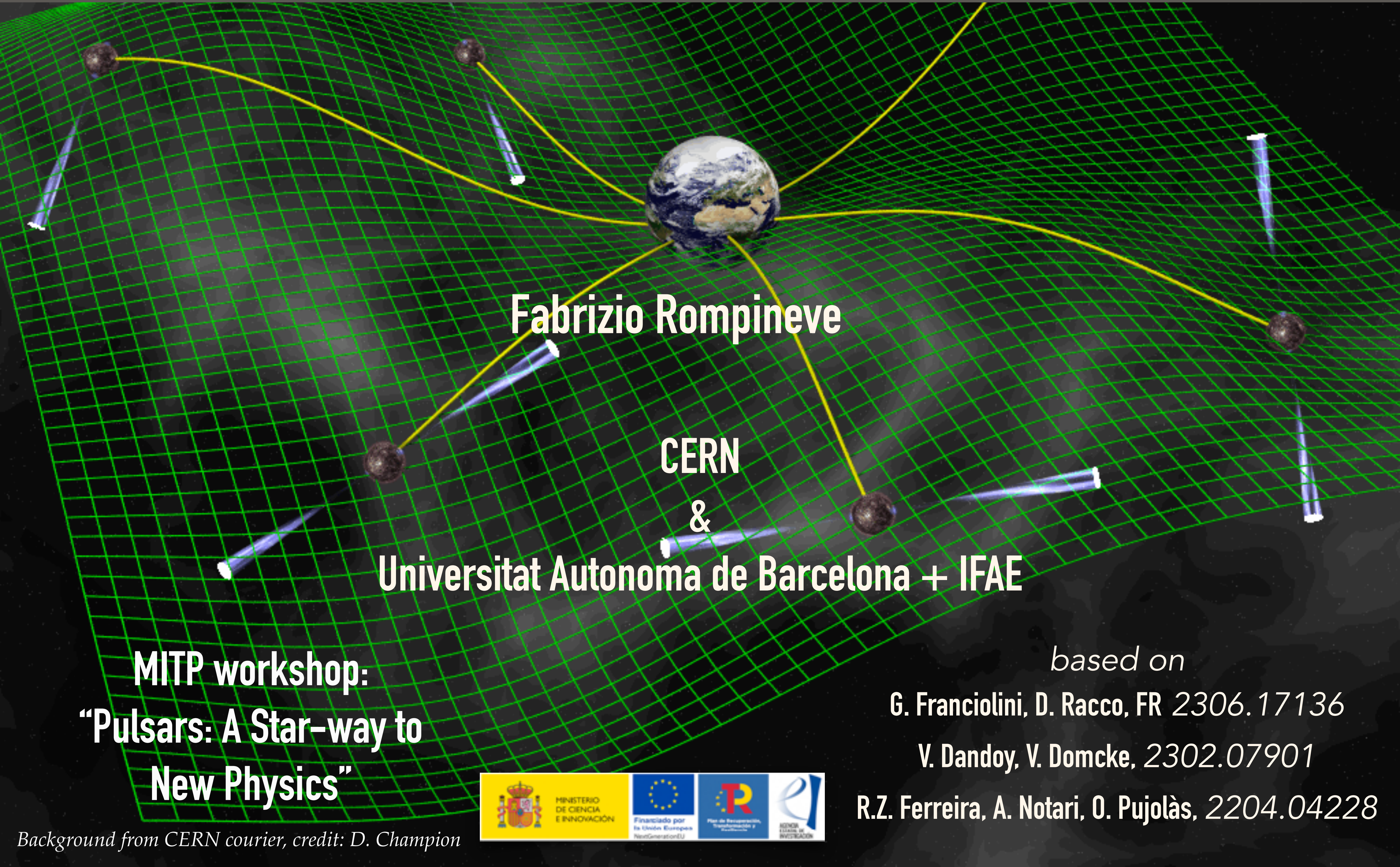
Features of Early Universe Gravitational Waves at PTAs



Fabrizio Rompineve

CERN

&

Universitat Autonoma de Barcelona + IFAE

MITP workshop:
"Pulsars: A Star-way to New Physics"

based on

G. Franciolini, D. Racco, FR *2306.17136*

V. Dandoy, V. Domcke, *2302.07901*

R.Z. Ferreira, A. Notari, O. Pujolàs, *2204.04228*

Background from CERN courier, credit: D. Champion

Origin of PTA GWs

See talks by Natalia, Andrea & Luke

See talks by Eric, Geraldine, Ken, Valerie, Dani, Frederik

Supermassive Black Hole Binaries (SMBHBs)

Early Universe/Particle Physics

(Requires new physics beyond the Standard Model, SM)

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Early Universe/Particle Physics

(Requires new physics beyond the Standard Model, SM)

Theory "Uncertainty":

Several candidate sources possible,
No one clearly better motivated than others

Challenges:

GW spectrum often model dependent,
case-by-case numerical simulations required,
Degeneracies between different sources

DIRECTIONS/OPPORTUNITIES FOR PARTICLE PHYSICS/COSMOLOGY @ PTAS

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Robust discriminating features

Set constraints

Motivated models for signal interpretation

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In this talk

Robust discriminating features

*Model-independent impact of **Standard Model physics** on broad class of GW sources*

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Cosmic Domain Walls

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SUB-HUBBLE TRANSIENT SOURCES

For non-transient,
see talk by Geraldine, Ken!

Broad class of (new physics) sources is active at a definite epoch/temperature (Then shuts off)

$$H \sim \frac{T^2}{M_p}, M_p \equiv (8\pi G)^{-1/2}$$

$$t_\star \lesssim H^{-1}(T_\star)$$

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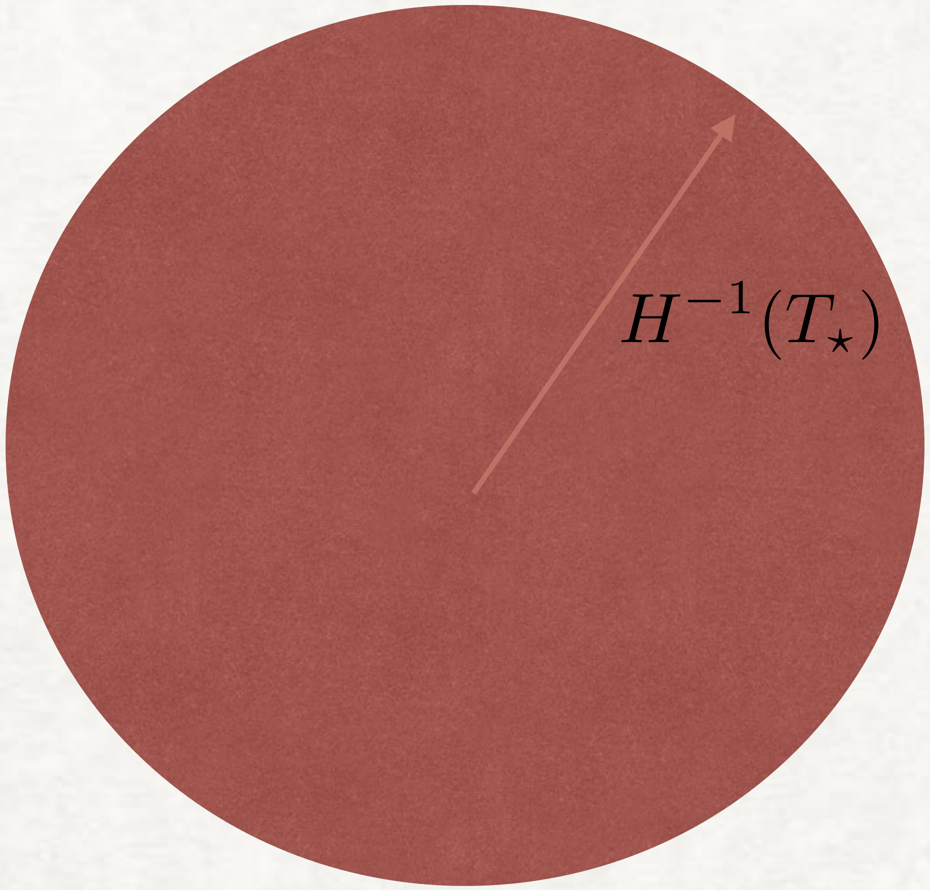

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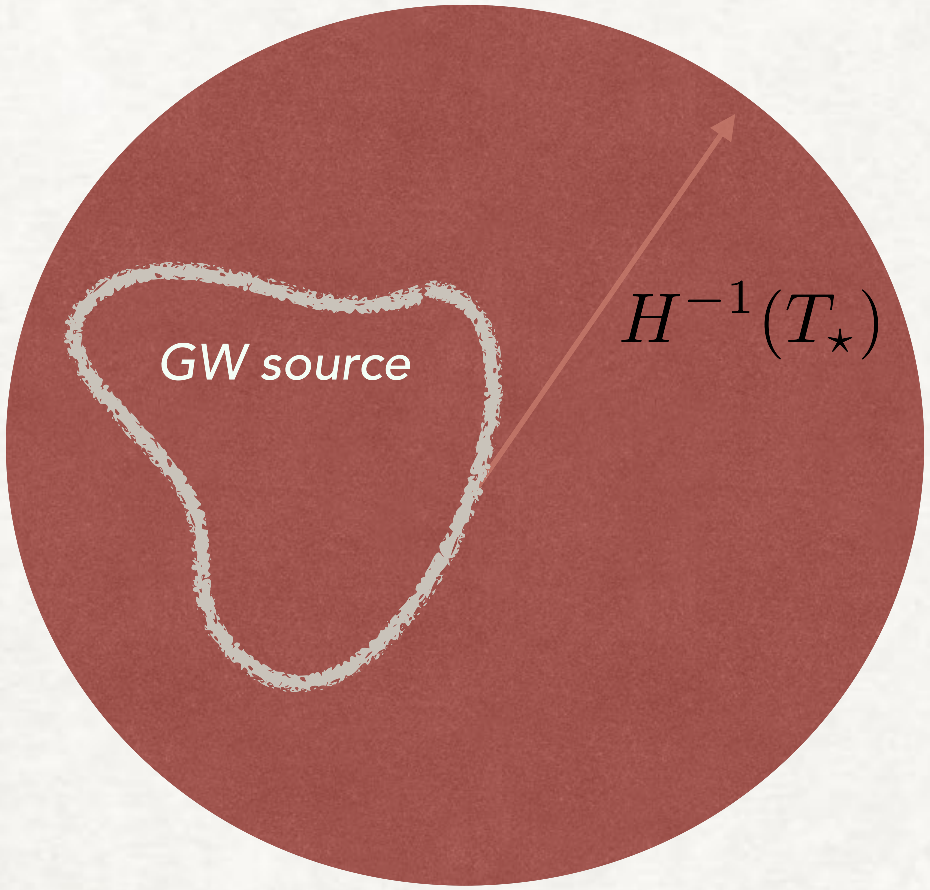

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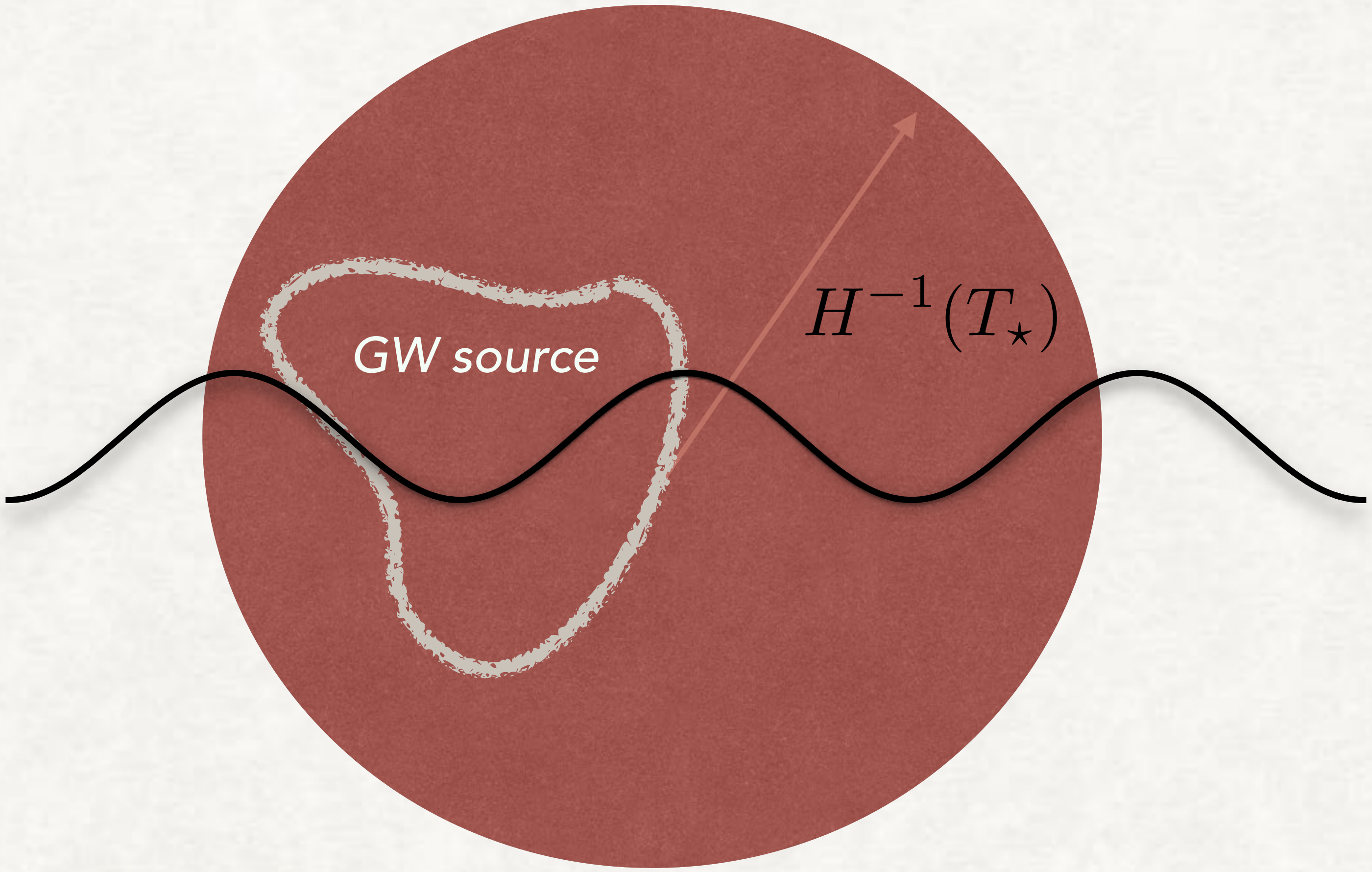

Typical GW (peak) frequency

$$f_\star \gtrsim 1/t_\star$$

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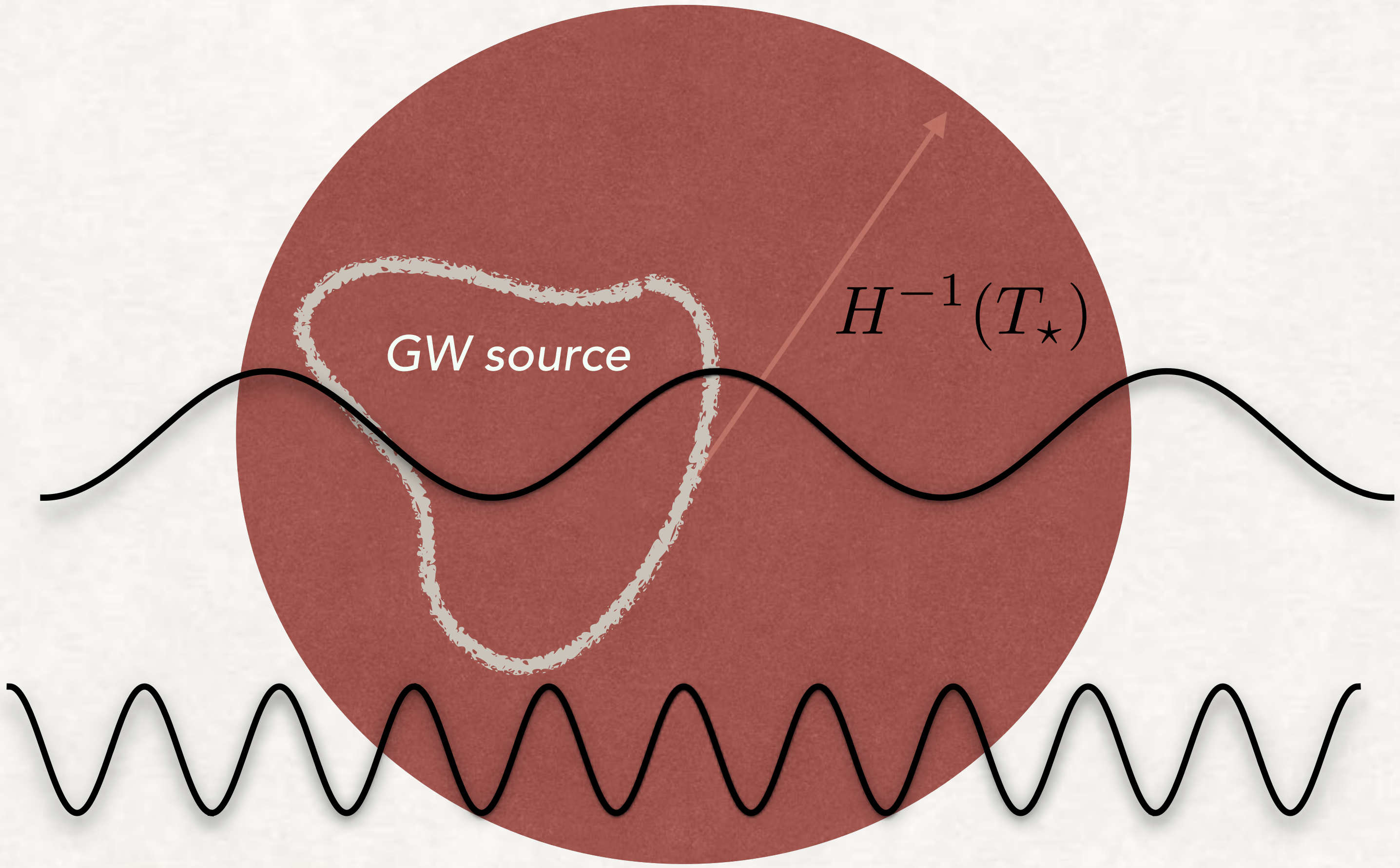

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Peak and high frequency tail probe microscopic properties of the source (Model-dependent)

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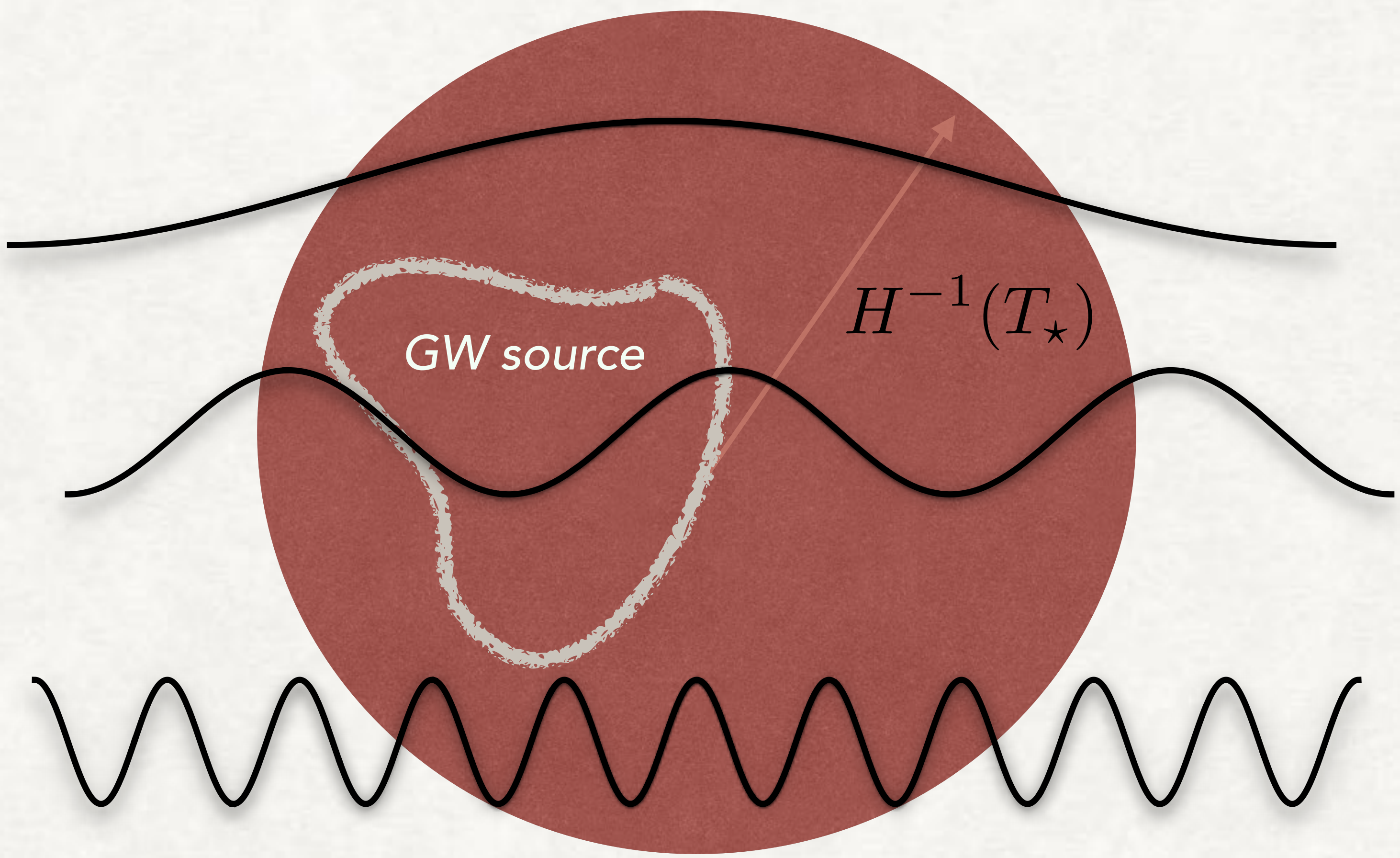

