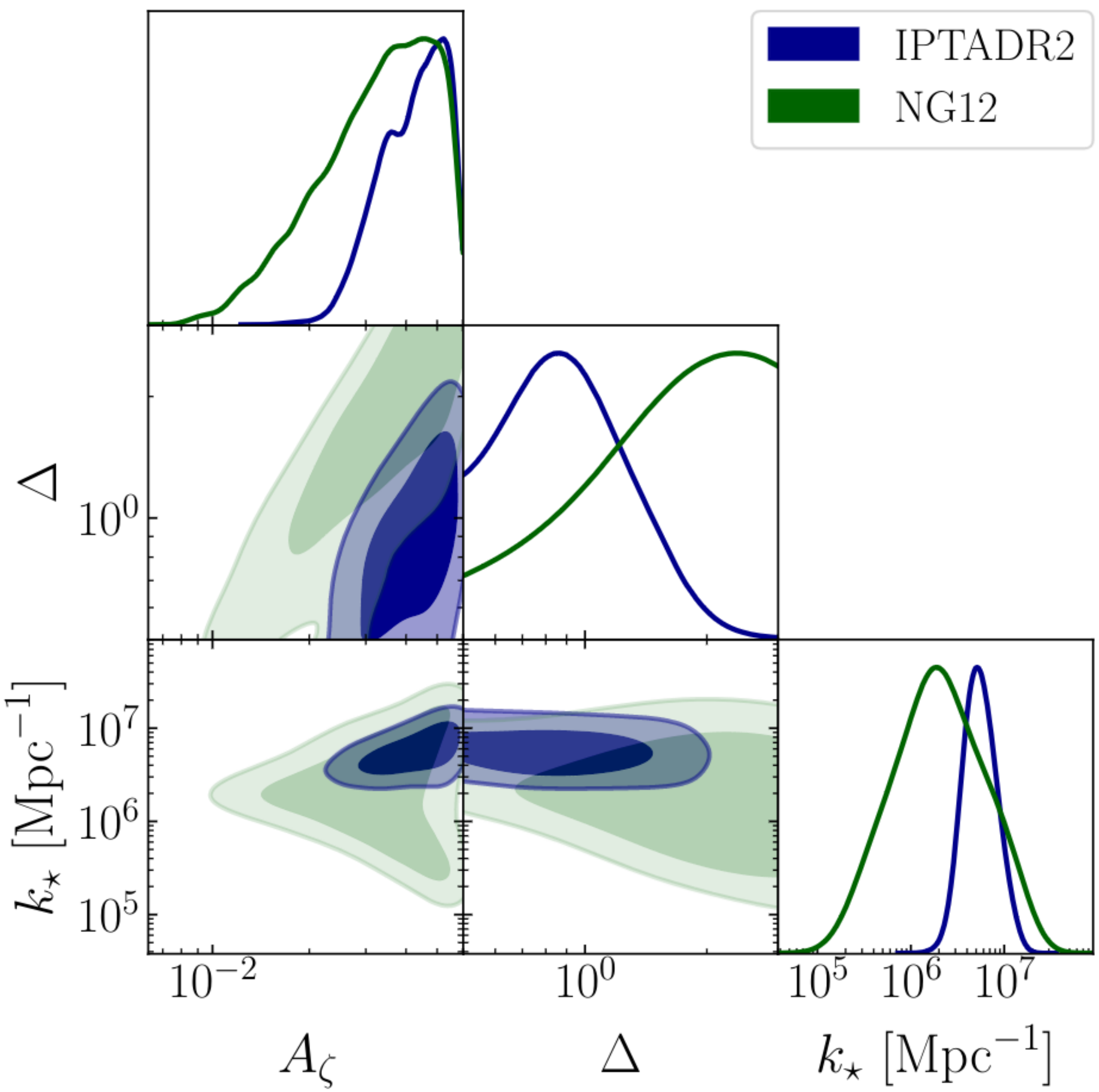
analytical approximation

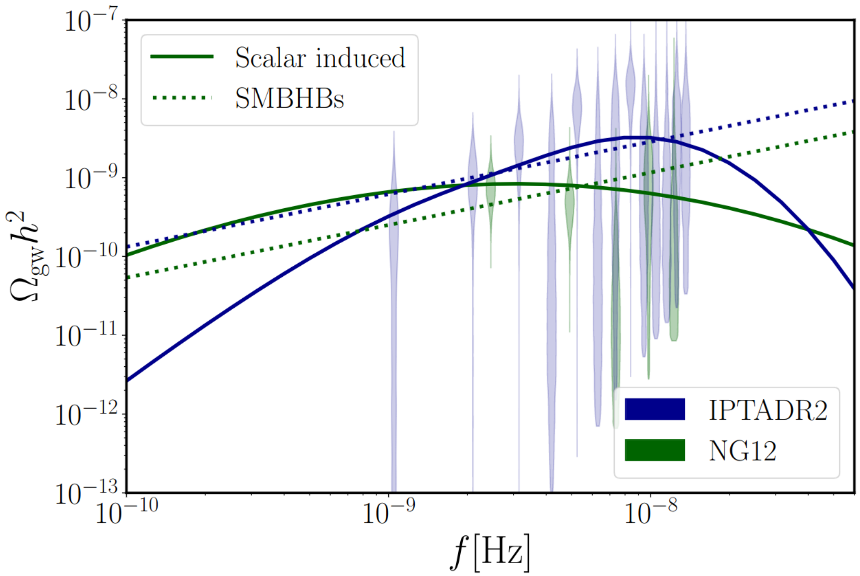
Pi, Sasaki `20,
Dandoy, VD, Rompineve `23