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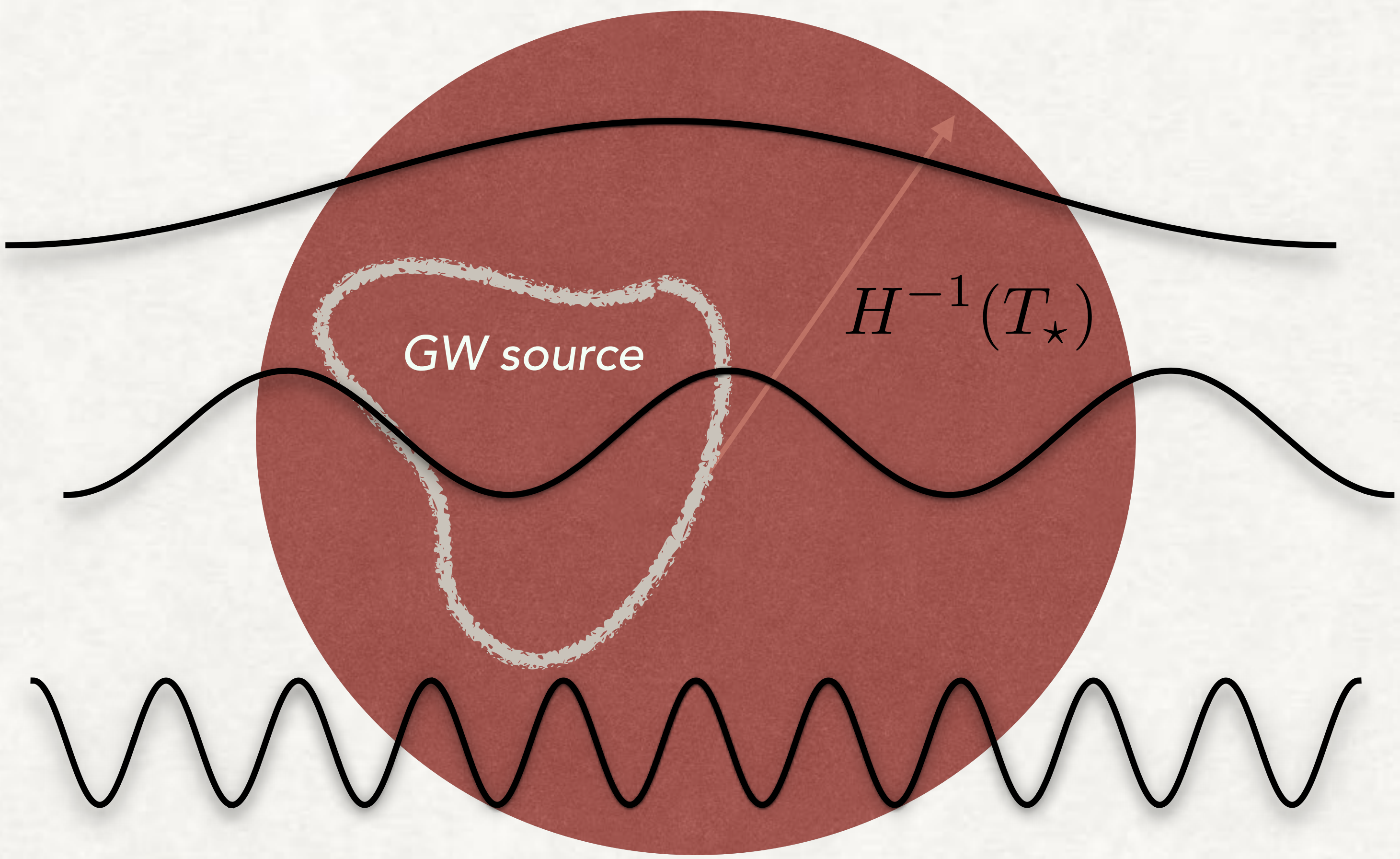

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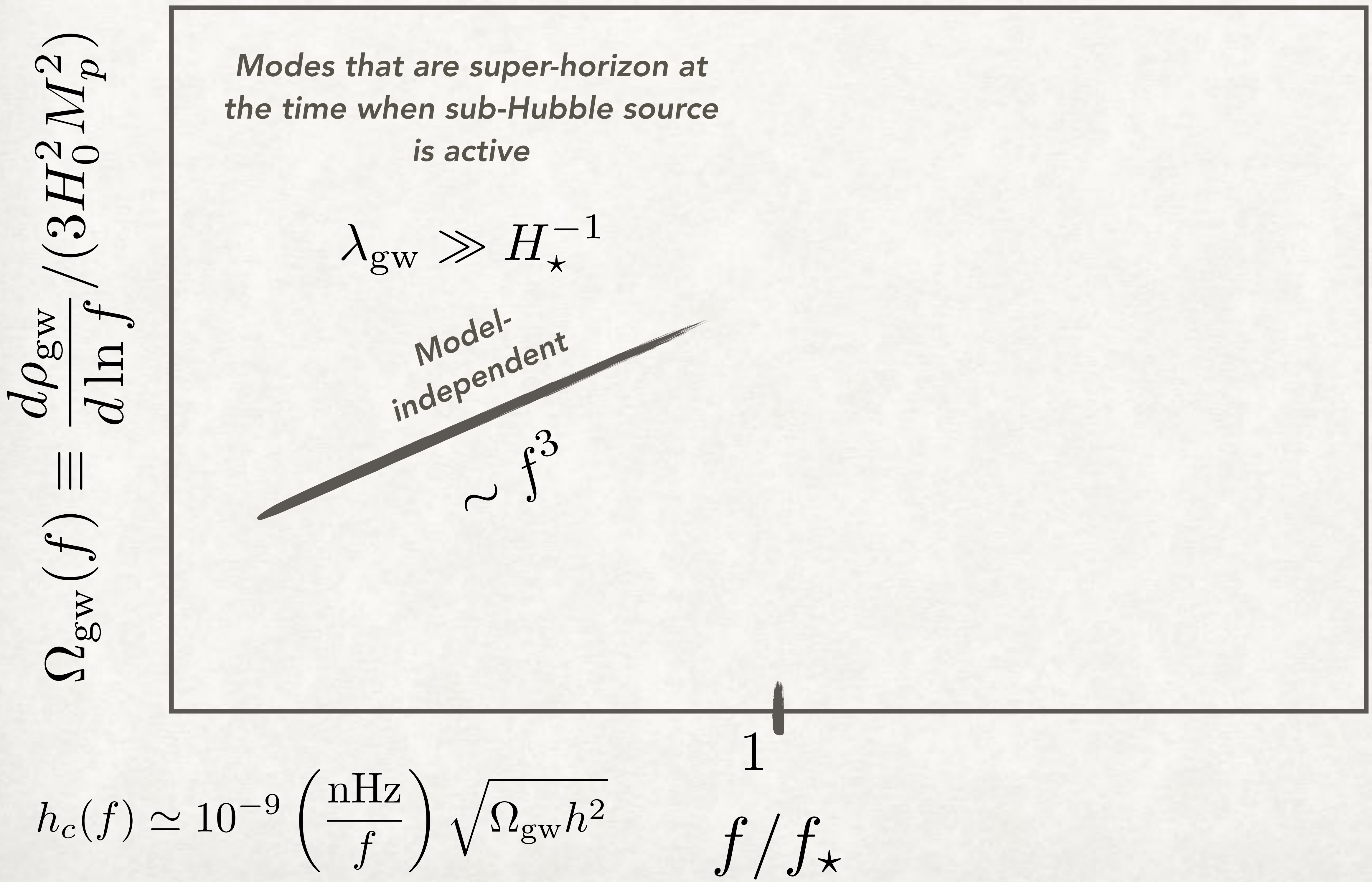
$$f_\star \gtrsim 1/t_\star$$

***Overdamped harmonic oscillator:** Power is suppressed!*

Peak and high frequency tail probe microscopic properties of the source (Model-dependent)

COSMOLOGICAL GW SPECTRUM



$$h_c(f) \simeq 10^{-9}\left(\frac{\rm nHz}{f}\right)\sqrt{\Omega_{\rm gw}h^2}$$

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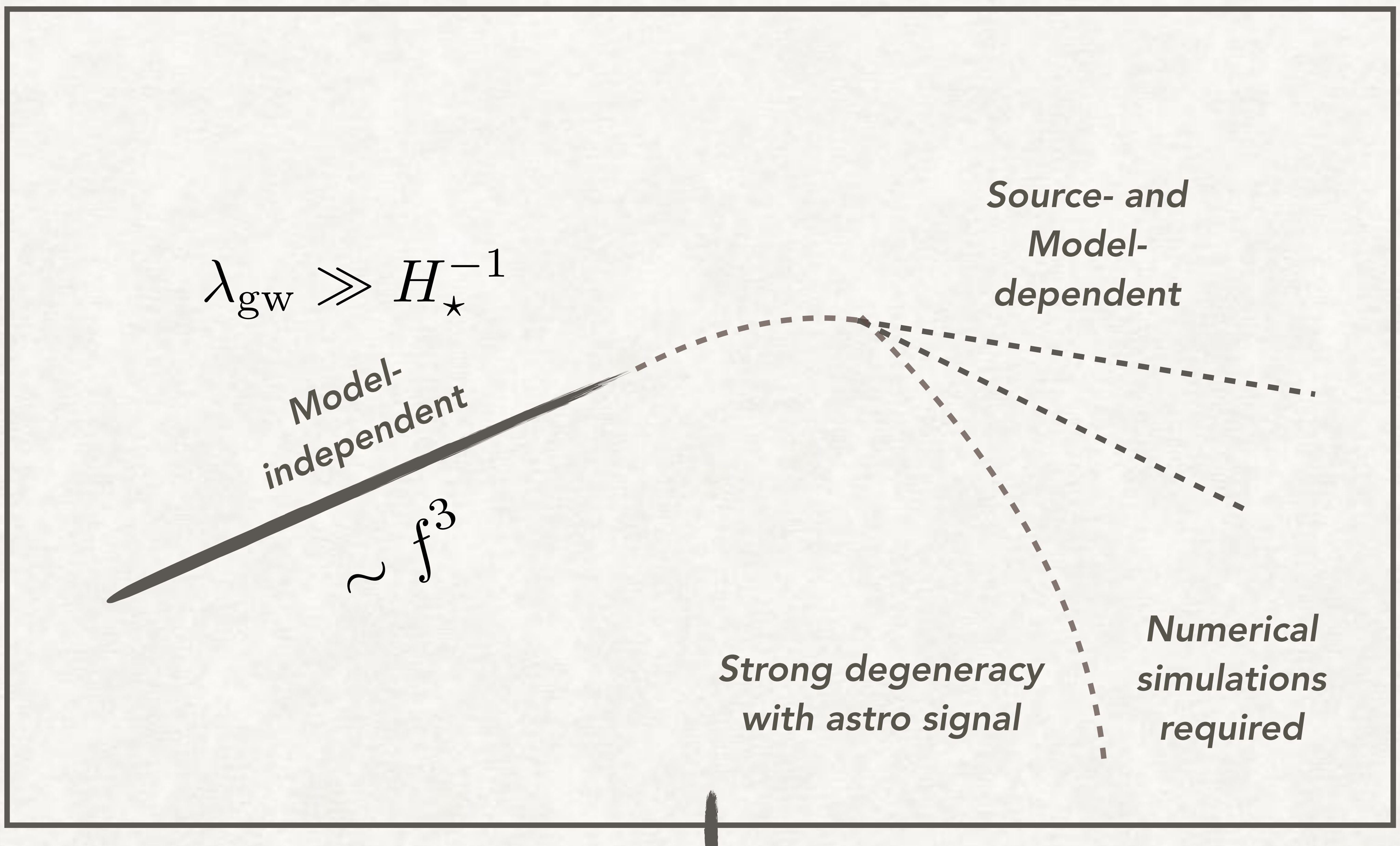

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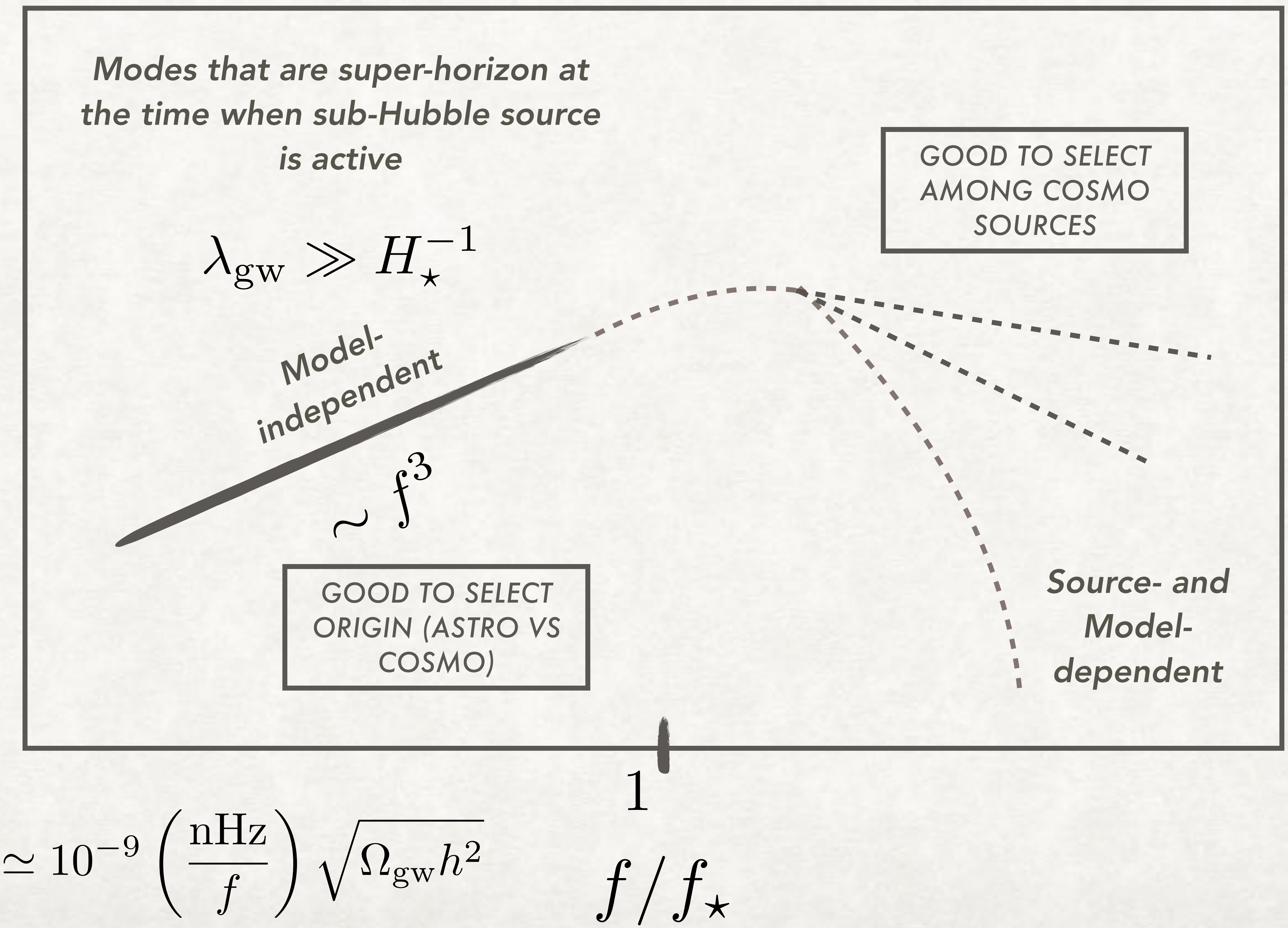

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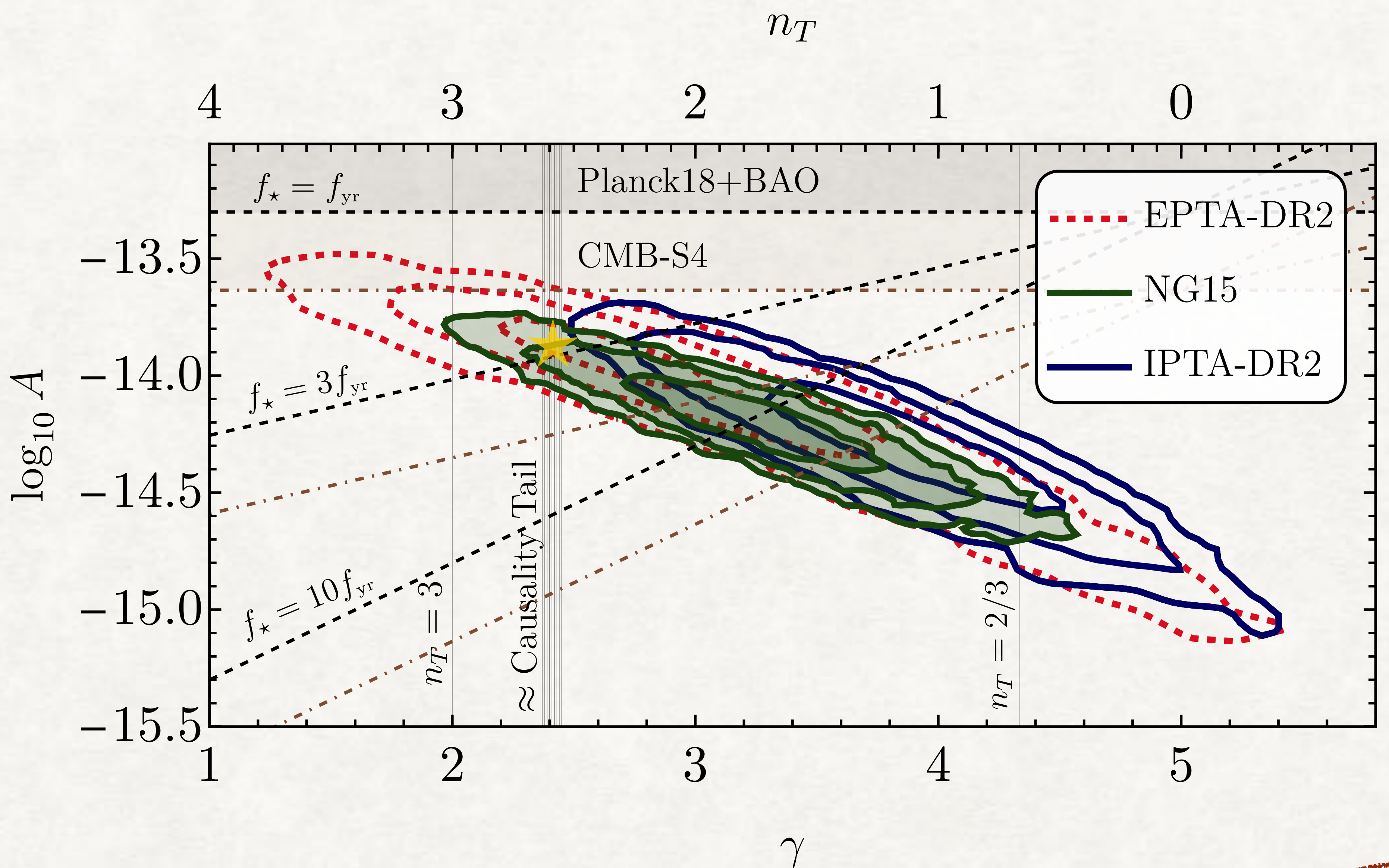
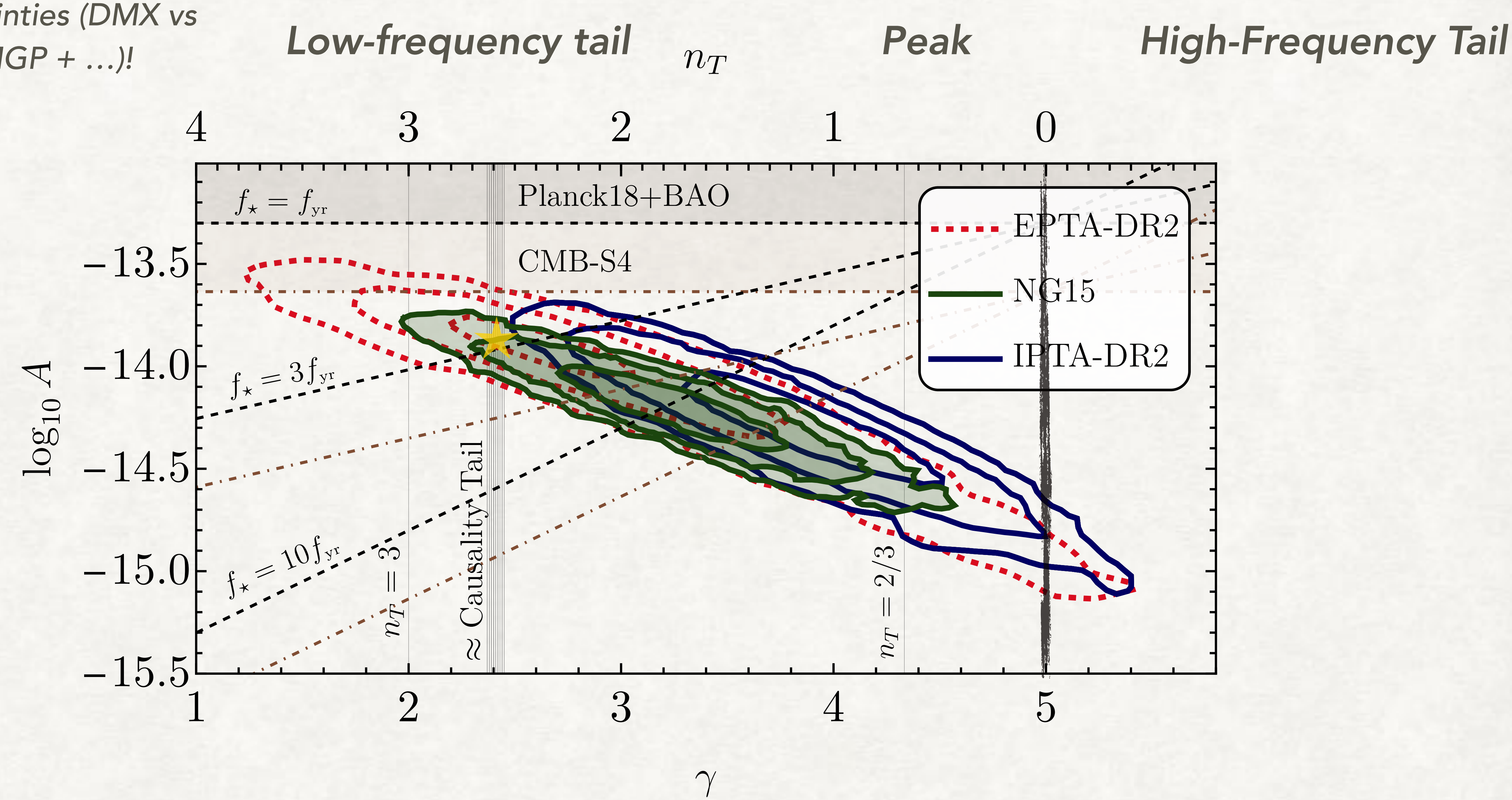
DATA



$$\Omega_{\rm gw} h^2 \simeq 10^{-8} \left(\frac{A}{5\cdot 10^{-15}}\right)^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma} \equiv n_T$$

DATA

Caveat:
Determination of tilt suffers from uncertainties (DMX vs DMGP + …)!



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MODEL-INDEPENDENT CONSTRAINT FROM COSMOLOGY

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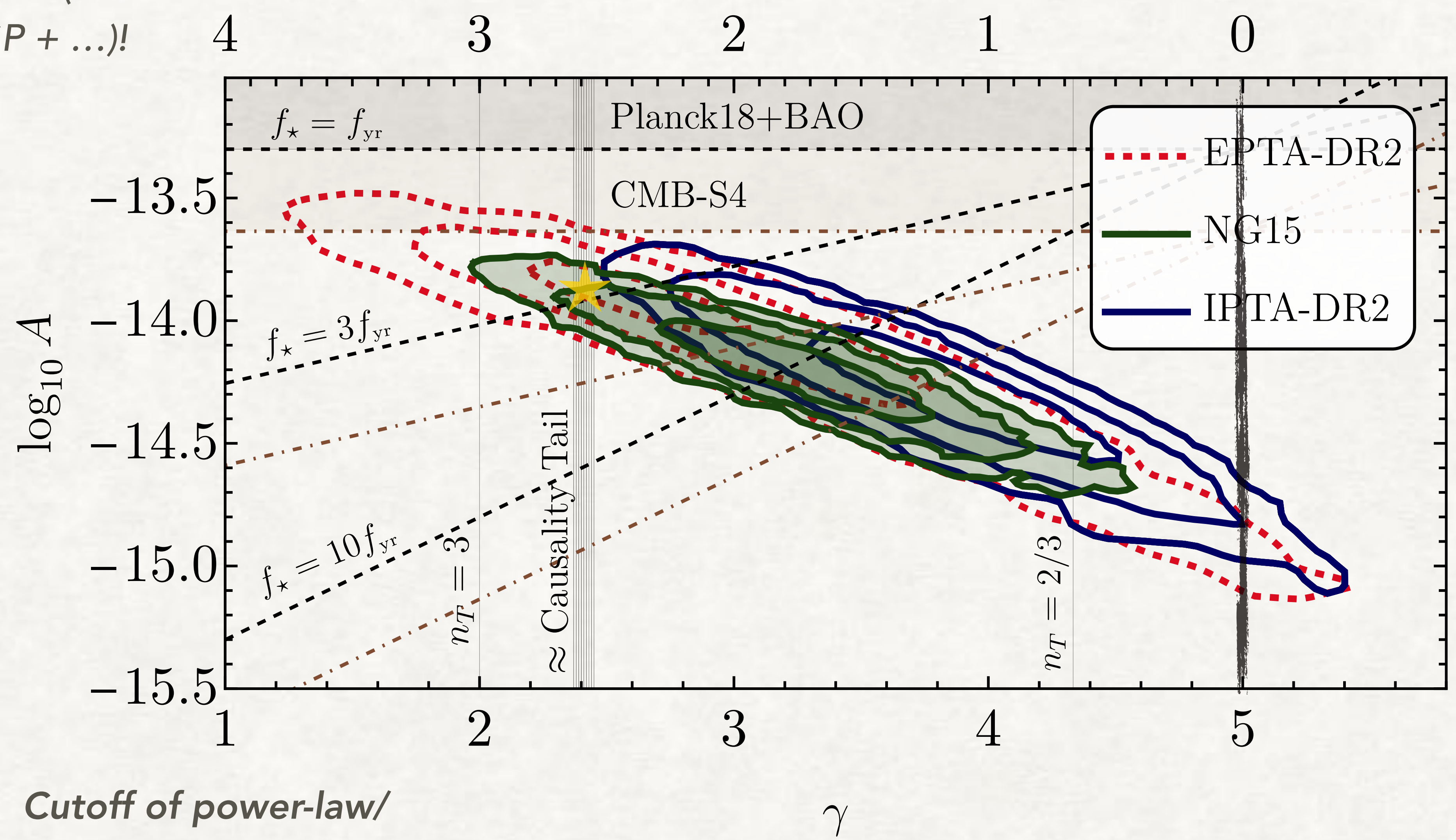
Determination of tilt suffers from uncertainties (DMX vs DMGP + …)!

Low-frequency tail ***Peak*** ***High-Frequency Tail***



$f_\star \equiv$ ***Cutoff of power-law/ peak***

Prior for any search for cosmological backgrounds

$$\Delta N_{\rm eff}^{\rm gw} \equiv \frac{\rho_{\rm gw}}{\rho_{\nu,1}}|_{\rm cmb} \leq 0.28(0.06), 95\%\text{C.L.} \Rightarrow A \leq 5(1)\cdot 10^{-14}\left(\frac{f_{\rm yr}}{f_\star}\right)^{\frac{5-\gamma}{2}}$$

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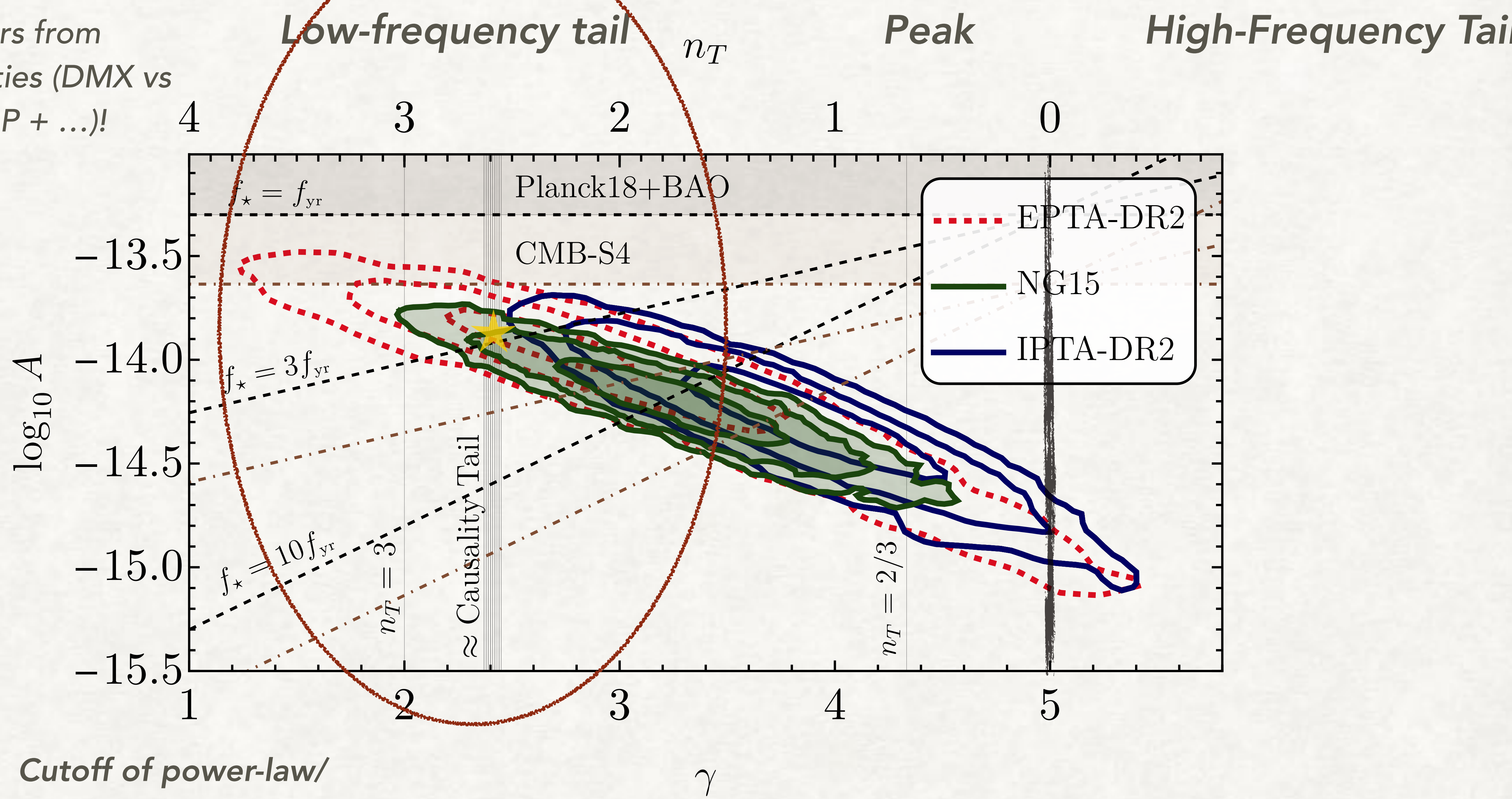

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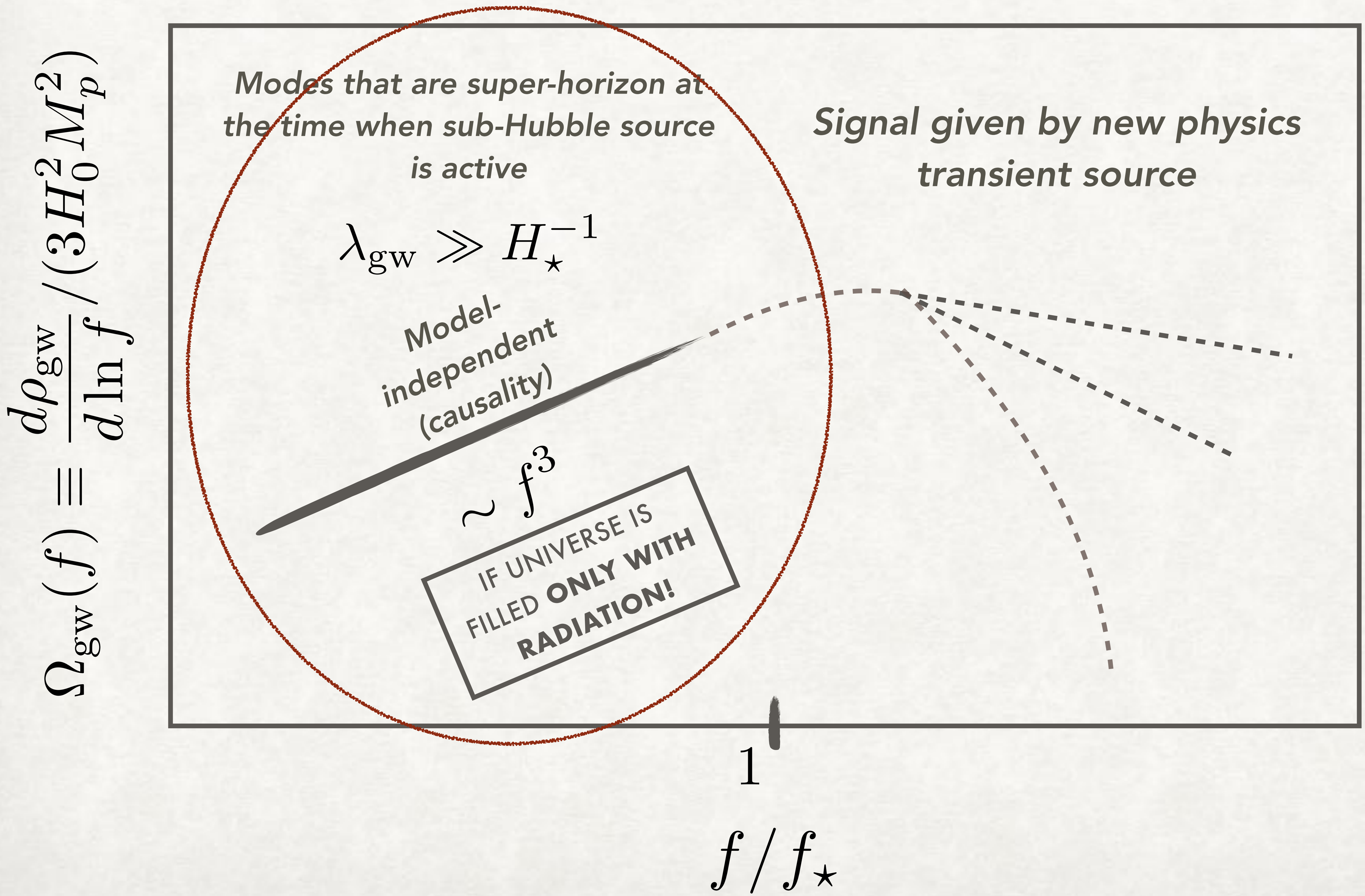
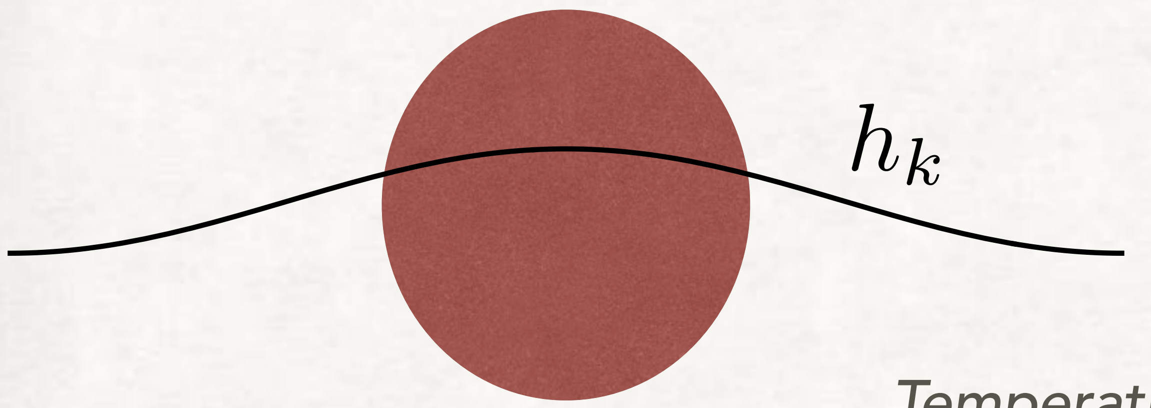
DISTINCTIVE FEATURES IN THE CAUSALITY TAIL



A FORTUITOUS COINCIDENCE



$$k \ll aH(T_\star)$$

Temperature until which source is active

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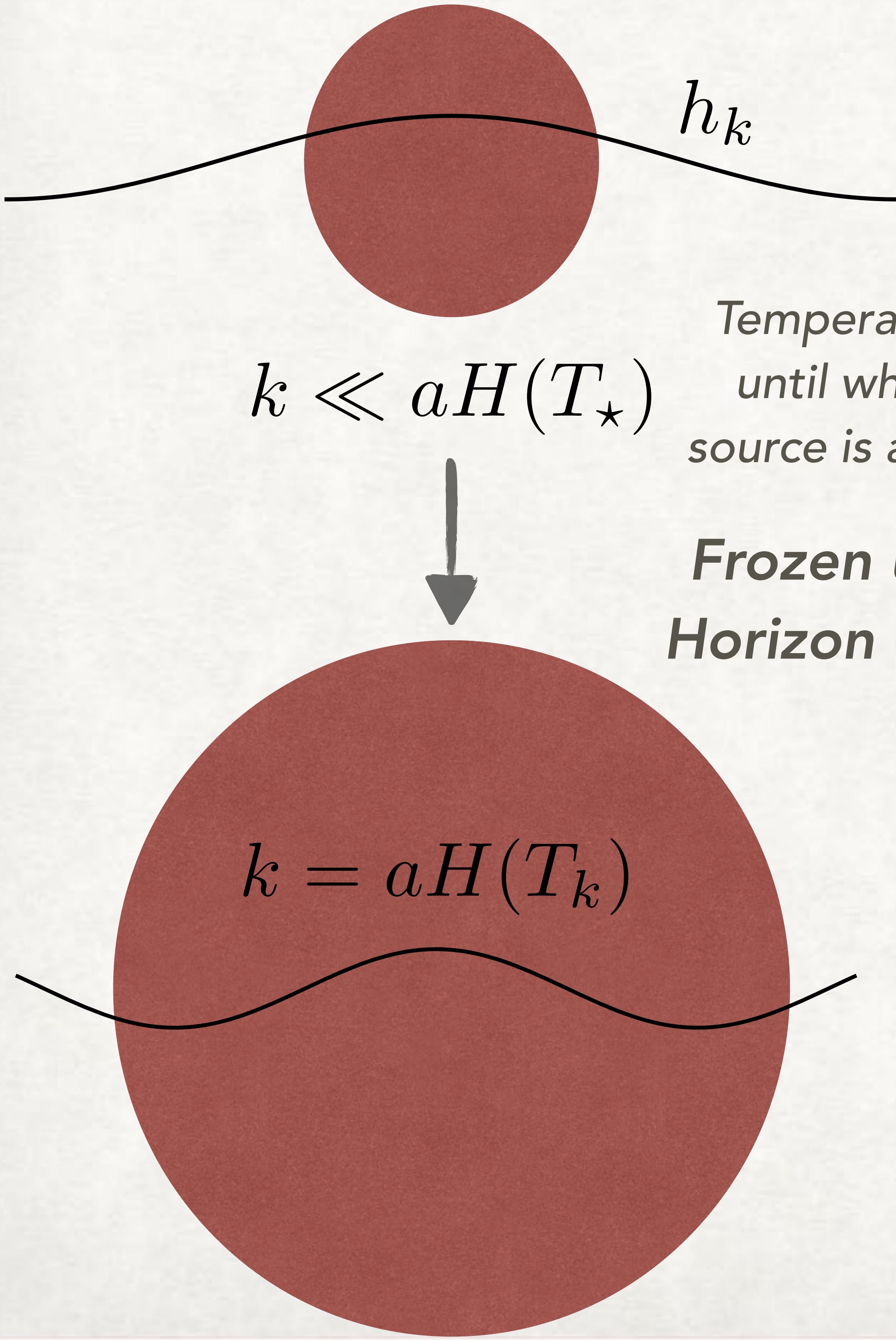