Bayesian search in PTA data

Dandoy, VD, Rompineve `23



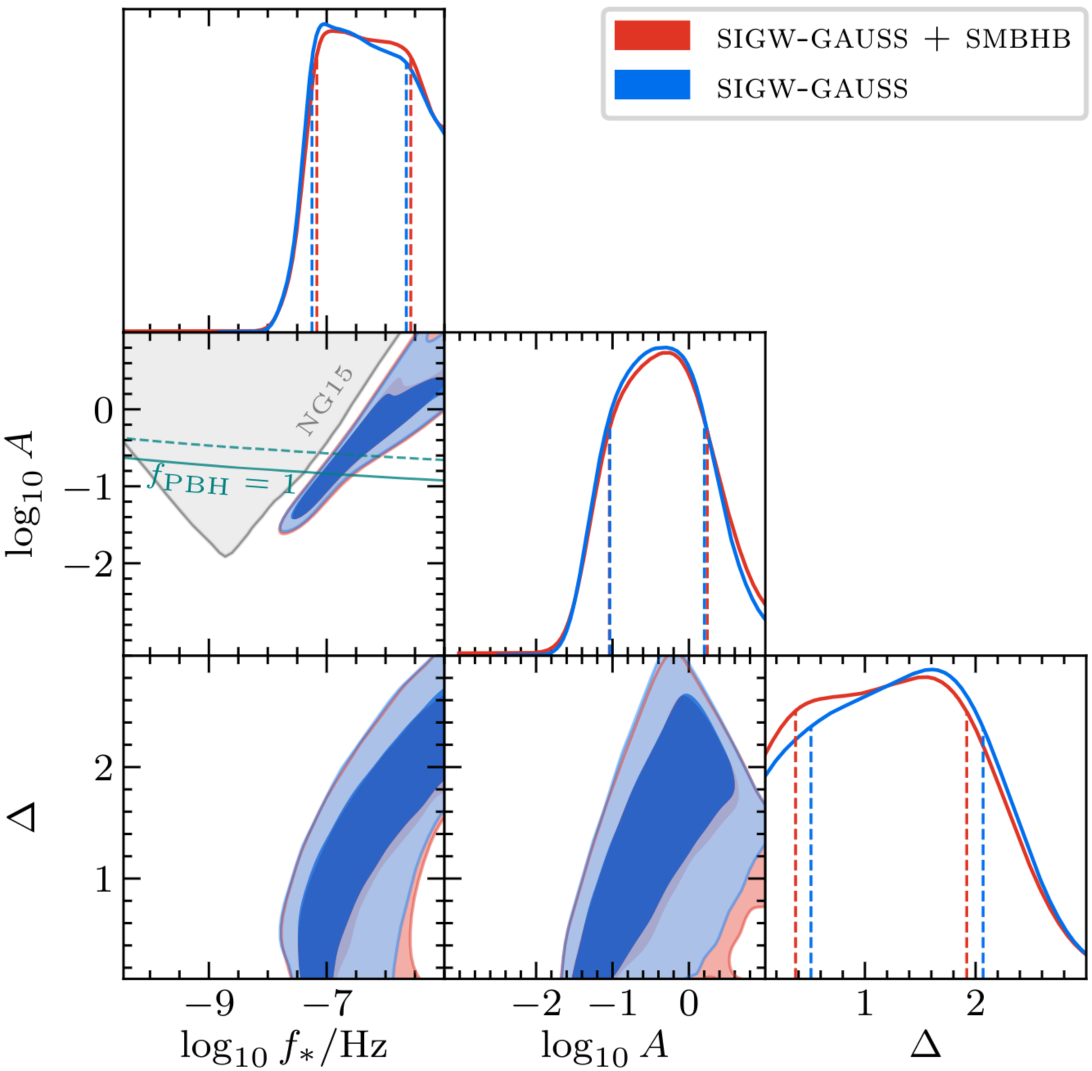


- good fit for

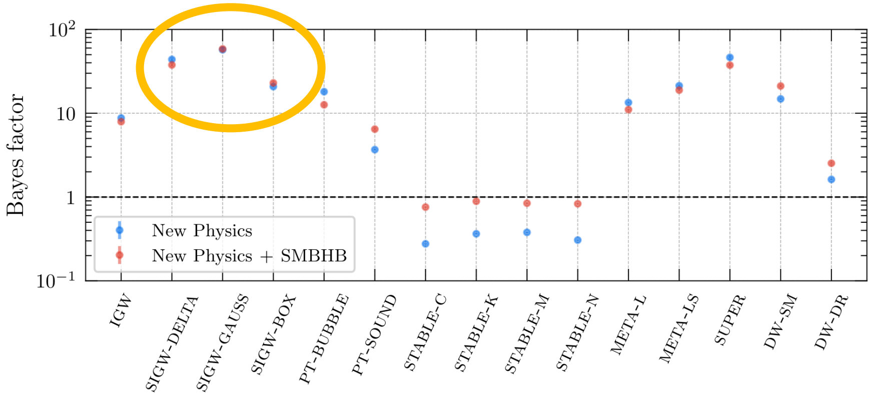
  $A_\zeta \sim \text{few } 10^{-2},\ k \sim \text{pc}^{-1},\ \Delta \sim 1$

- ITPA DR2 similar to 2023 DR

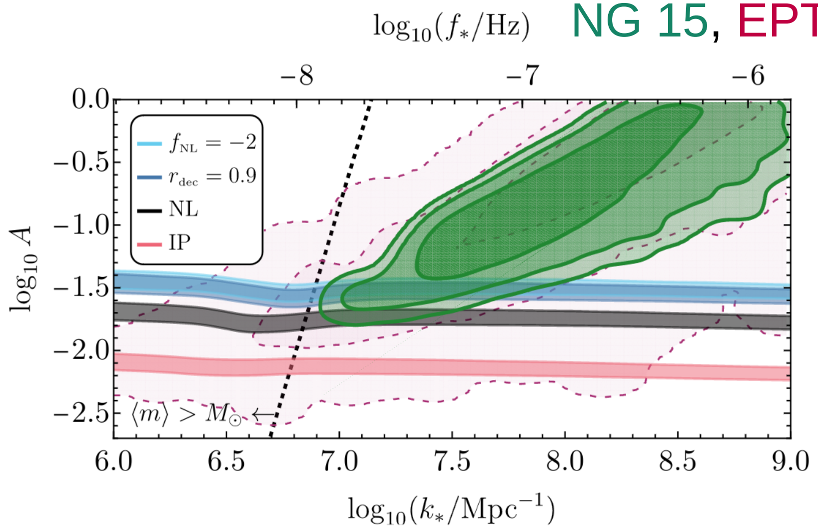
2023 data release



Nanograv 15 New Physics Paper



NG 15, EPTA



Franciolini, Iovino, Vaskonen, Veermäe `23

primordial black holes

- fraction of PBH dark matter:

$$f_{\mathrm{PBH}} = \frac{1}{\Omega_{\mathrm{DM}}} \int d\ln M \int d\ln k \; \beta_k(M) \; \frac{\rho_\gamma(T_k)}{\rho_c^0} \frac{s^0}{s(T_k)}$$

radiation component

fraction of radiation collapsed to PBH of mass M at horizon re-entry

primordial black holes

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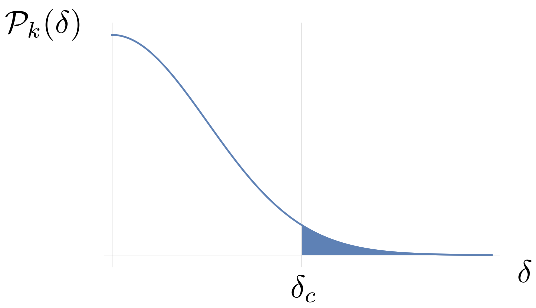
fraction of radiation collapsed to PBH of mass M at horizon re-entry