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Frozen until Horizon entry

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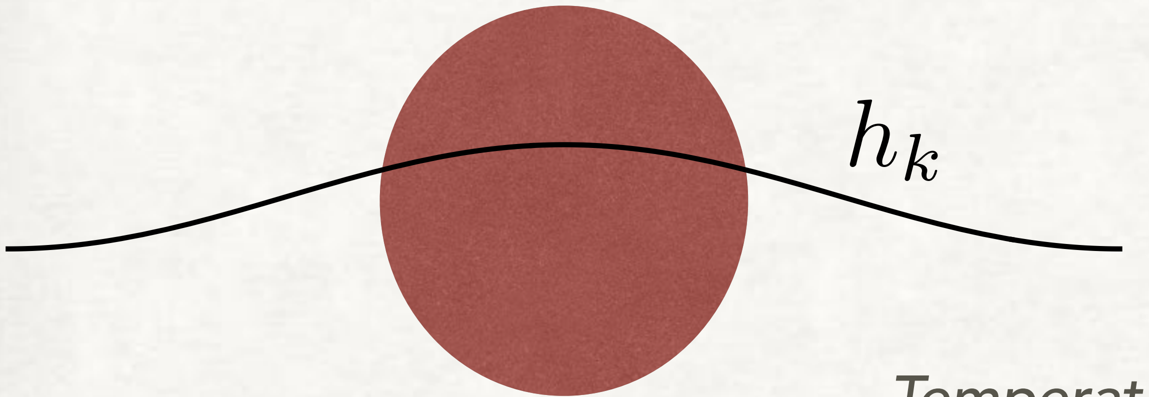

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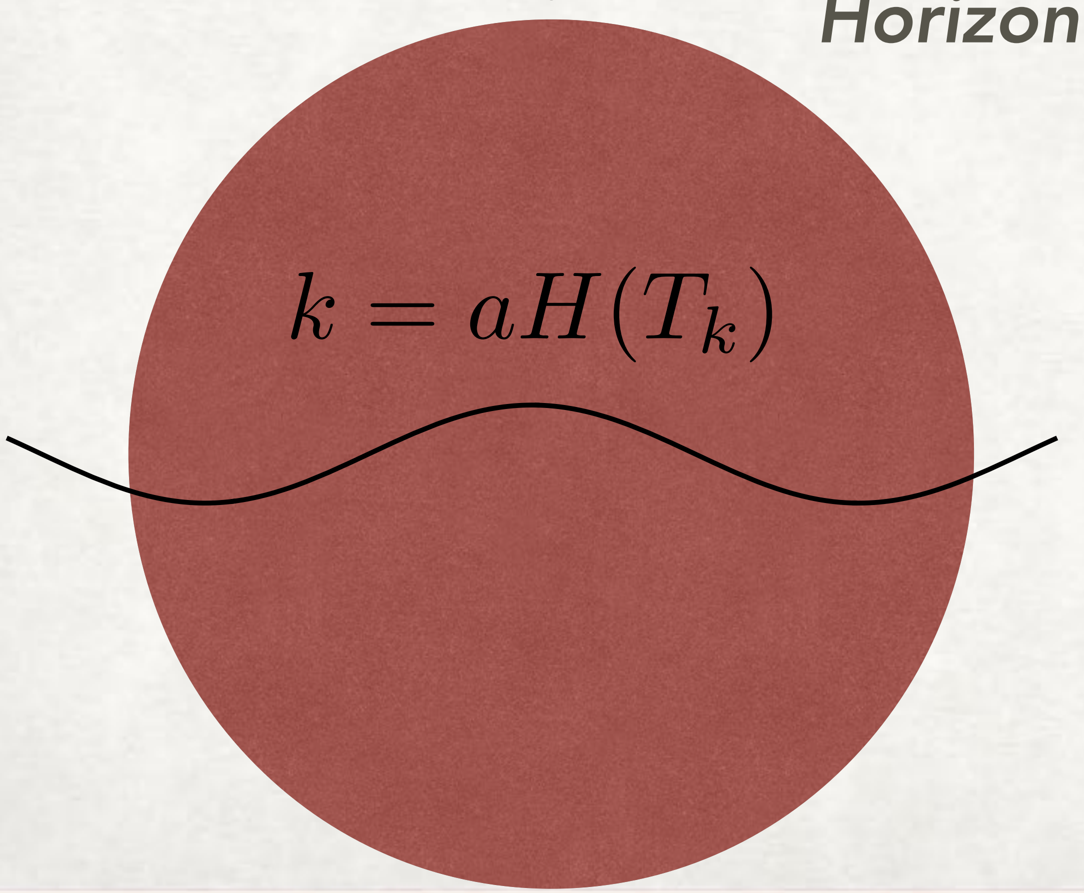

Frequency of "Causality Tail" modes

$$f = \frac{k}{2\pi} = aH(T_k)$$

Redshift

$$f \simeq 3.0\,\mathrm{nHz} \cdot \left(\frac{g_{*,\mathrm{s}}(T)}{20}\right)^{1/6} \left(\frac{T}{150\,\mathrm{MeV}}\right).$$

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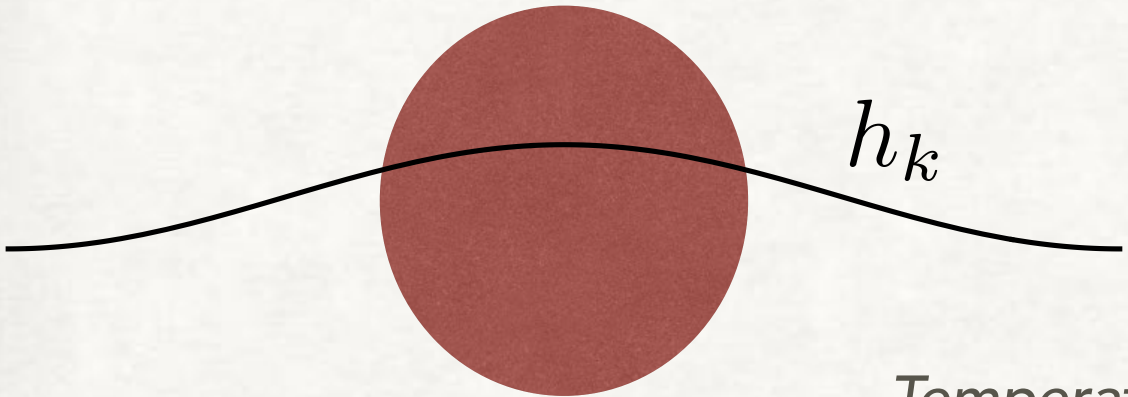

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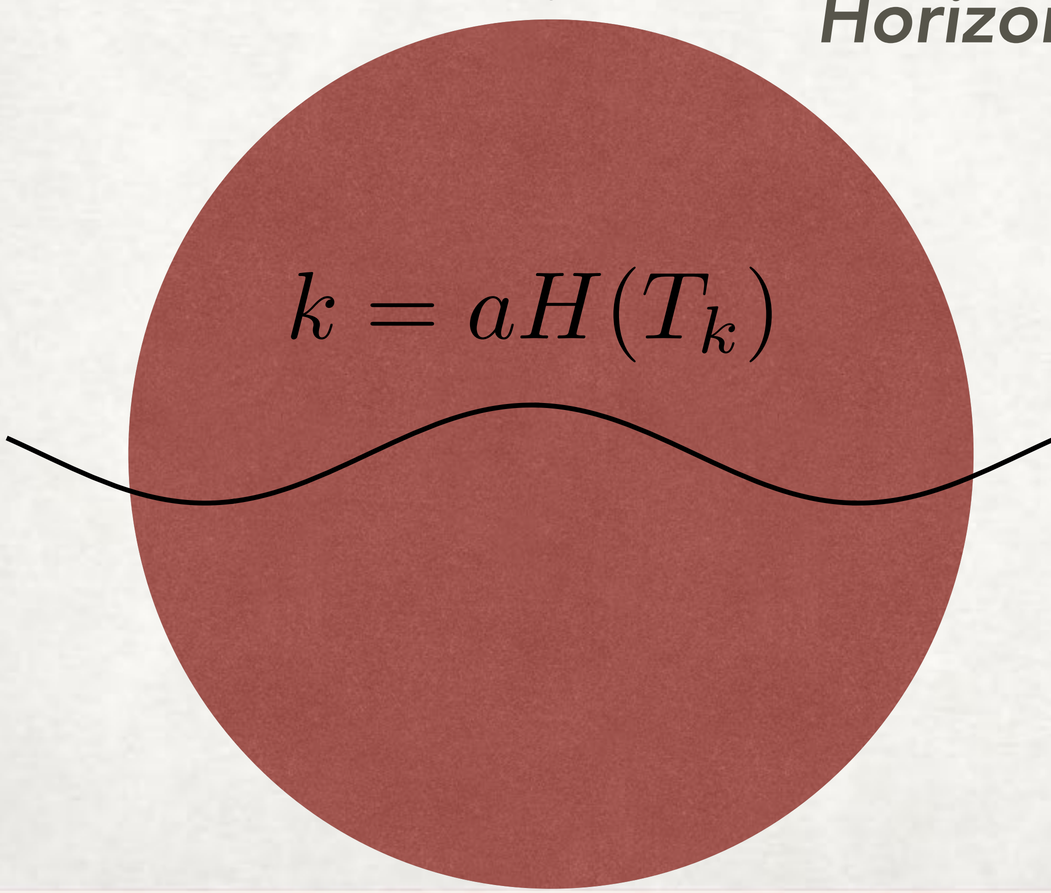

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Notice: *different from usual relation for peak frequency!*

Region where PTAs are most sensitive coincides with modes that enter horizon ***during confinement of strong interactions (QCD)!***

QCD EFFECTS ON COSMOLOGICAL EVOLUTION

QCD crossover not expected to produce GWs

Under most reasonable Circumstances

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***Nonetheless it** affects cosmological evolution*

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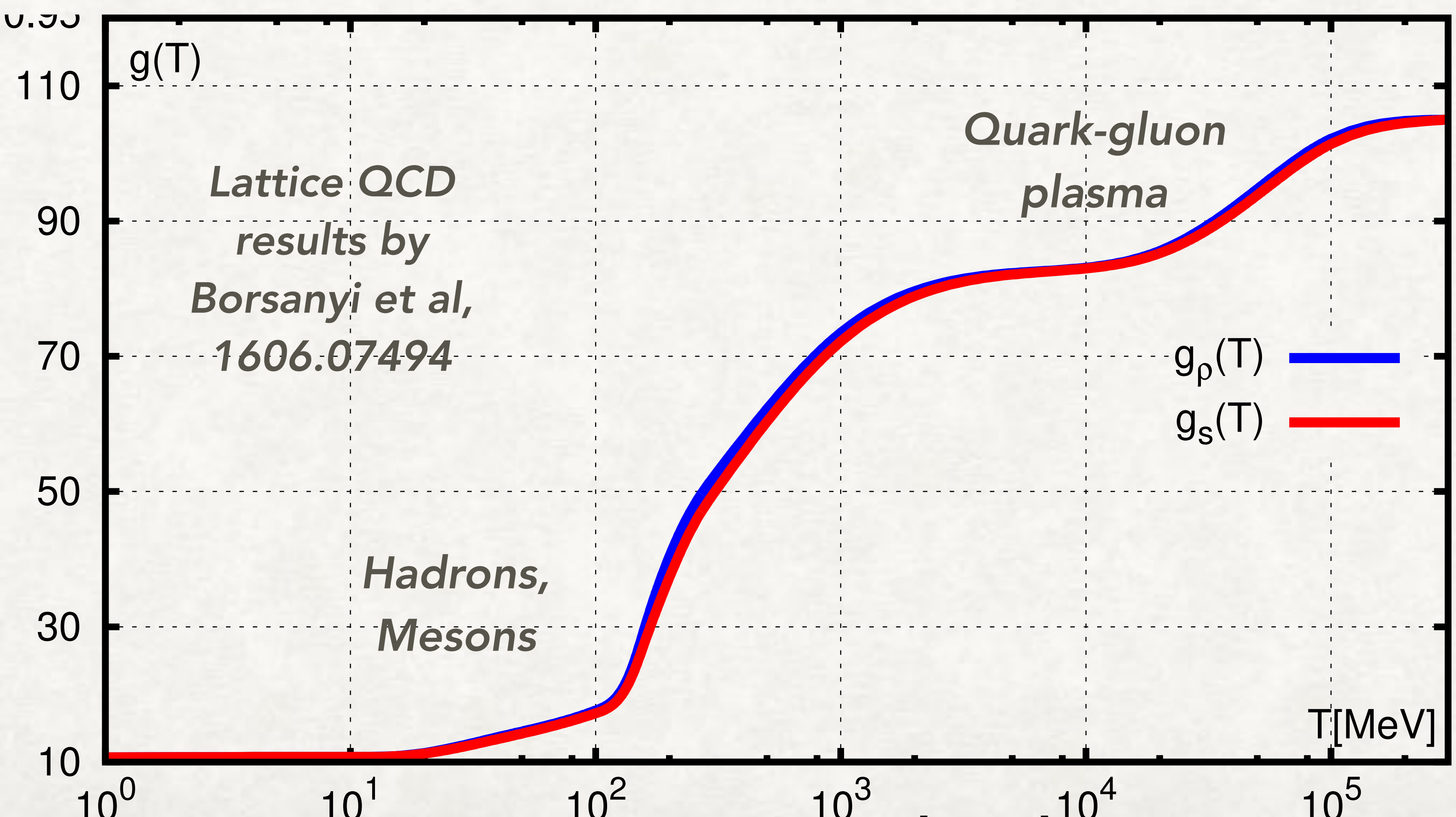
Energy and Entropy Densities

$$s \sim g_{*,s} T^3$$

$$\rho \sim g_* T^4$$



$T[\mathrm{MeV}]$

QCD EFFECTS ON COSMOLOGICAL EVOLUTION

Under most reasonable Circumstances

QCD crossover not expected to produce GWs

Nonetheless it *affects cosmological evolution*

Many particles become non-relativistic (hadronization) and their entropy is transferred to remaining light d.o.f.s

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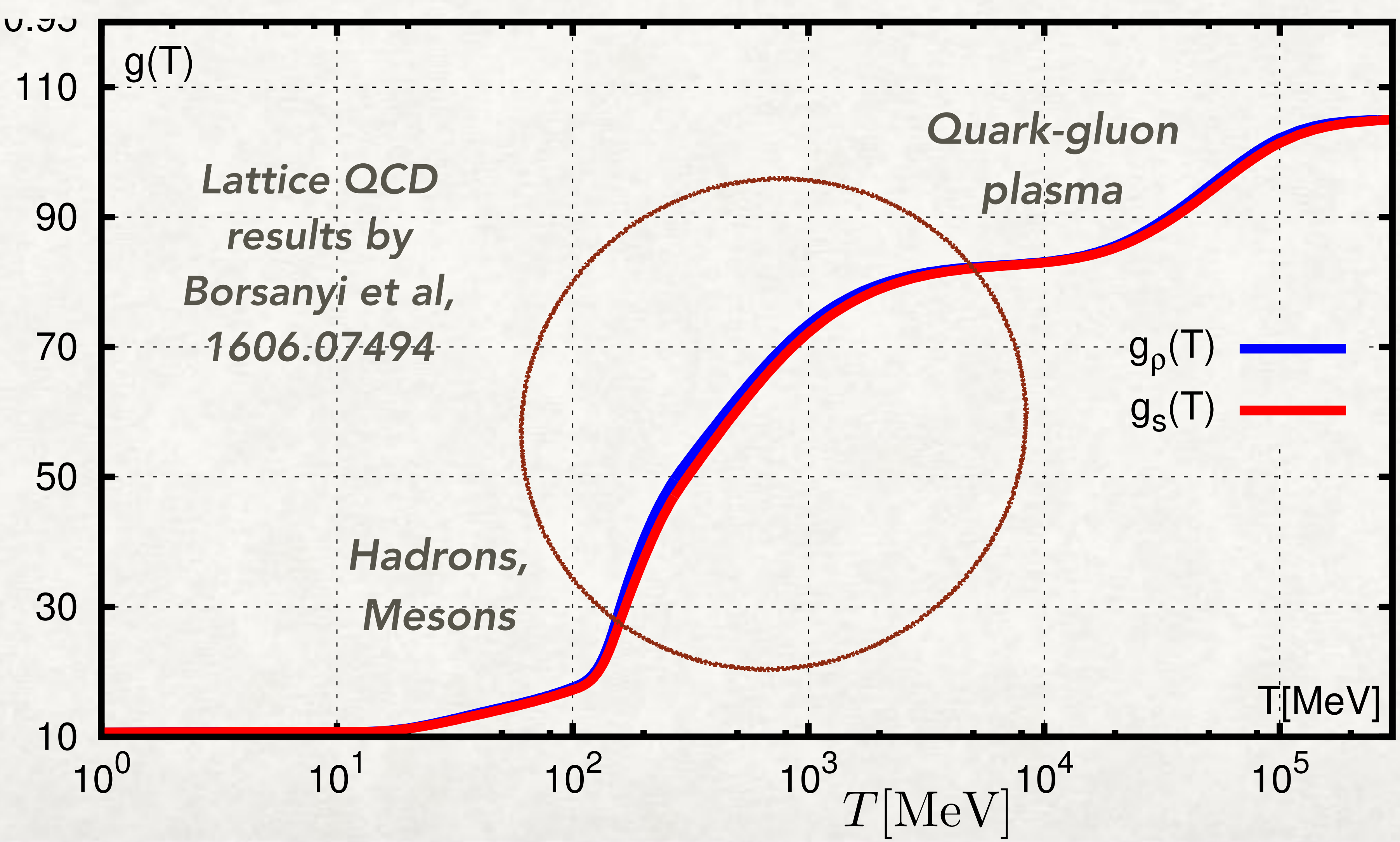