- Press-Schechter formalism for spherical collapse:

$$\beta_k(M) = \int_{\delta_c}^{\infty} d\delta \; \underbrace{\mathcal{P}_k(\delta)}_{\frac{\exp(-\delta^2/(2\sigma_k^2))}{\sqrt{2\pi}\sigma_k}} \; \underbrace{\frac{M(\delta)}{M_H(k)}}_{\simeq 1} \; \underbrace{\delta_D\left[\ln\frac{M}{M(\delta)}\right]}_{M(\delta)=M}$$

probability distribution



$$\delta_c \sim c_s^2 = 1/3 \qquad \sigma_k^2 \sim P_\delta(k) \sim P_\zeta(k)$$

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primordial black holes

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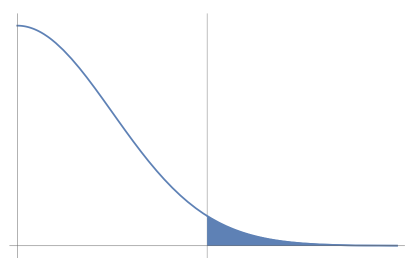

$\delta_c \sim c_s^2 = 1/3 \qquad \sigma_k^2 \sim P_\delta(k) \sim P_\zeta(k)$

- Bounds on PBH abundance from $f_{\rm PBH} < 1$, microlensing, LIGO/VIRGO

  → constraints on power spectrum $P_\zeta(k)$

The devil is in the detail (1)

$$\beta_k(M) = \int_{\delta_c}^{\infty} d\delta \underbrace{\mathcal{P}_k(\delta)}_{\frac{\exp(-\delta^2/(2\sigma_k^2))}{\sqrt{2\pi}\sigma_k}} \frac{M(\delta)}{M_H(k)} \delta_D\left[\ln \frac{M}{M(\delta)}\right]$$

gaussian

$$M(\delta) = \kappa M_H(k)(\delta - \delta_c)^\gamma\,, \quad \gamma = 0.36\,,\ \kappa = 1..10$$

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$\delta \mapsto \delta_l$

$\delta_c \mapsto \delta_c(W)$

gaussian

$M(\delta) = \kappa M_H(k)(\delta - \delta_c)^\gamma\,, \quad \gamma = 0.36\,,\ \kappa = 1..10$

smoothed density contrast: $\delta_m = \frac{1}{V}\int dR\, 4\pi R^2\, \frac{\delta\rho}{\bar{\rho}}(R, t_H)\, W(R, R_m)$

non-linear relation $\delta\rho(\zeta) \mapsto \delta_m(\delta_l)$ depends on choice of window function

$\delta_l \equiv$ linearized smooth density contrast

Young `19

The devil is in the detail (1)

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$\delta \mapsto \delta_l$

$\delta_c \mapsto \delta_c(W)$

$\delta_c \mapsto \delta_c(W, \Delta)$

gaussian

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Young `19

shape parameter: $P_\zeta(k)$ broader → more modes involved in collapse → lower δ_c

The devil is in the detail (2)

$$\beta_k(M) = \int_{\delta_c}^{\infty} d\delta \underbrace{\mathcal{P}_k(\delta)}_{\frac{\exp(-\delta^2/(2\sigma_k^2))}{\sqrt{2\pi}\sigma_k}} \frac{M(\delta)}{M_H(k)} \delta_D\left[\ln \frac{M}{M(\delta)}\right]$$

$\delta \mapsto \delta_l$

$\delta_c \mapsto \delta_c(W)$

$\delta_c \mapsto \delta_c(W, \Delta)$

see Dani‘s talk → gaussian

Franciolini *et al* `23
Figueroa *et al* `23

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$\sigma_k \mapsto \sigma_k(W)$

see Dani's talk → gaussian

Franciolini *et al* `23
Figueroa *et al* `23

variance: $\sigma_k^2 = \int d\ln k' \, W^2(k', k) \, P_\delta(k') = \int d\ln k' \, W^2(k', k) \, (k'/k)^4 \, T^2(k', k) \, P_\zeta(k)$

use same window function as in density contrast
→ most of W-dependence drops

Young `19; Musco, De Luca, Franciolini, Riotto `20

non-linear transfer function
→ density contrast at horizon crossing

Musco, De Luca, Franciolini, Riotto `20; Riotto `23

The devil is in the detail (2)

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$\delta \mapsto \delta_l$

$\delta_c \mapsto \delta_c(W)$

$\delta_c \mapsto \delta_c(W, \Delta)$

$\sigma_k \mapsto \sigma_k(W)$

$\delta_c \mapsto \delta_c(W, \Delta, k)$

see Dani's talk → gaussian

Franciolini *et al* \`23
Figueroa *et al* \`23

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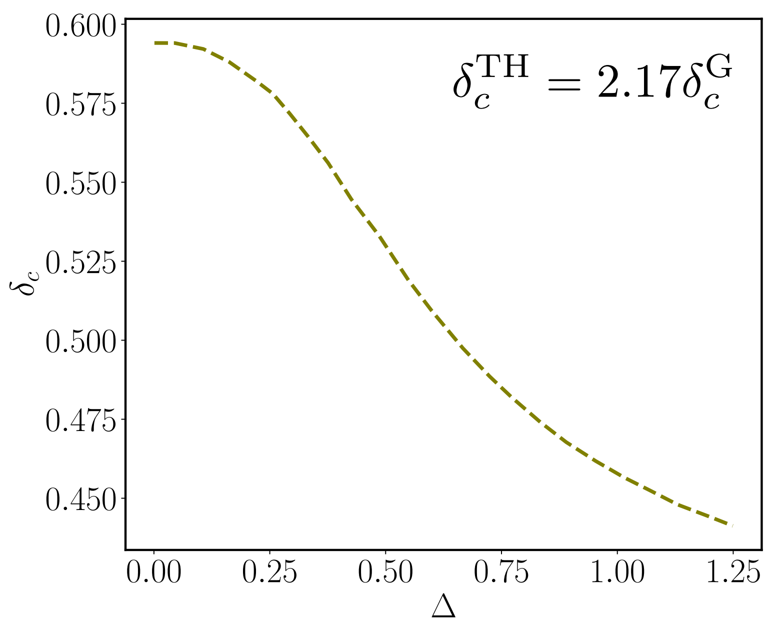
Musco, De Luca, Franciolini, Riotto \`20; Riotto \`23