EQUATION OF STATE

$$w \equiv \frac{p}{\rho} = \frac{4}{3}\frac{g_{*,s}(T)}{g_*(T)} - 1$$

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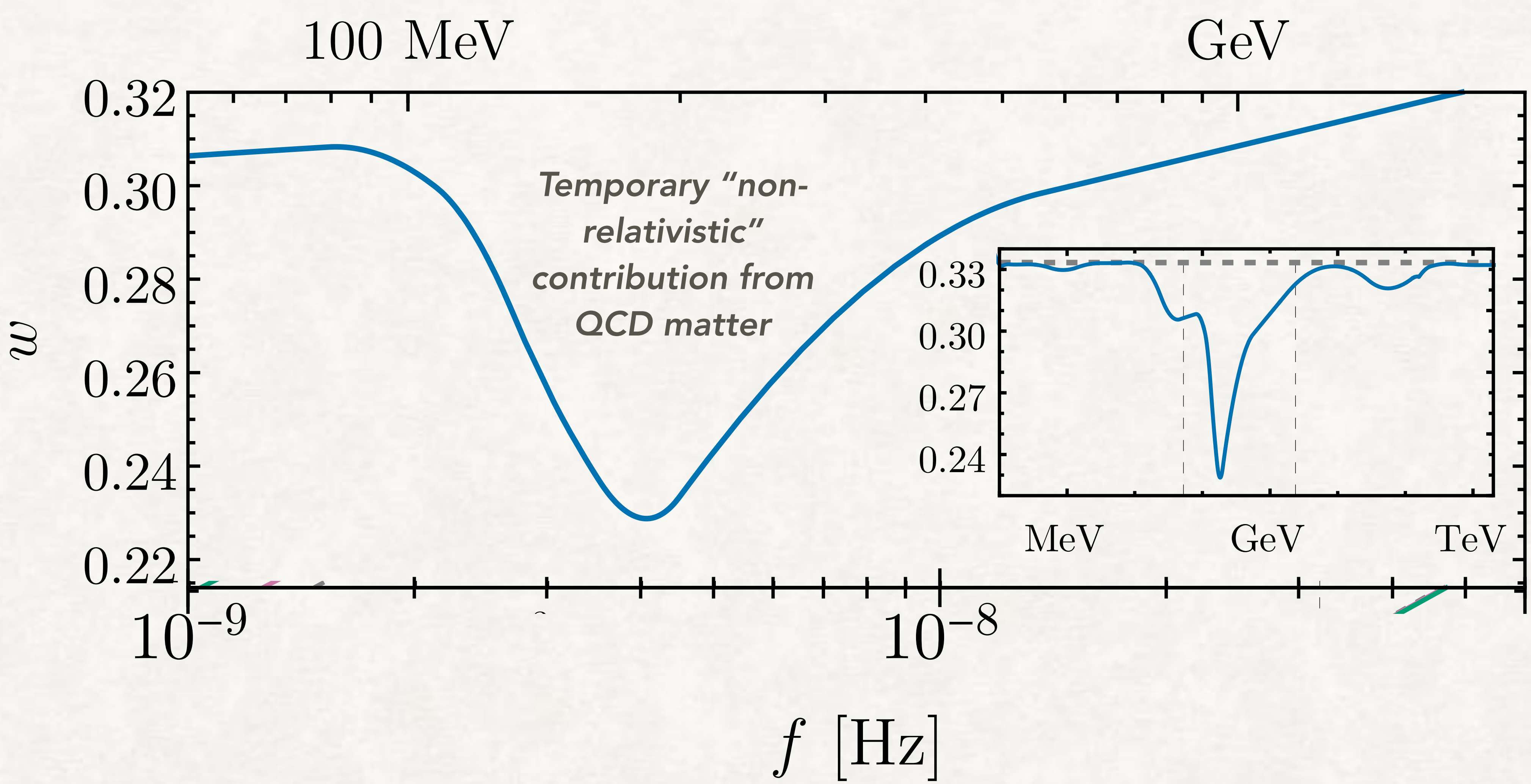
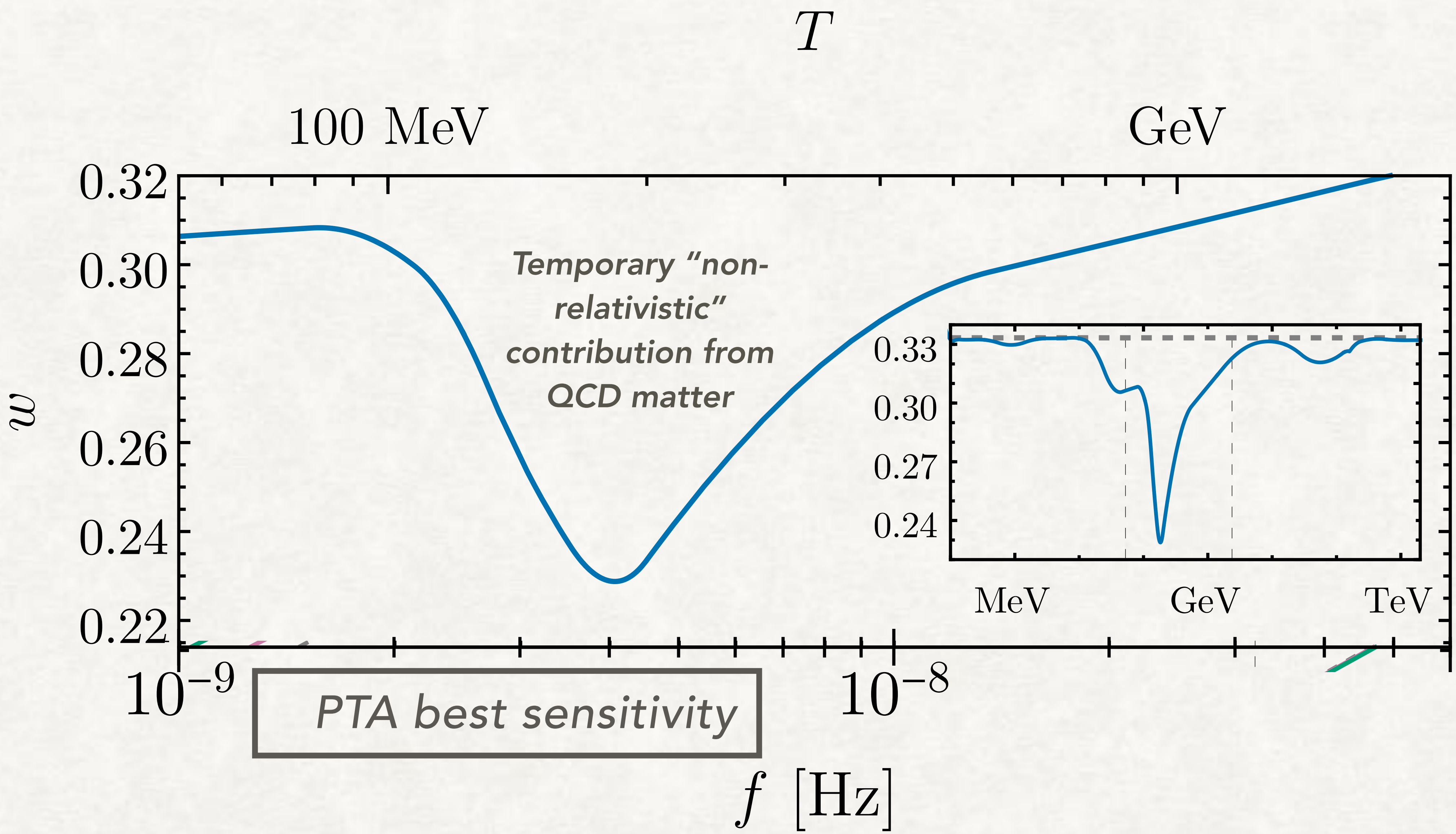
$$T$$



EQUATION OF STATE

Standard Model prediction:
~30% deviation from radiation domination around QCD crossover!



PTA best sensitivity

$$w \equiv \frac{p}{\rho} = \frac{4}{3}\frac{g_{*,s}(T)}{g_*(T)} - 1$$

IMPRINTS OF QCD ON GWS

Low-frequency super-horizon GW modes evolve differently from sub-horizon modes

They are less excited (overdamped) by the source

But their amplitude stays frozen until horizon re-entry!

See:
../Hook, Racco, Marques-Tavares 20

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$$f \ll f_\star$$

$$\frac{d\Omega_{\rm gw}}{d\ln f}\Big|_{\rm Early\ Universe} = \frac{\frac{d\rho_{\rm gw}}{d\ln f}}{\rho_{\rm rad}} \propto f^{3+2\frac{3w-1}{3w+1}}$$

Background Equation of State

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Background Equation of State

Shallower Causality Tail spectrum for $0 \leq w < 1/3$

See:
../Hook, Racco, Marques-Tavares 20

IMPRINTS OF THE QCD CROSSOVER ON CAUSALITY TAIL

Low-frequency super-horizon GW modes evolve differently from sub-horizon modes

They are less excited (overdamped) by the source

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Causality Tail Spectral Shape depends on

$$\propto f^{3+2\frac{3w-1}{3w+1}}$$

Background
Equation of State

$$\frac{d\Omega_{\rm gw}}{d\ln f}\Big|_{\rm Early\ Universe} = \frac{\frac{d\rho_{\rm gw}}{d\ln f}}{\rho_{\rm rad}}$$

Intuition:
Sub-horizon modes dilute faster for w<1/3
than in radiation domination

$$\rho_{\rm sub} \sim a^{-4} \qquad a(t) \propto t^{\frac{2}{3(1+w)}}$$

See:
../Hook, Racco, Marques-Tavares 20

IMPRINTS OF THE QCD CROSSOVER ON CAUSALITY TAIL

Spectral shape of low-frequency causality tail is
independent of the microphysics of the source

See: Watanabe, Komatsu 06/ Schettler + 10

***But** depends on*

Background Equation of State

$$\propto f^{3+2\frac{3w-1}{3w+1}}$$

$$\frac{d\Omega_{\rm gw}}{d\ln f}\Big|_{\rm Early\ Universe} = \frac{\frac{d\rho_{\rm gw}}{d\ln f}}{\rho_{\rm rad}}$$

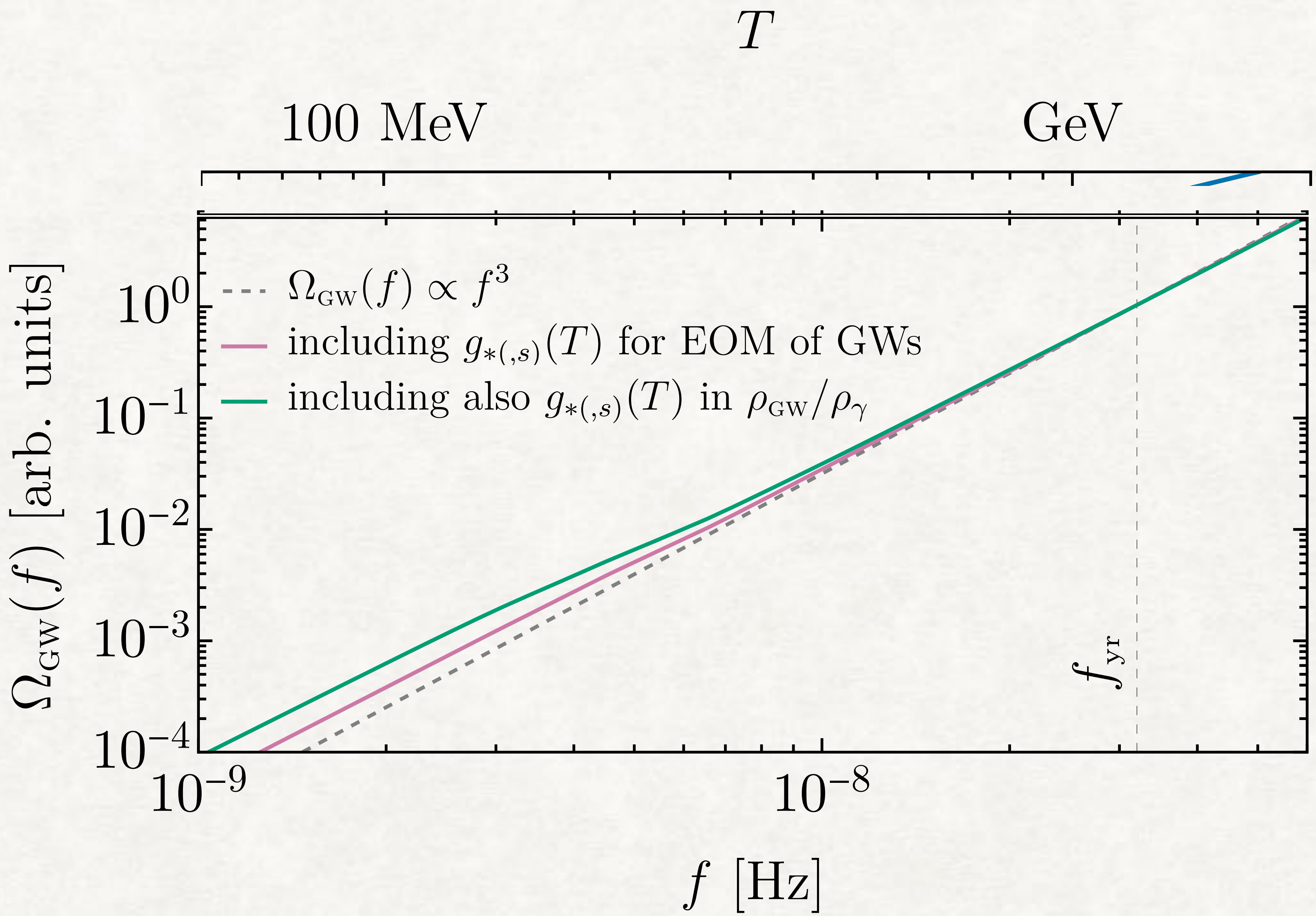
$$\propto g_{*,s}^{-\frac{4}{3}}\, g_*$$

Additional effect

Redshifts as

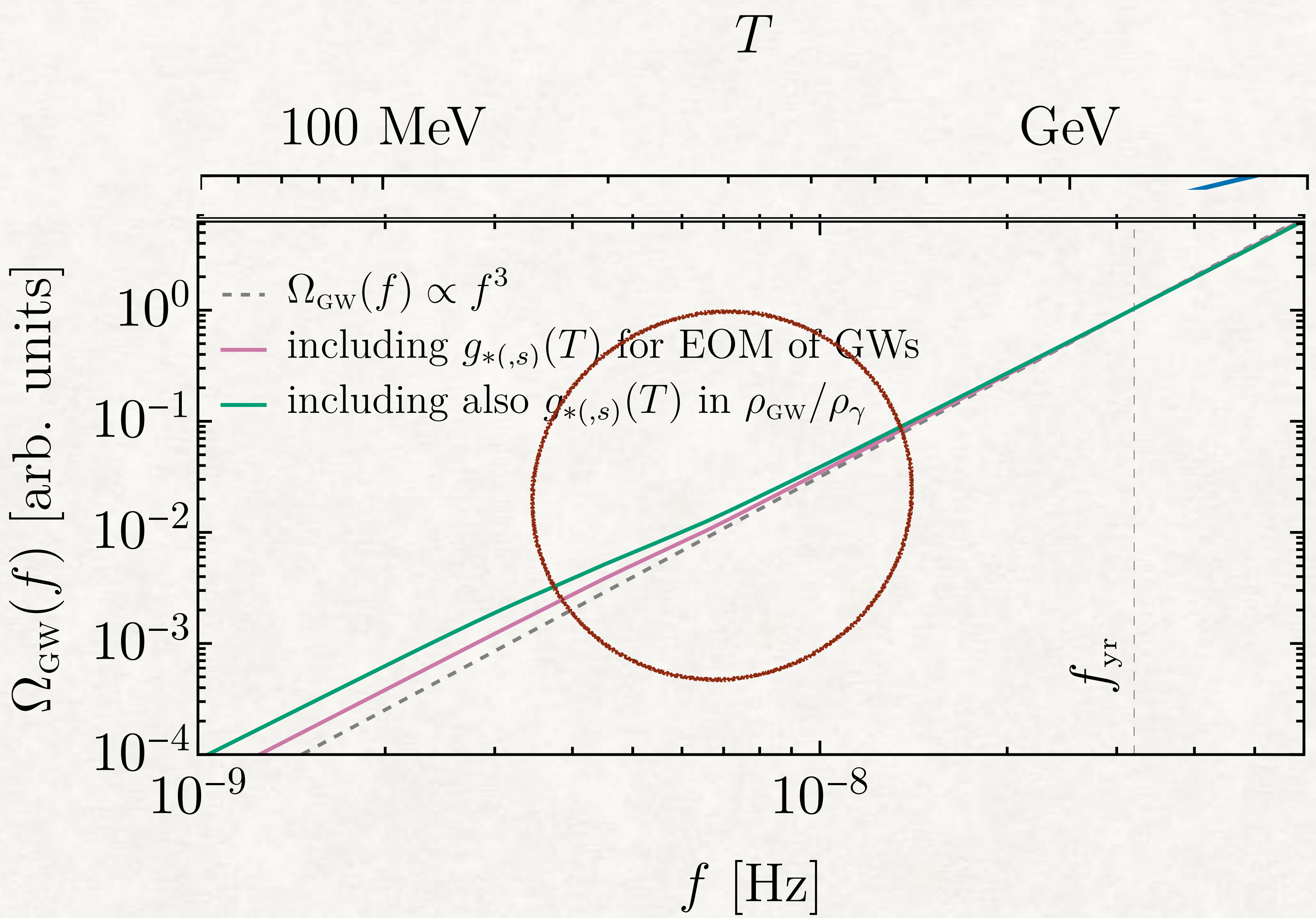
Entropy injections only to Standard Model bath (GWs are decoupled)

THE CAUSALITY TAIL IN THE PTA BAND



Relevant for all early Universe sources active slightly before QCD crossover!

THE CAUSALITY TAIL IN THE PTA BAND



Relevant for all sources active slightly before QCD crossover!

SM predicts distinctive *frequency-dependent shape of the signal* ***(not simple power law)***

Amplitude ***in first bins 2-3 times larger than naive spectrum!***

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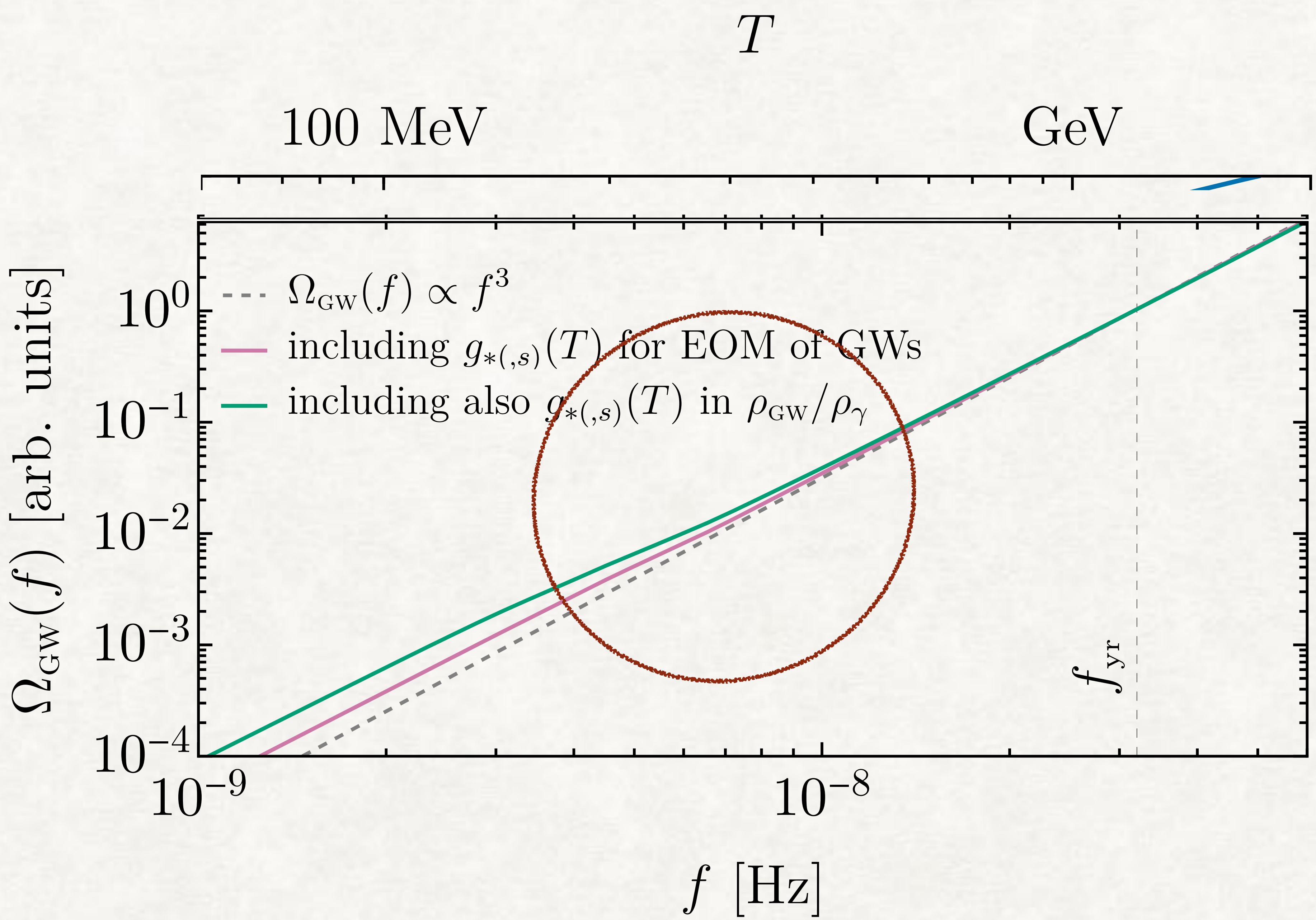

Relevant for all sources active slightly before QCD crossover!

Tabulated spectrum provided for future searches!

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IS THE SIGNATURE OBSERVABLE?