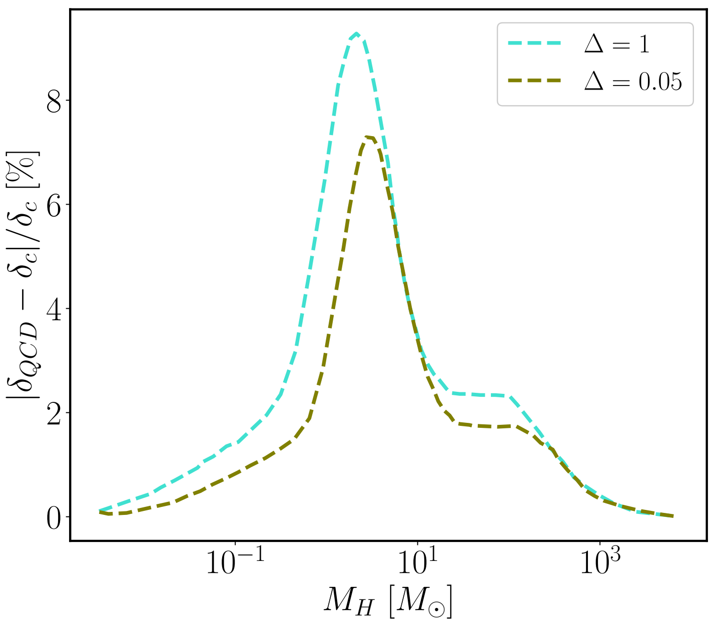
QCD phase transition: $c_s \mapsto c_s(T) \quad \Rightarrow \delta_c \mapsto \delta_c(k)$

The devil is in the detail (summary)

window function and shape parameter



QCD phase transition



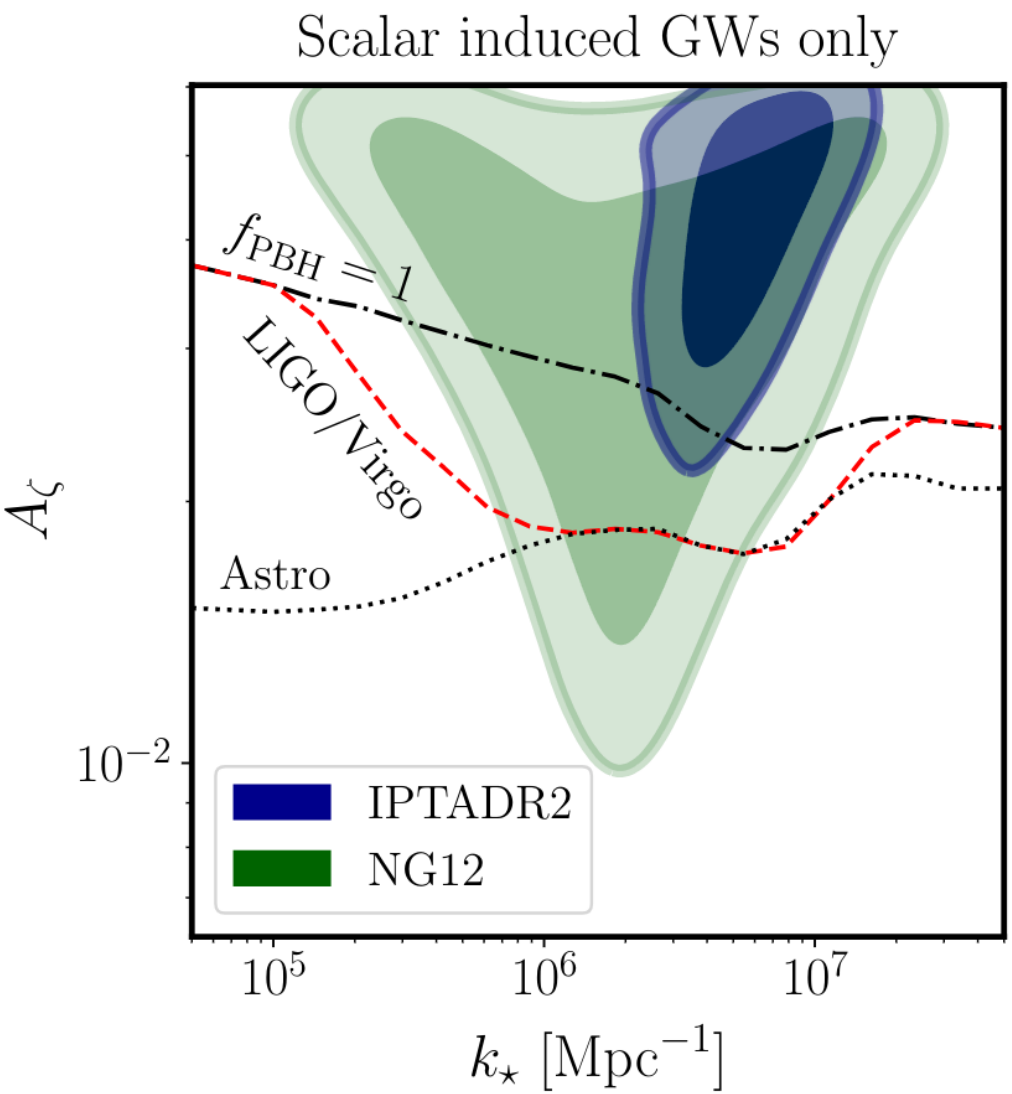
Most important are exponential factors :

critical density δ_c → shape parameter, window function, non-linear relation

variance σ_k → window function, non-linear relation (?)

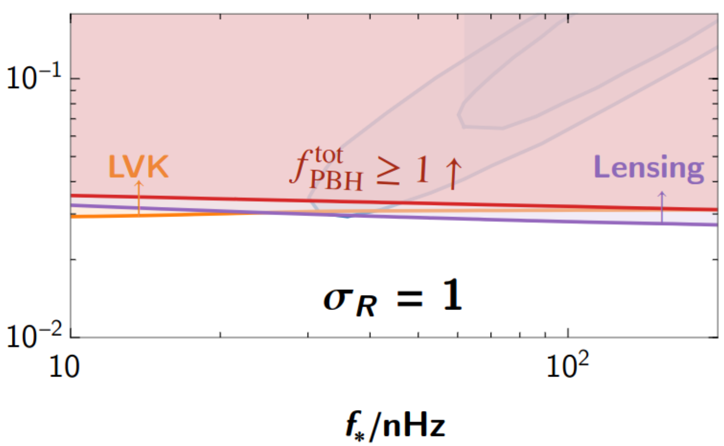
GWs vs PBHs

Dandoy, VD, Rompineve `23



IPTA DR2 (~ DR `23) preferred region excluded by PBH constraints.

Figueroa et al `23, w NG 15 data:



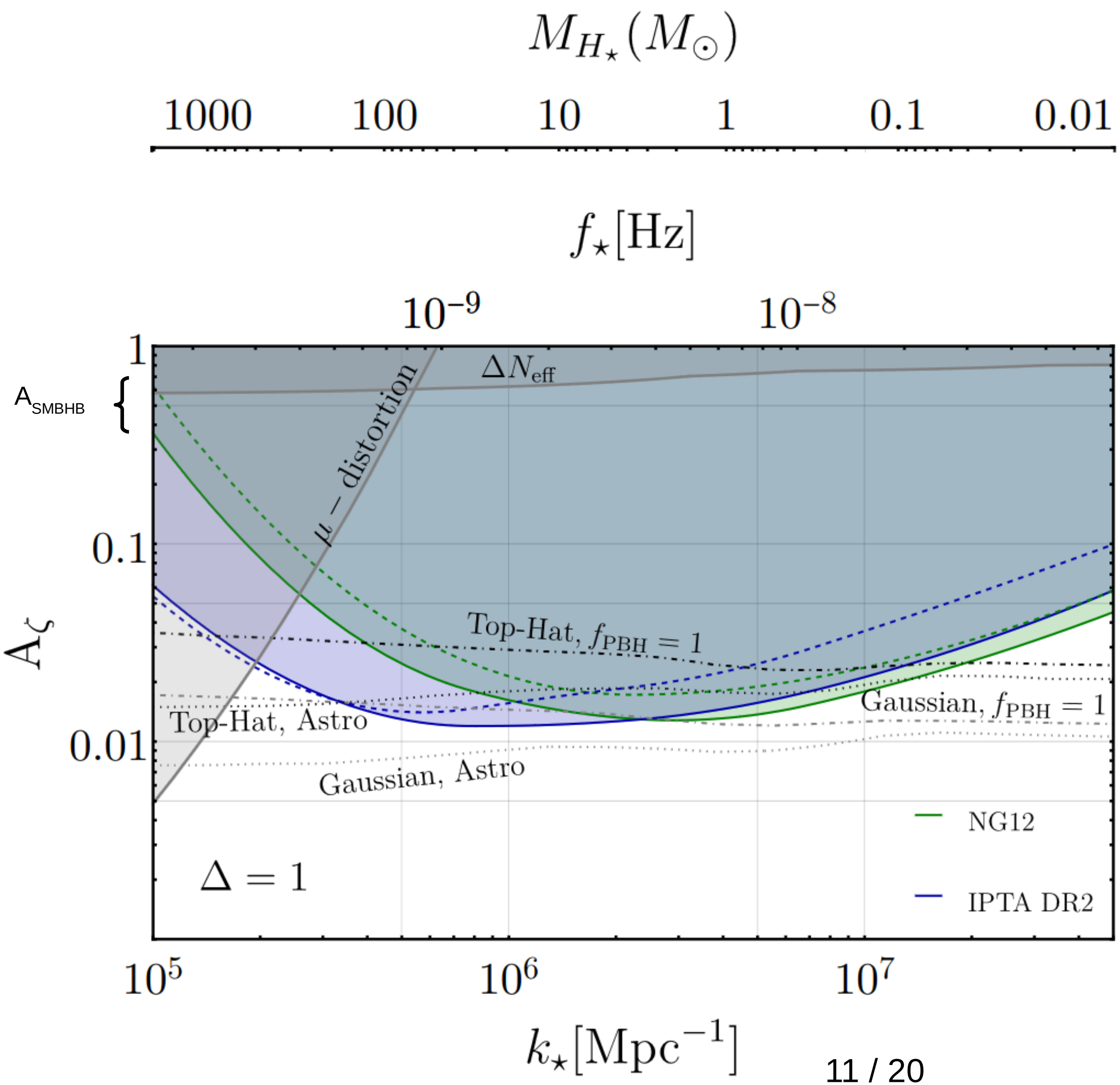
Exponential sensitivity of $f_{\rm PBH}$ to A_ζ :

$$f_{\rm PBH} \to A_\zeta \quad : \quad \checkmark$$

$$A_\zeta \to f_{\rm PBH} \quad : \quad ✘$$

constraints on scalar power spectrum

Dandoy, VD, Rompineve `23



GW constraints in presence of SMBHB foreground (IPTA DR2, NG 12)