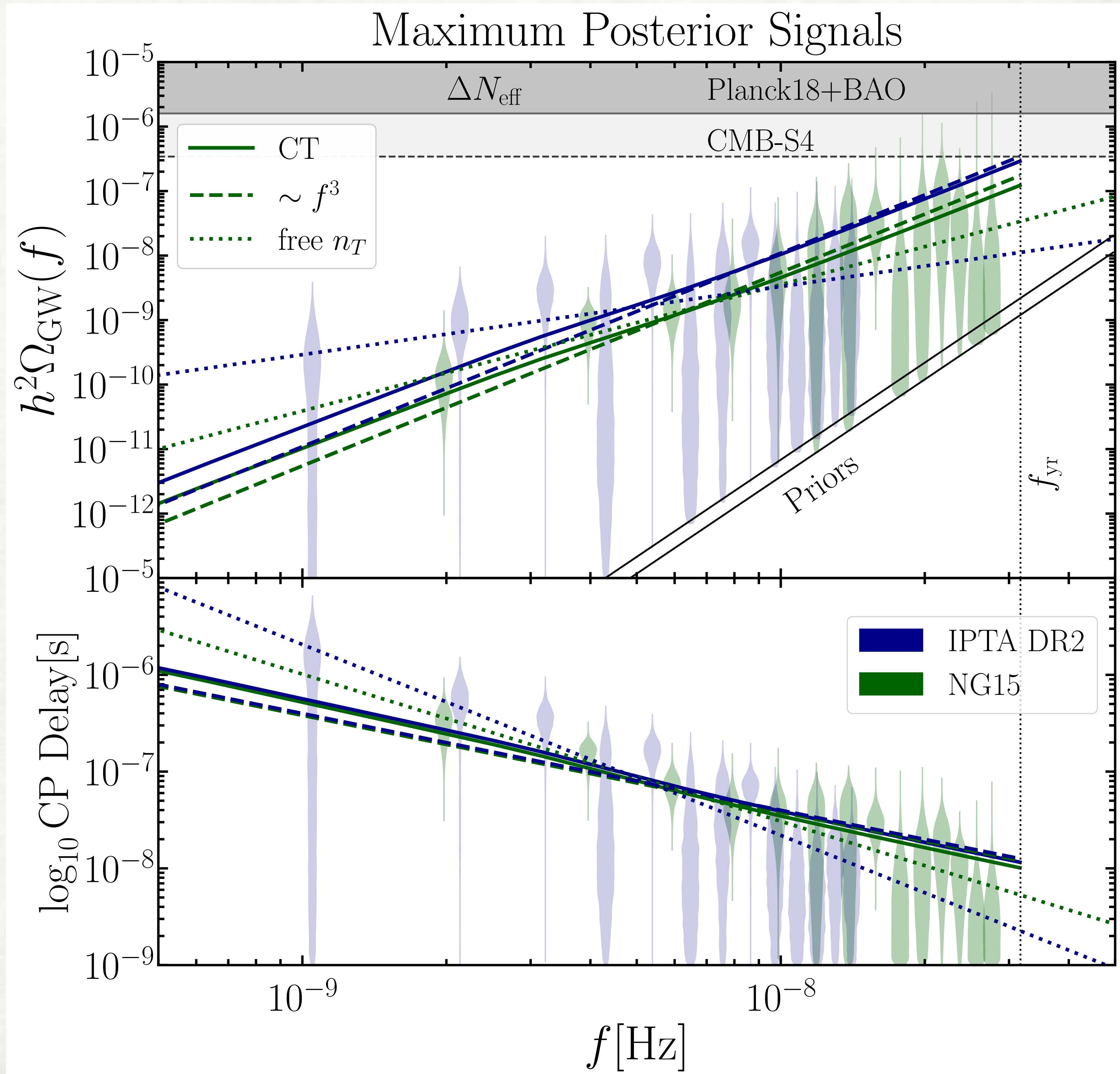
Bayesian analysis in International PTA DR2 and NG15 datasets

`enterprise` `PTArcade`

Bayes factor (Including CMB prior!)

$$\mathcal{B}_{\mathrm{CT\,vs}\,f^3} \simeq 20 - 40$$

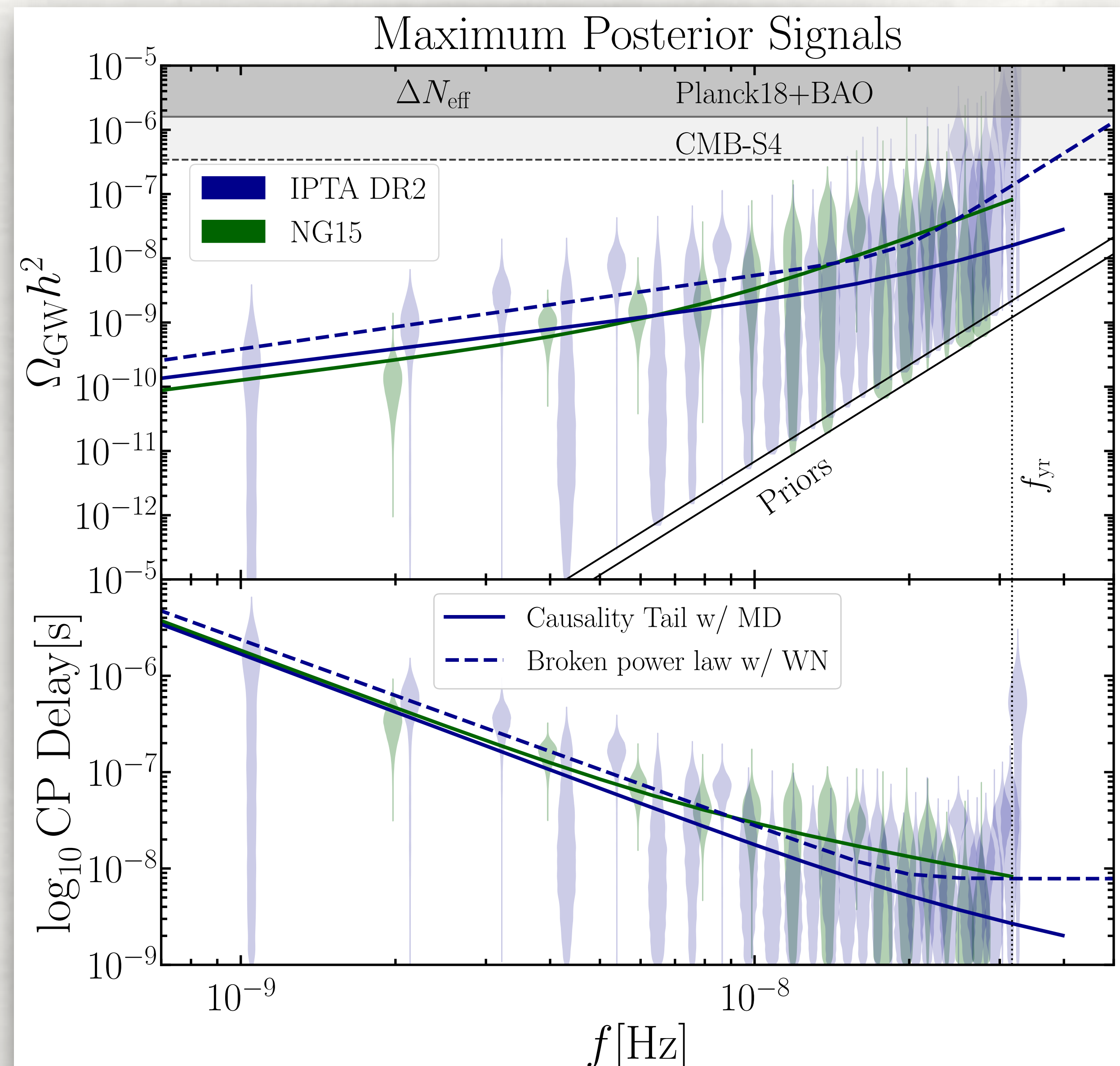
PTA data able to see SM physics in GWs!

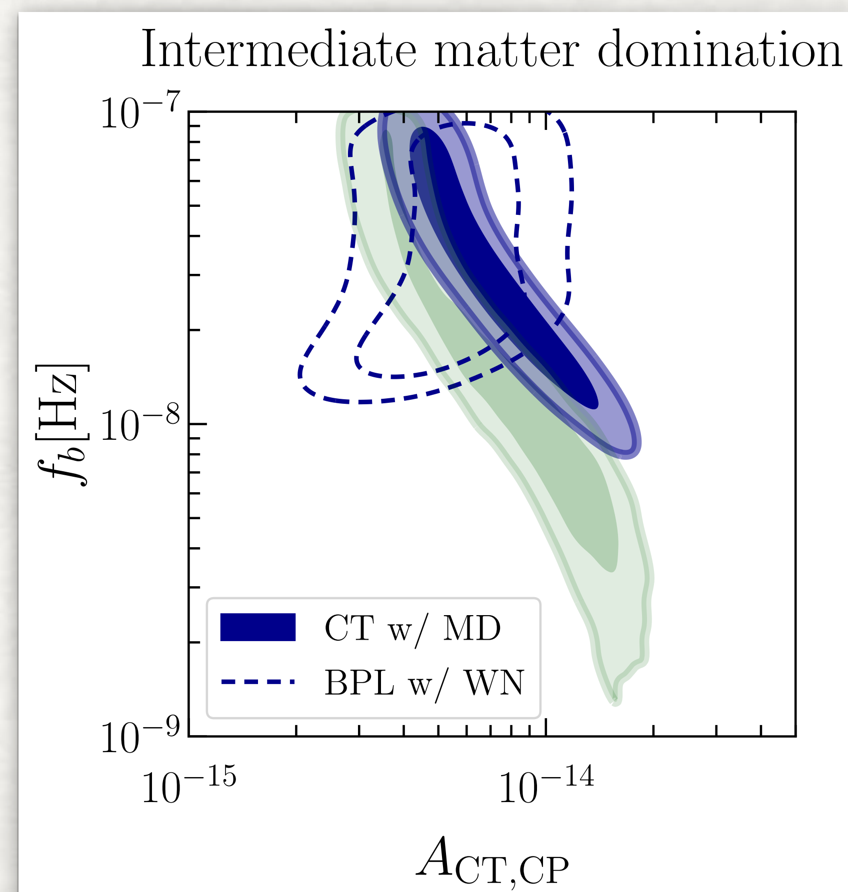


EXPLORING THE COSMOLOGICAL HISTORY

Also possible to test non-standard expansion histories, such as Matter Domination (low reheating)

$$w \to 0 \Rightarrow \Omega_{\rm gw} h^2 (f \ll f_\star) \propto f$$





DIRECTIONS/OPPORTUNITIES FOR PARTICLE PHYSICS/COSMOLOGY @ PTAS

V. Dandoy, V. Domcke, FR *2302.07901*

Set constraints

Scalar-induced Gravitational Waves

SCALAR-INDUCED GWS (SIGW)

Scalar (curvature) & tensor perturbations generated independently during inflation, Then stretched to super horizon scales

$$k_\star = \frac{2\pi}{\lambda_\star} \ll aH$$

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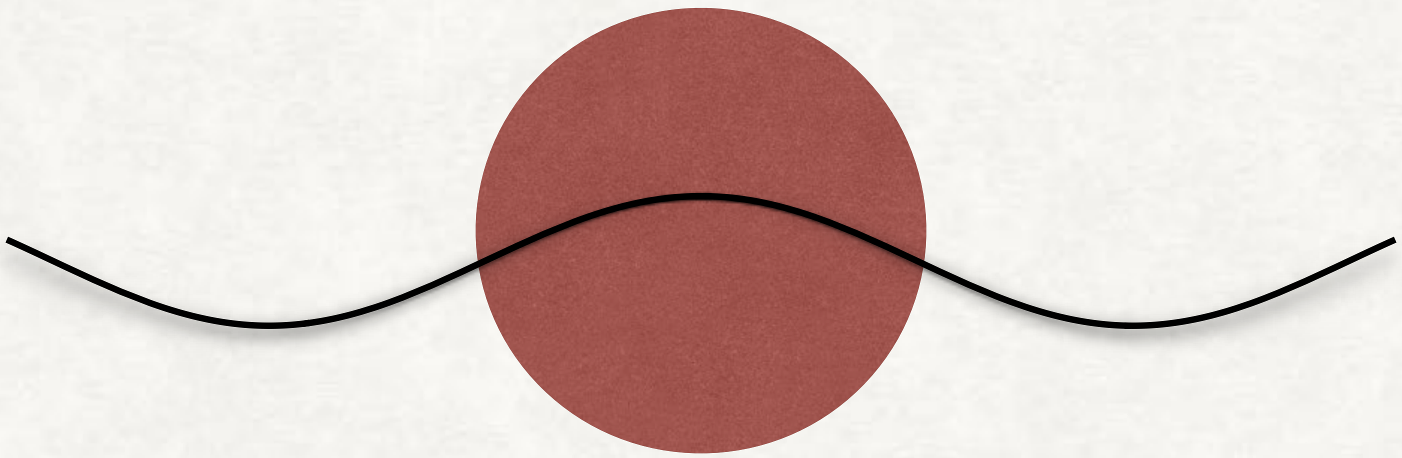

SCALAR-INDUCED GWS

Re-enter the Hubble sphere at some epoch ***after inflation***

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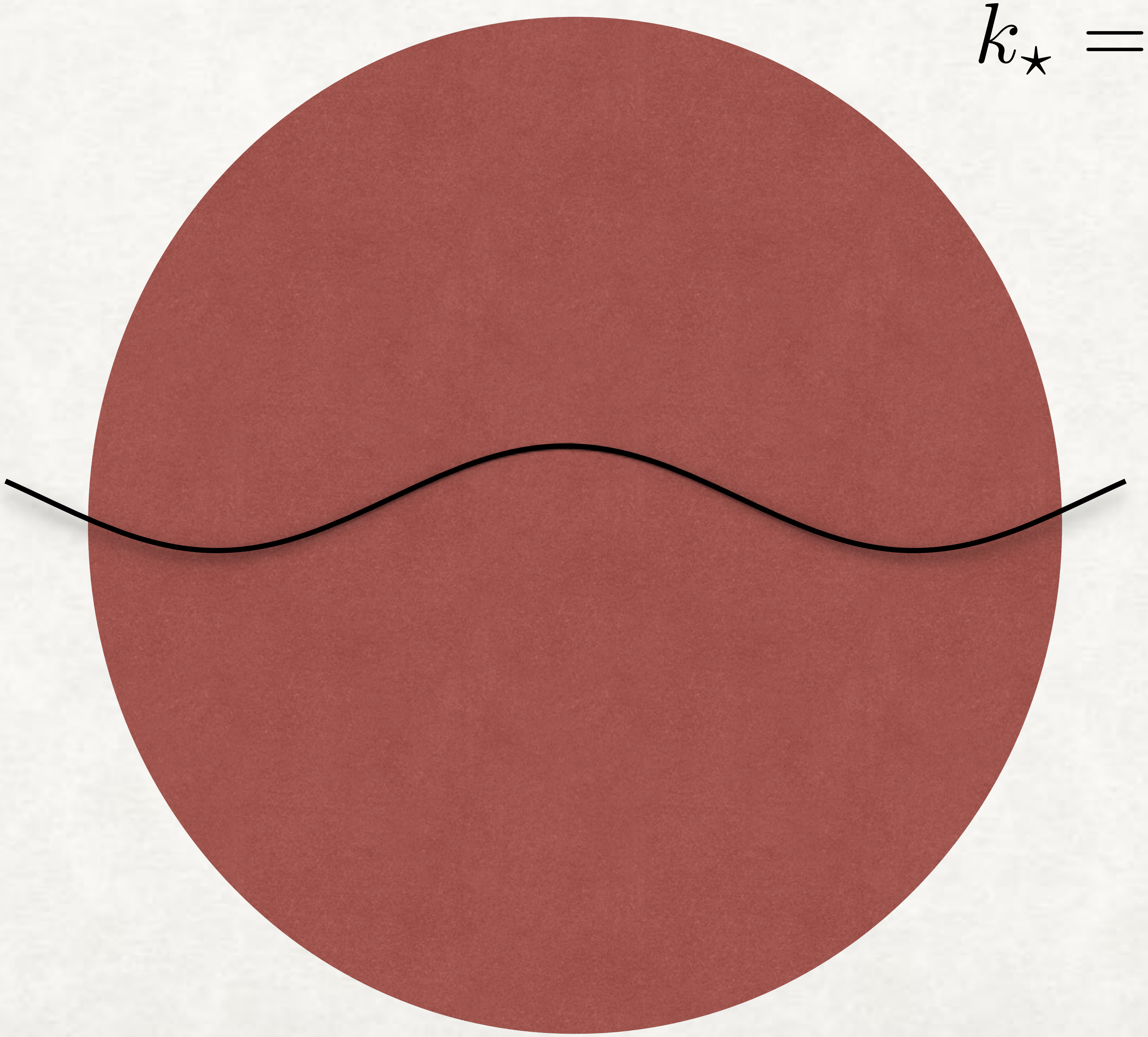


SCALAR-INDUCED GWS

*At CMB scales, **scalar spectrum is small and approximately scale invariant,** tensors yet to be detected*

$$\Delta^2_\zeta(k) \equiv A_\zeta \left(\frac{k}{0.05\ \mathrm{Mpc}^{-1}}\right)^{n_s-1} \sim 10^{-9}, \quad \Delta^2_t(k) \sim r\Delta^2_\zeta(k) \lesssim 10^{-11}$$

$$n_s \simeq 0.97 \qquad\qquad \Rightarrow \Omega_{\rm gw}h^2 \lesssim 10^{-17}$$

*These perturbations **are independent at first order in GR perturbation theory***

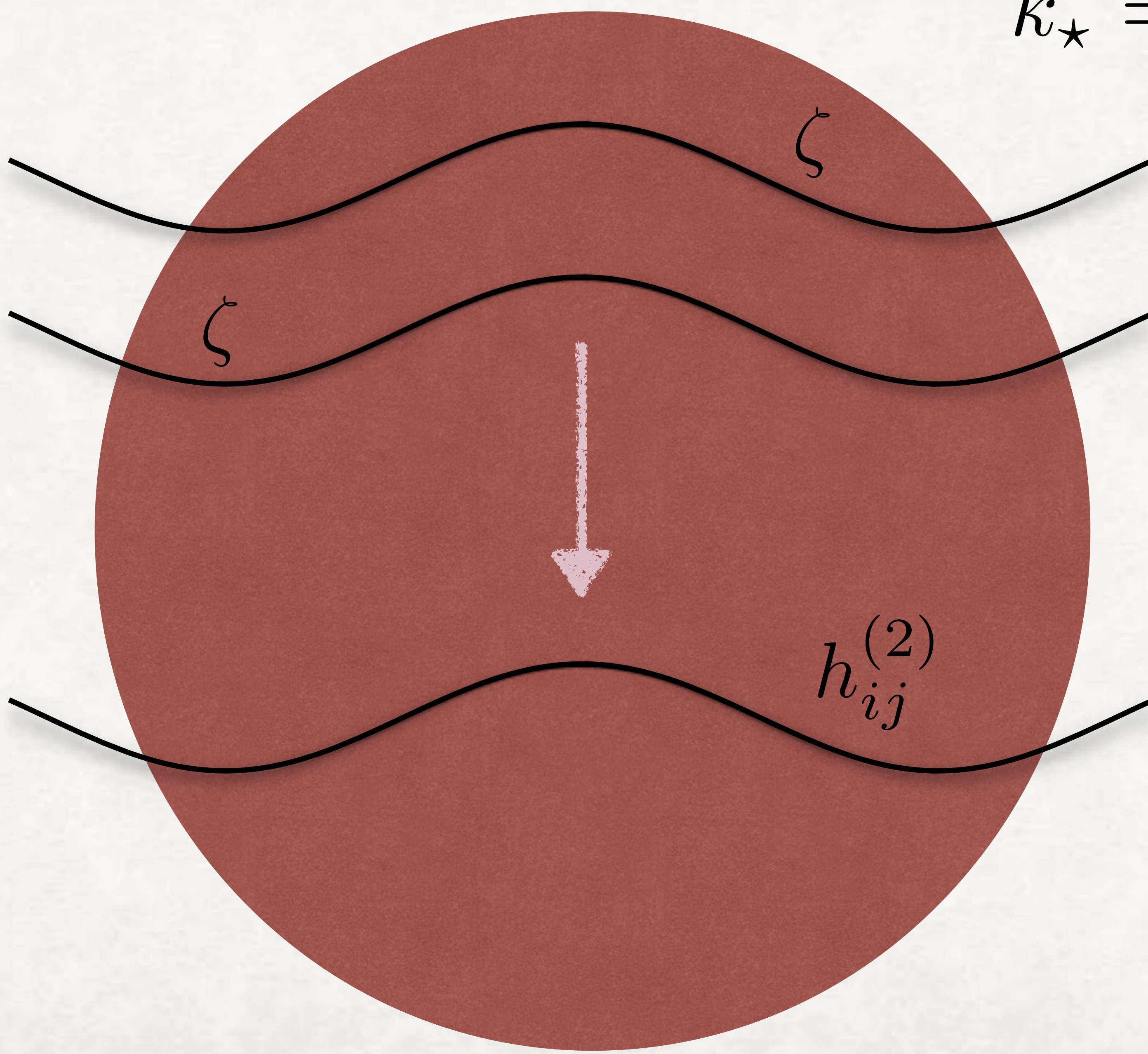
*At NLO, **(two) first order scalar** perturbations source **second order tensor** perturbations*

$$h^{(2)''}_{ij} + 2\mathcal{H}h^{(2)'}_{ij} + k^2 h^{(2)}_{ij} = S^{TT}_{ij}(\Phi^{(1)}, \Psi^{(1)})$$

SCALAR-INDUCED GWS

Most significant production occurs at horizon re-entry of similar-k perturbations (causality limited afterwards)