astro constraints with uncertainty

GWs and PBHs yield independent bounds of comparable strength

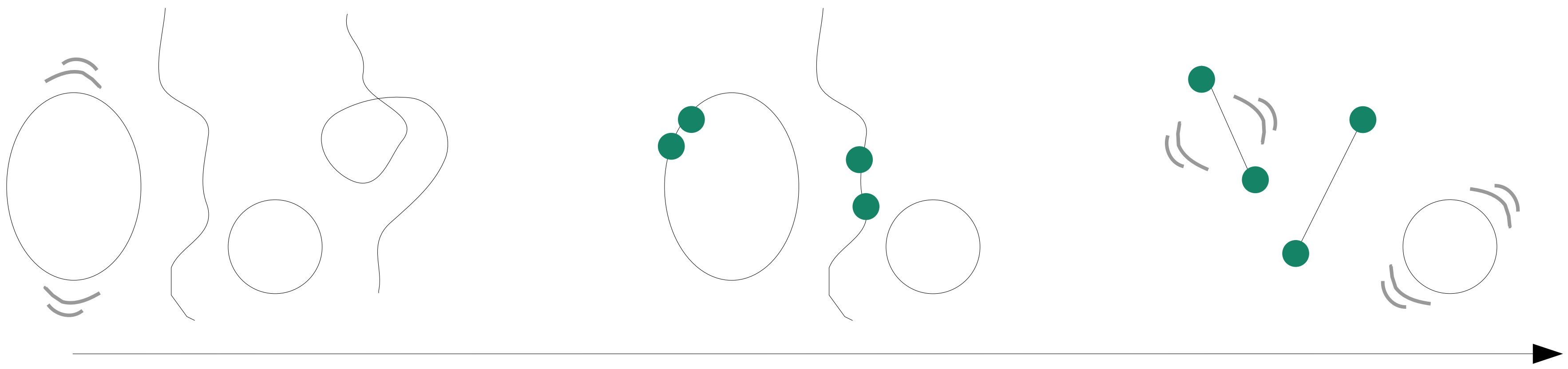
Conclusions

PBH bounds make a SIGW interpretation of PTA data difficult at best

some uncertainties and model dependence in PBH calculation remain, but a lot of progress in recent years!

PTAs are powerful probe of scalar power spectrum at ~ pc scale

One slide on metastable cosmic strings



scaling regime
(long strings & loops)

$t_s = 1/\Gamma_d^{1/2}$

segments & loops

[see also Leblond, Shlaer, Simons `09]

cosmic strings formed
in phase transition, eg

$$G_{SM} \times U(1)_{B-L} \to G_{SM}$$

spontaneous creation of monopoles
due to GUT embedding

$$G_{SM} \times U(1)_{B-L} \subset SO(10)$$

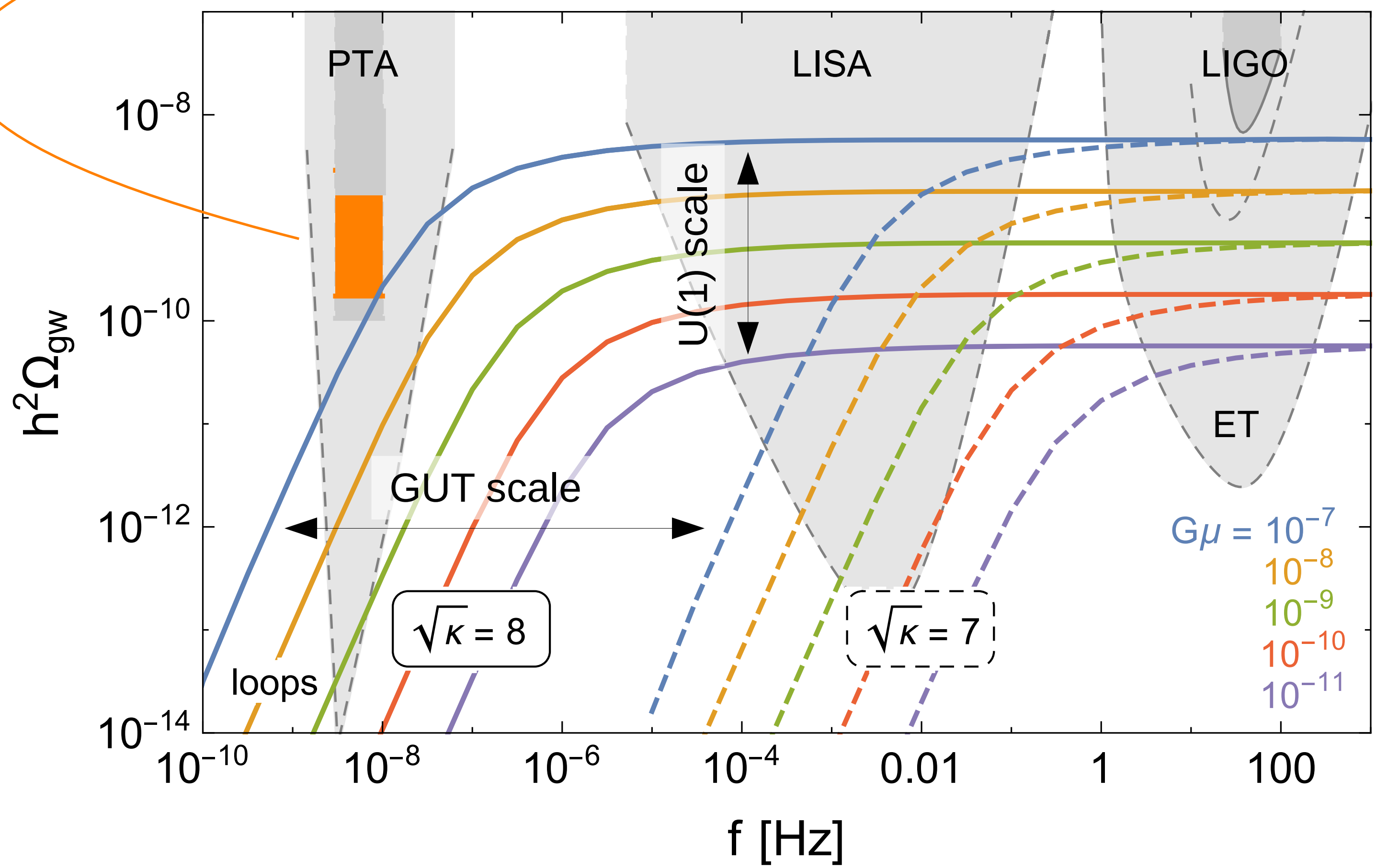
$$\Gamma_d \sim \mu \exp(-\pi \kappa^2)\,, \quad \kappa^2 = m^2/\mu$$

$\mu \sim v_{B-L}^2$ string tension
$m \sim v_{GUT}$ monopole mass

(One) slide on metastable cosmic strings

Buchmüller, VD, Schmitz `21, `23

PTA preferred region



$SO(10)$

$\downarrow$

$G_{\rm SM} \times U(1)$

$\downarrow$

$G_{\rm SM}$

$\sqrt{\kappa} \sim v_{\rm SO(10)}/v_{U(1)}$

$G\mu \sim (v_{U(1)}/M_P)^2$

GUT-scale U(1) phase transition can be tested with GWs

… and (one) advertisement

CERN TH visitor program https://theory.cern/visitor-info

short-term visits typically O(week)

long term visits (> 3 months, usually sabbaticals)

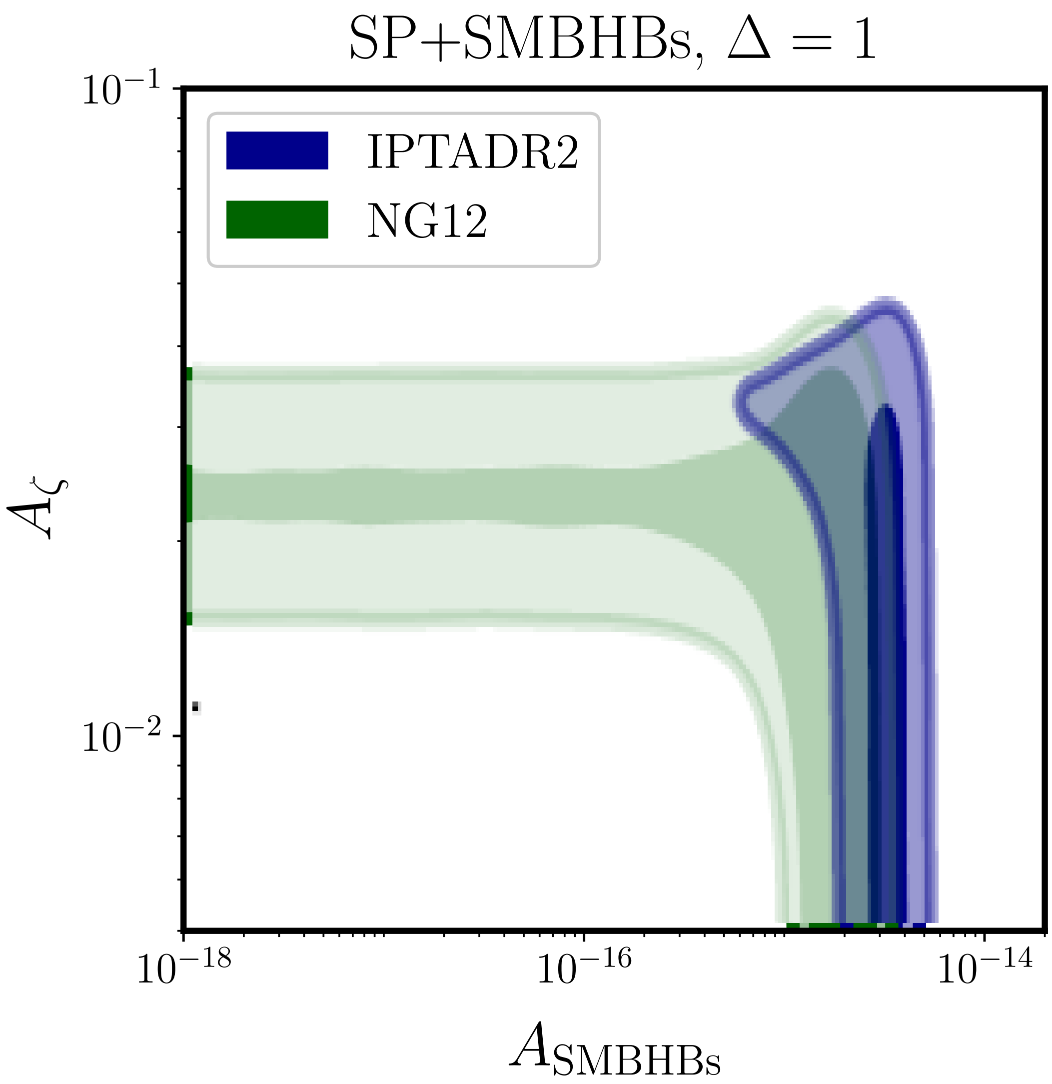
CERN fellowship program https://theory.cern/jobs

deadline September 3rd (!!) for CERN member state nationals

consider applying!