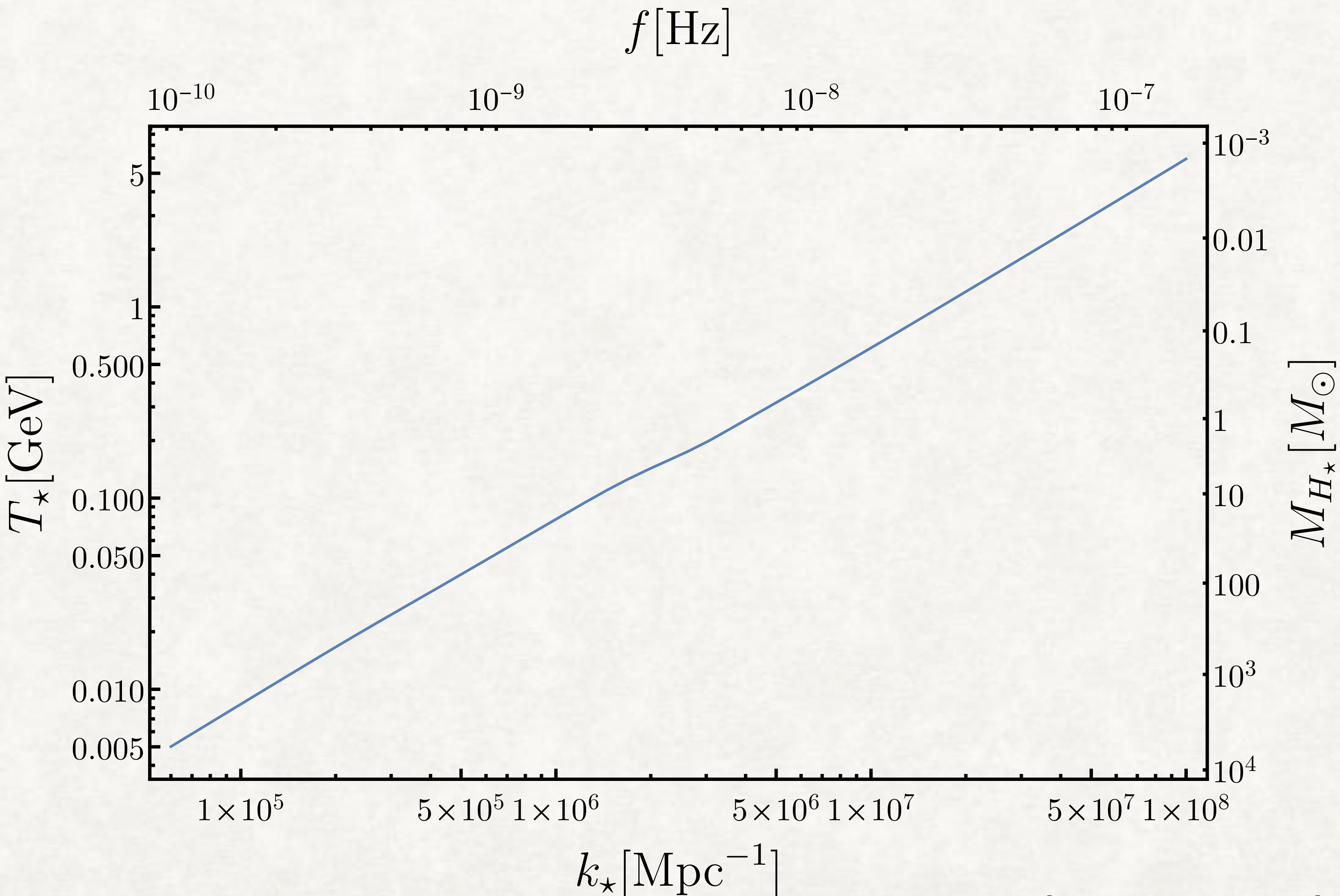
$$k_\star = \frac{2\pi}{\lambda_\star} \simeq aH|_\star$$



$$\Omega_{\rm gw} \sim A_\zeta^2$$

SCALAR-INDUCED GWS

Observable ***only if curvature power spectrum at small scales is much bigger than at CMB scales***

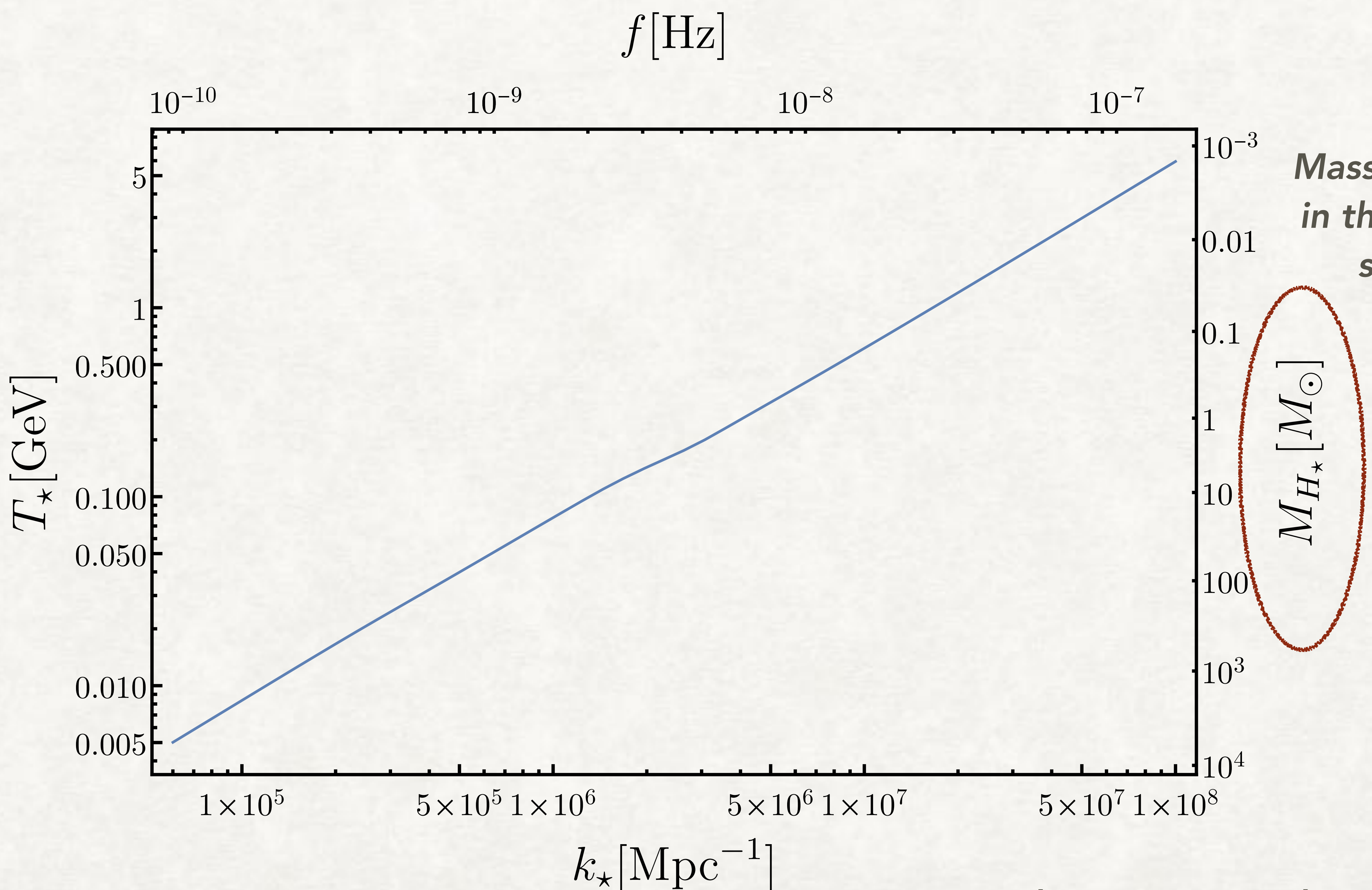


$\gg 0.05\ \mathrm{Mpc}^{-1}$

Scalar spectrum only weakly constrained at these scales!

PRIMORDIAL BLACK HOLES

*If amplitude is sufficiently large, scalar perturbations undergo gravitational collapse and form **Primordial Black Holes (PBHs)***



Mass enclosed in the Hubble sphere

$$\gg 0.05\ \mathrm{Mpc}^{-1}$$

Scalar spectrum only weakly constrained at these scales!

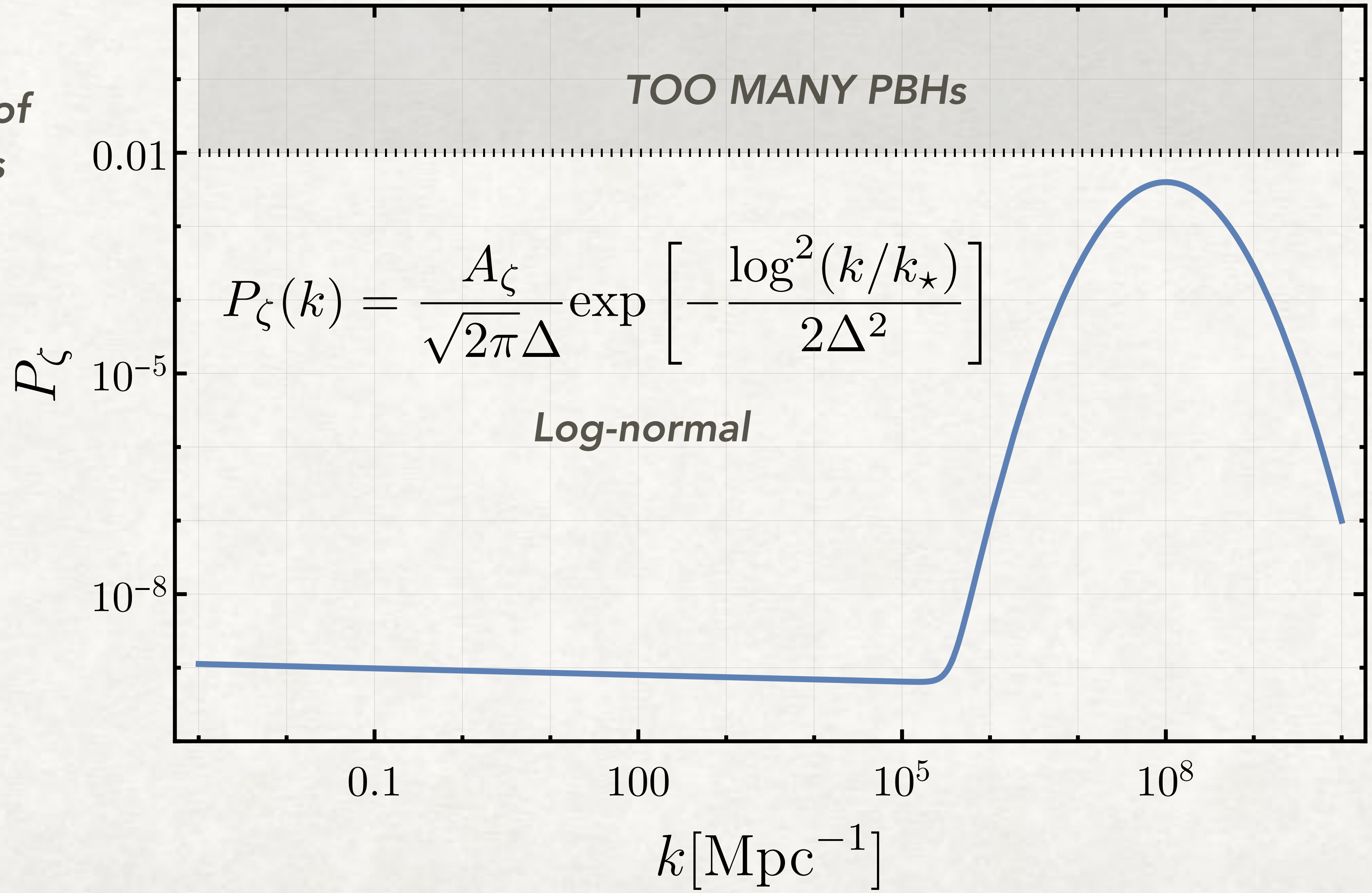
SCALAR-INDUCED GWS

Warning: enhancement requires strong deviations from slow-roll, non-minimal inflationary model

Spectral shape of GW signal determined by shape of power spectrum at small scales

Simple parametrisation to capture possible enhancement

Common magnitude of constraints



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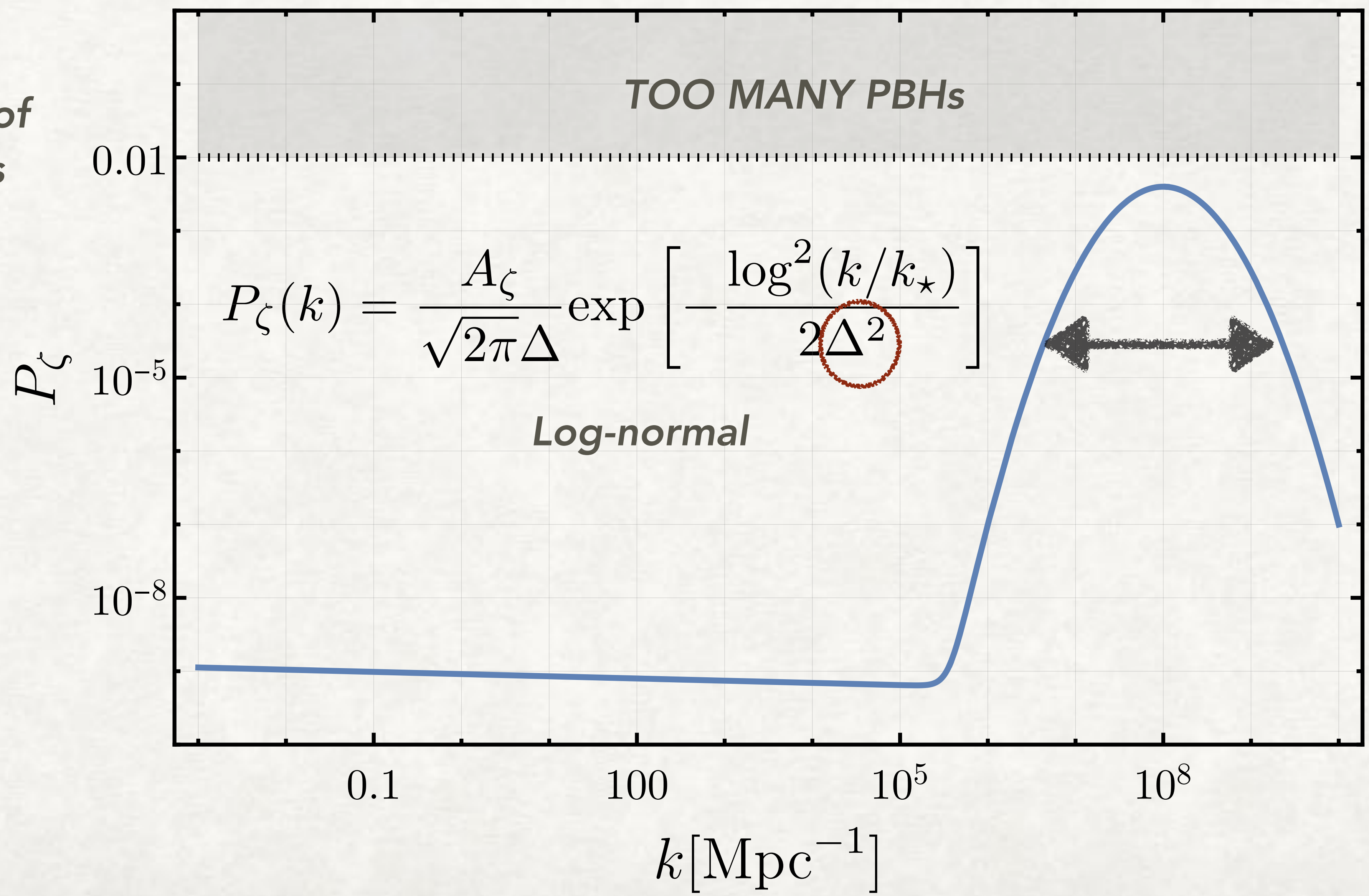

$$P_\zeta(k) = \frac{A_\zeta}{\sqrt{2\pi}\Delta}\exp\left[-\frac{\log^2(k/k_\star)}{2\Delta^2}\right]$$

Log-normal

SCALAR-INDUCED GWS

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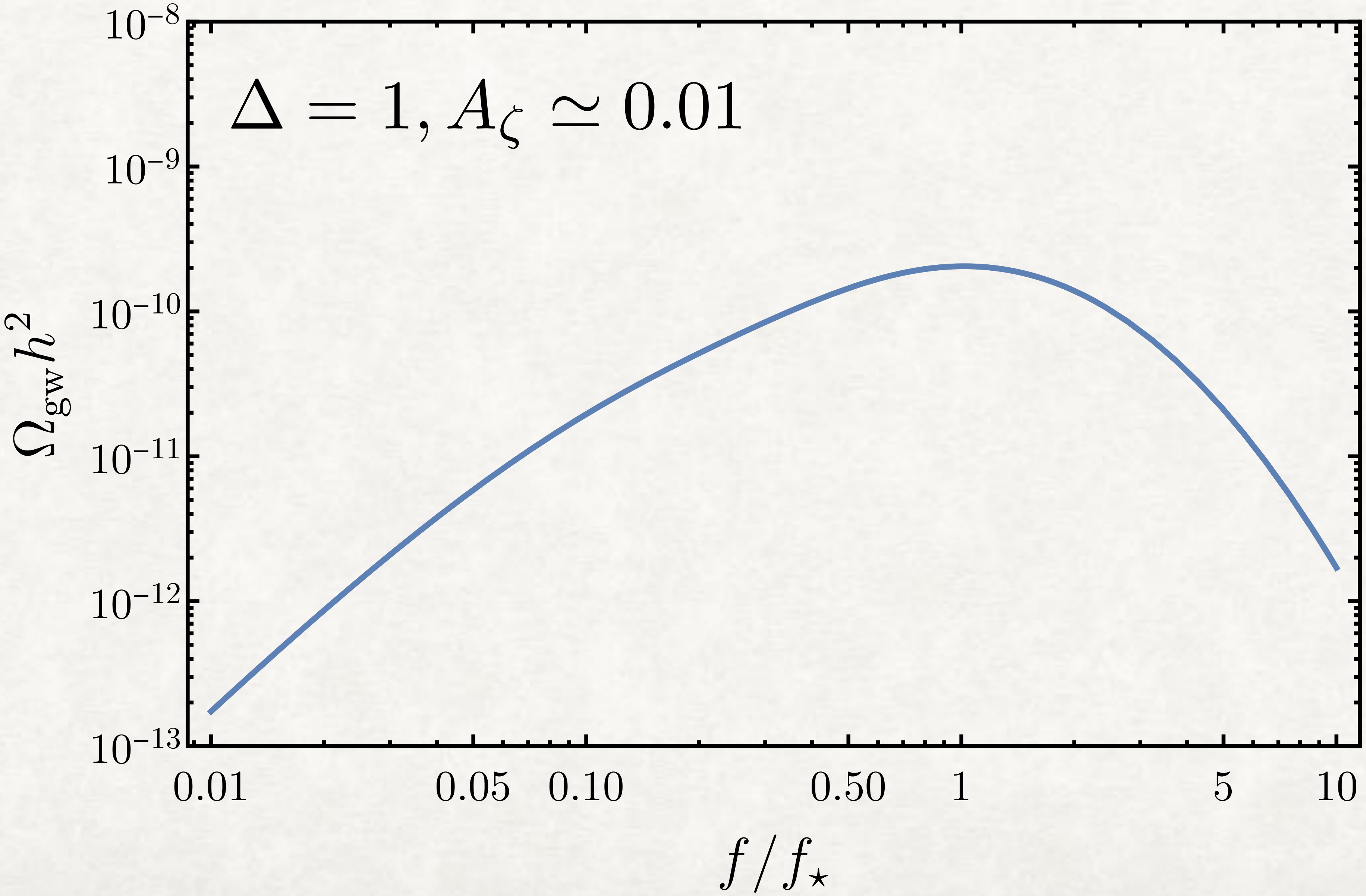

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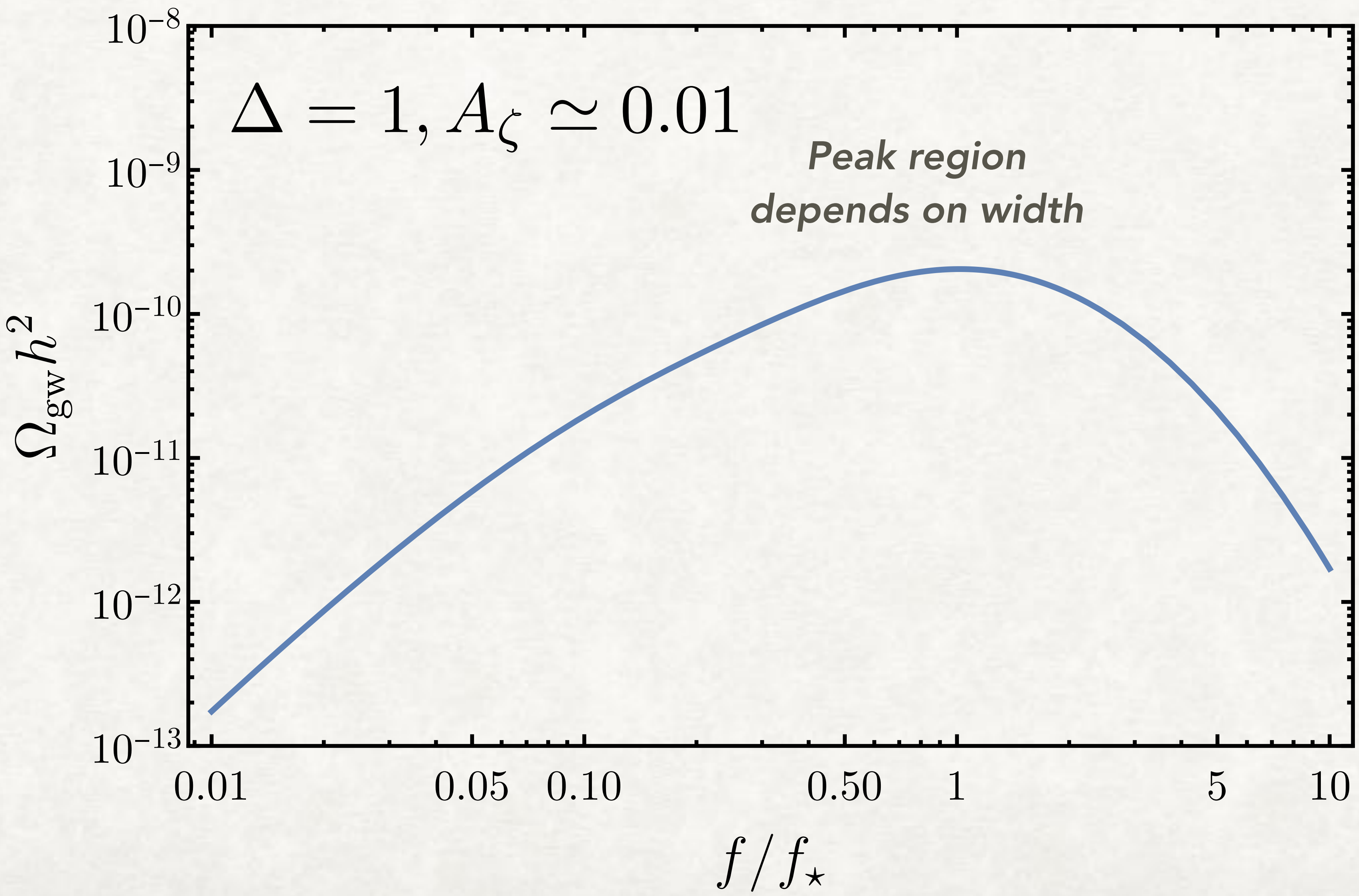