backup

SMBHB + SIGW analysis

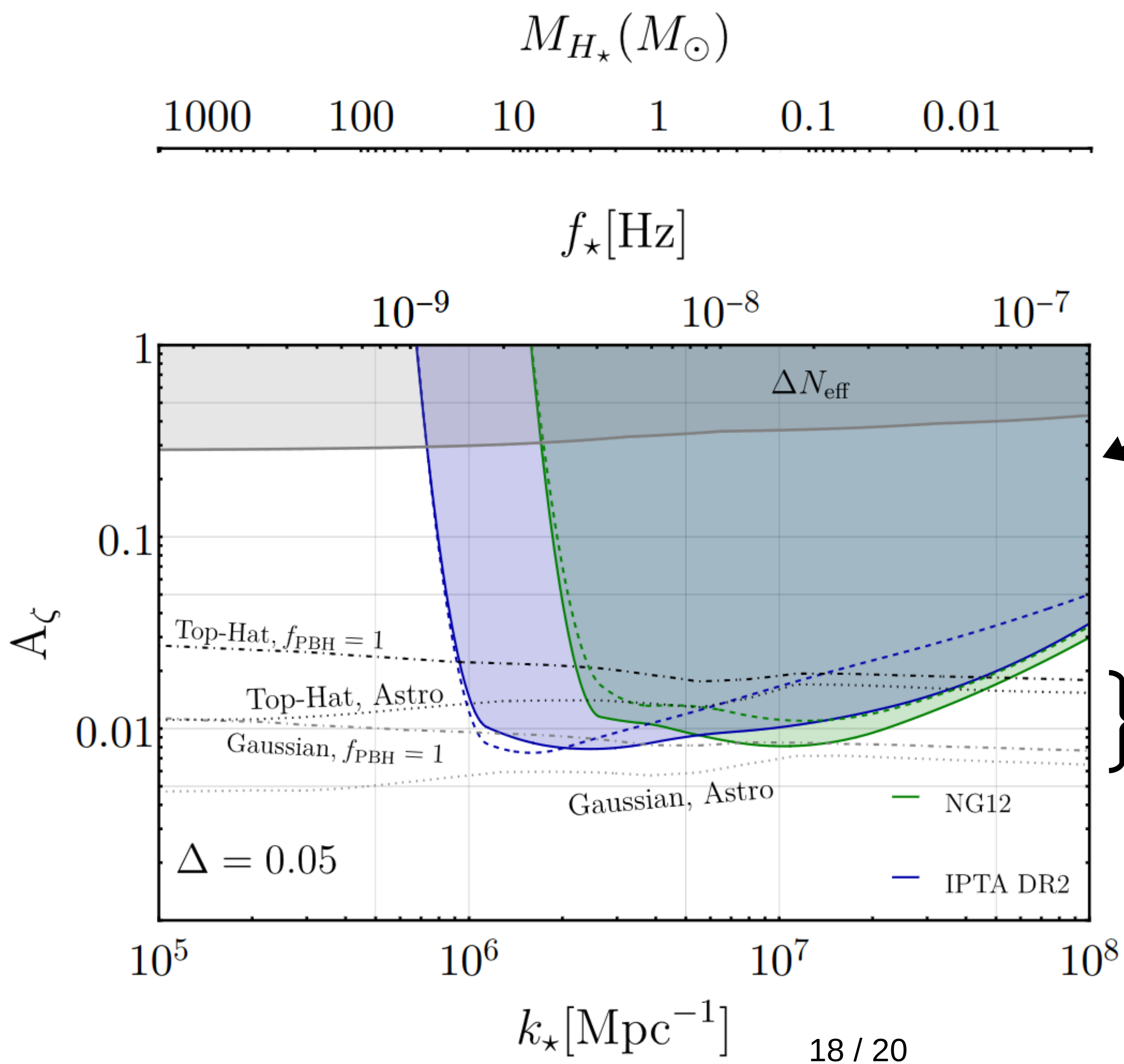


NG12: both SMBHB and SIGW fit well
$\ln_{10} B_{\zeta,\rm SMBHB} = 0.05$
(inconclusive)

IPTA DR2: requires larger value of A_ζ , above prior set by f_{PBH} bound.
$\ln_{10} B_{\zeta,\rm SMBHB} = 2.2$
(decisive)

constraints on scalar power spectrum

narrow peak



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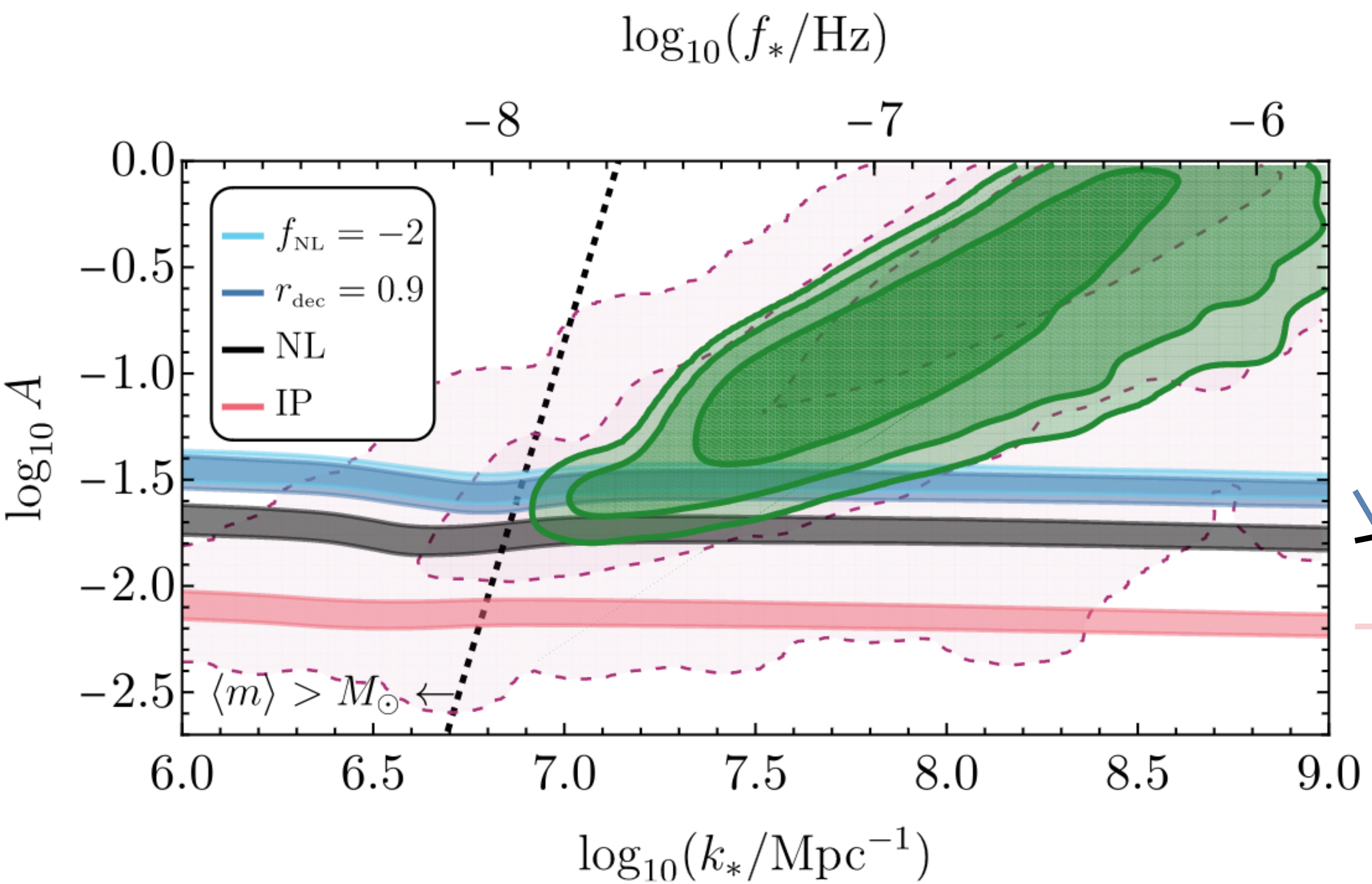
GWs vs PTAs (2023 DR)

Franciolini, Iovino, Vaskonen, Veermäe `23



NG 15, EPTA

fPHB bounds

non-gaussian

metastable cosmic strings : spectal tilt