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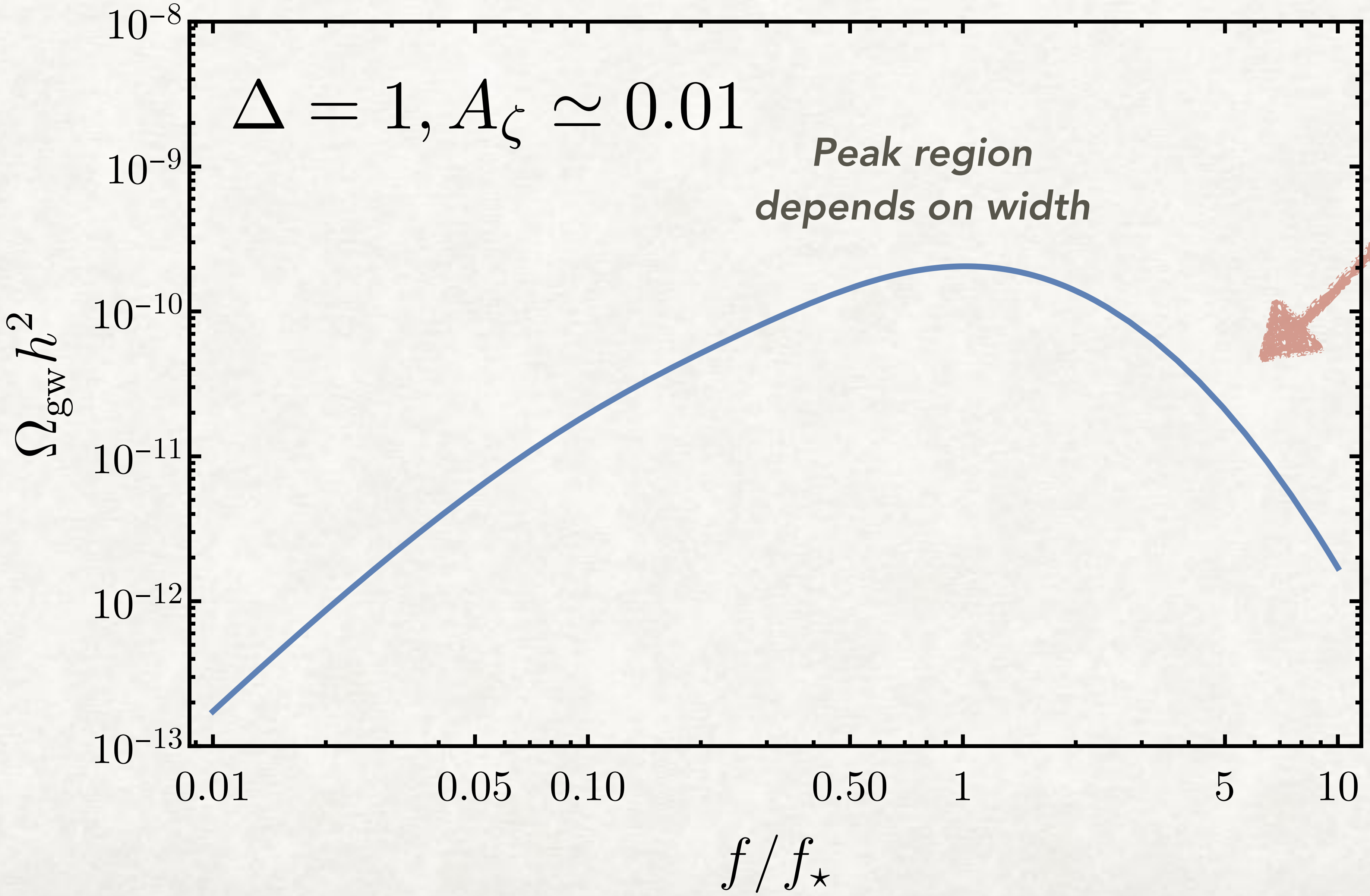
(Smaller) Scales re-enter earlier, no enhancement



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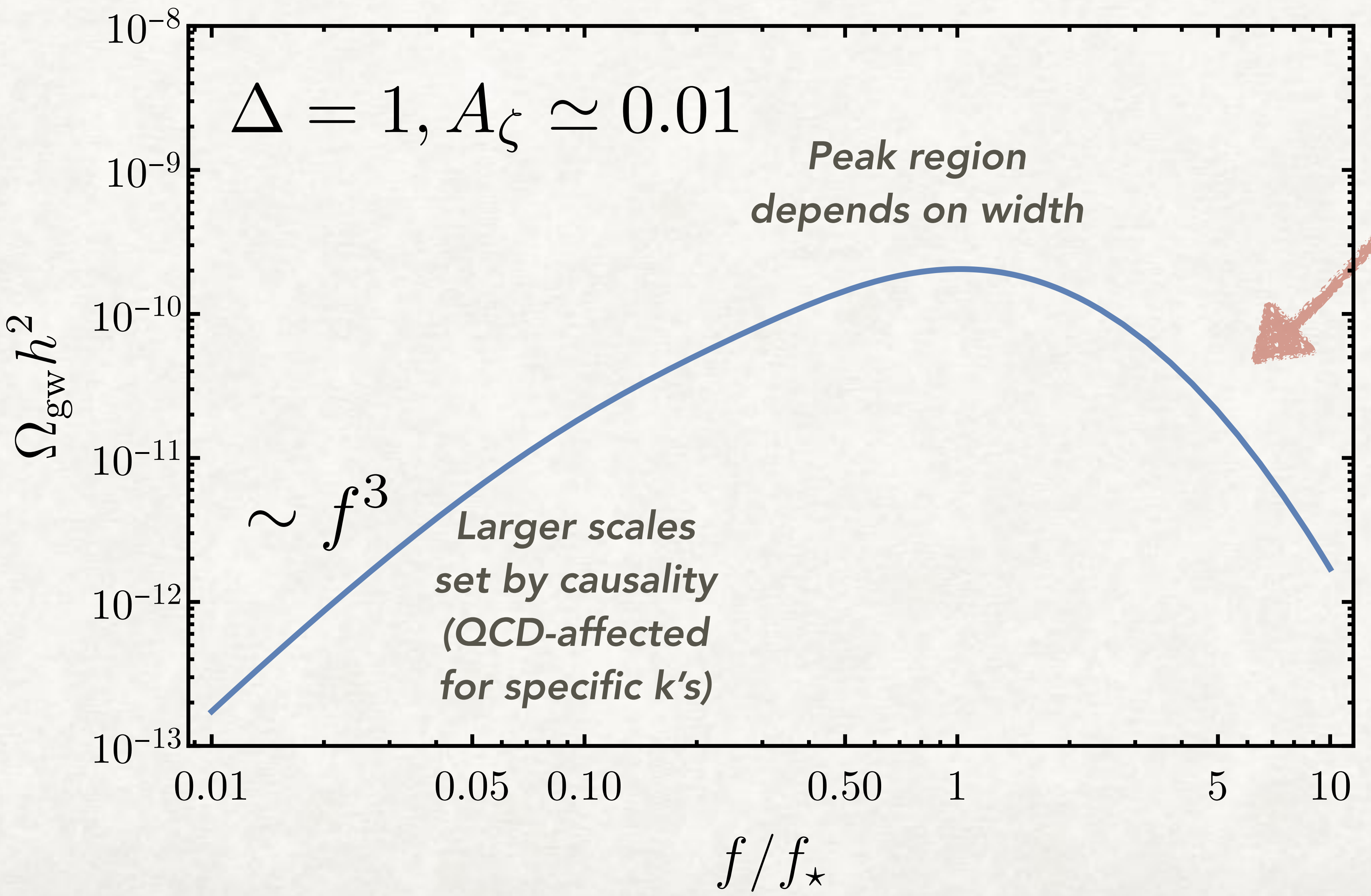

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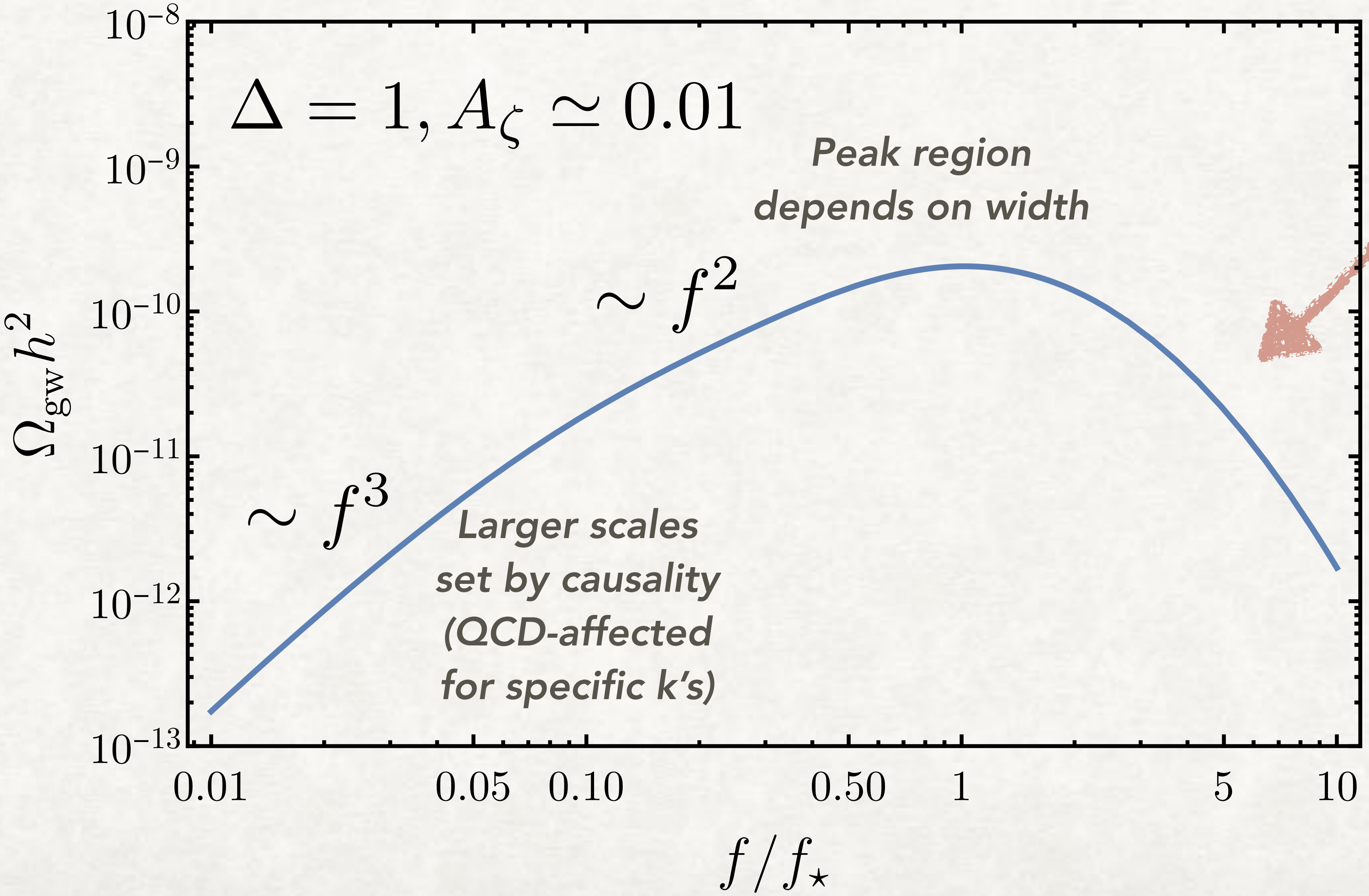


RELEVANCE OF & FOR PTAS

Non-observation (or incompatible spectrum) of GWs provide way to (indirectly) constrain the power spectrum at small scales

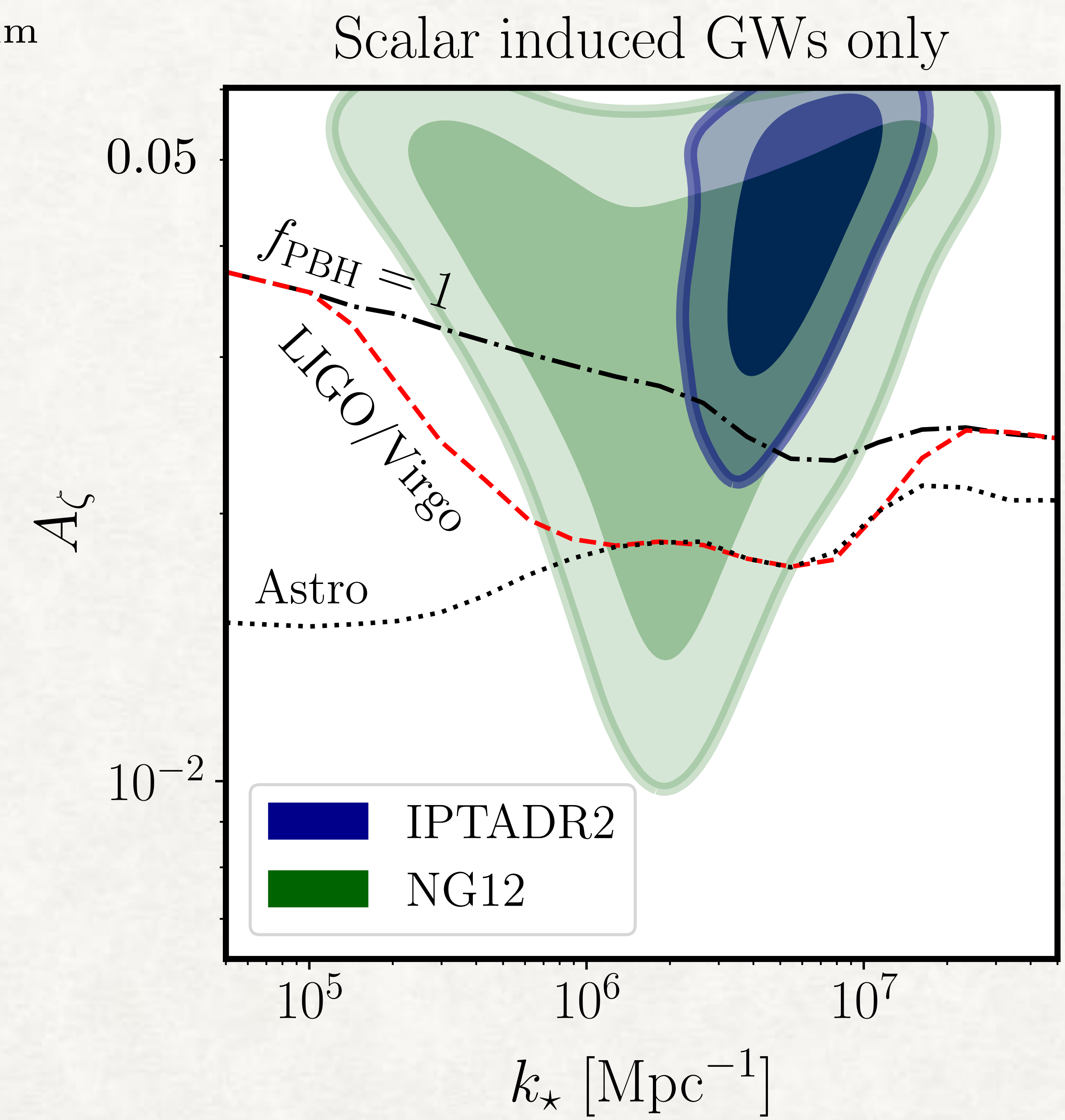
Scenario does not require new physics at low temperatures, *evades constraints on dark sectors*

Connection with PBHs in interesting mass region *(LIGO/Virgo)*

DETECTION ANALYSIS

Analytical approx by Pi, Sasaki implemented (and improved)in `enterprise`

$f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm cdm}$



After NG12, several papers claiming interpretation in terms of SIGW

DETECTION ANALYSIS

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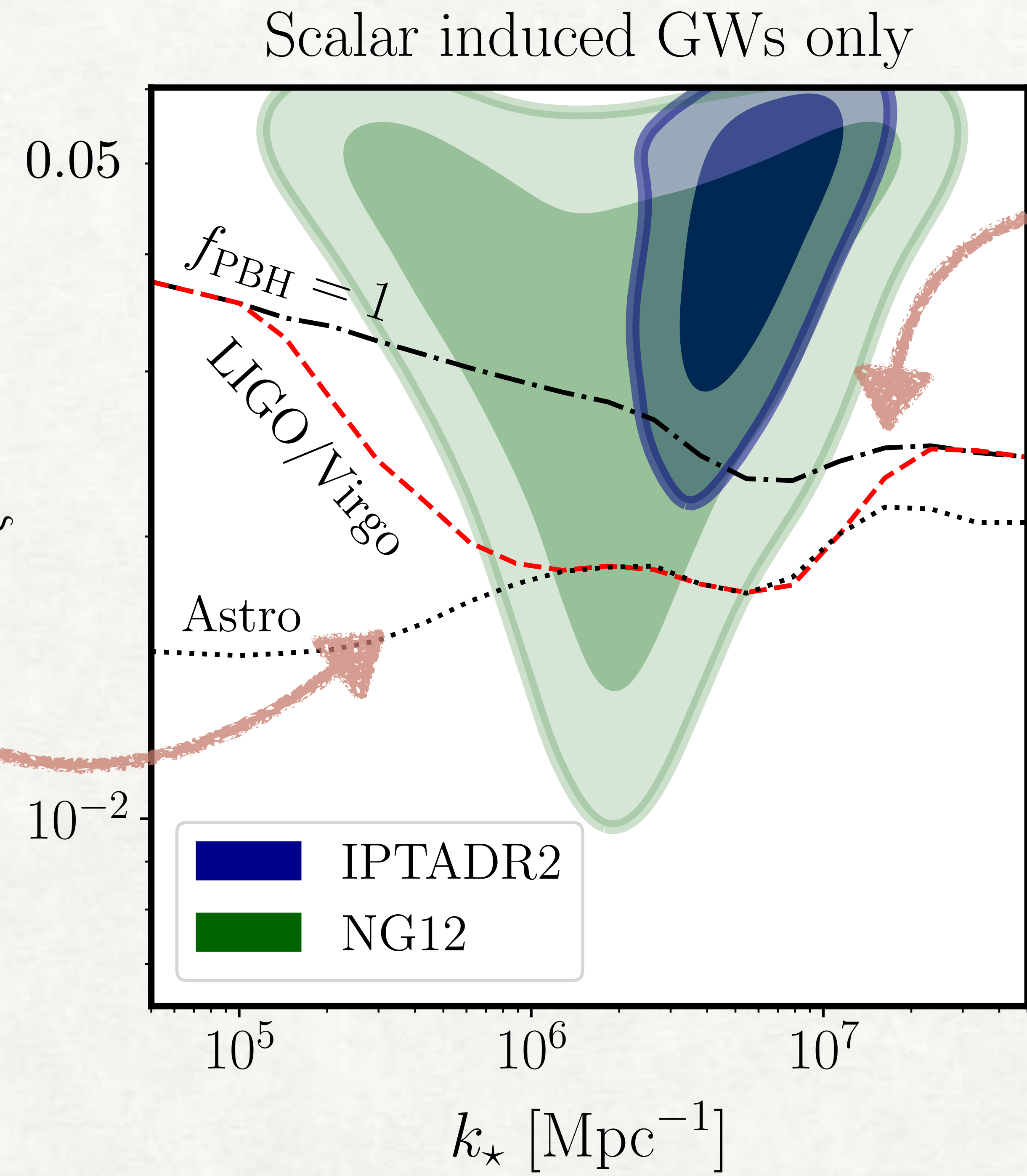


Constraints from LIGO/Virgo (PBH merger rate)
+
Astro probes

Indirect constraints from PBHs (Uncertain, We assessed to the state-of-the-art understanding)

See talk by Valerie!

Analysis For Gaussian perturbations

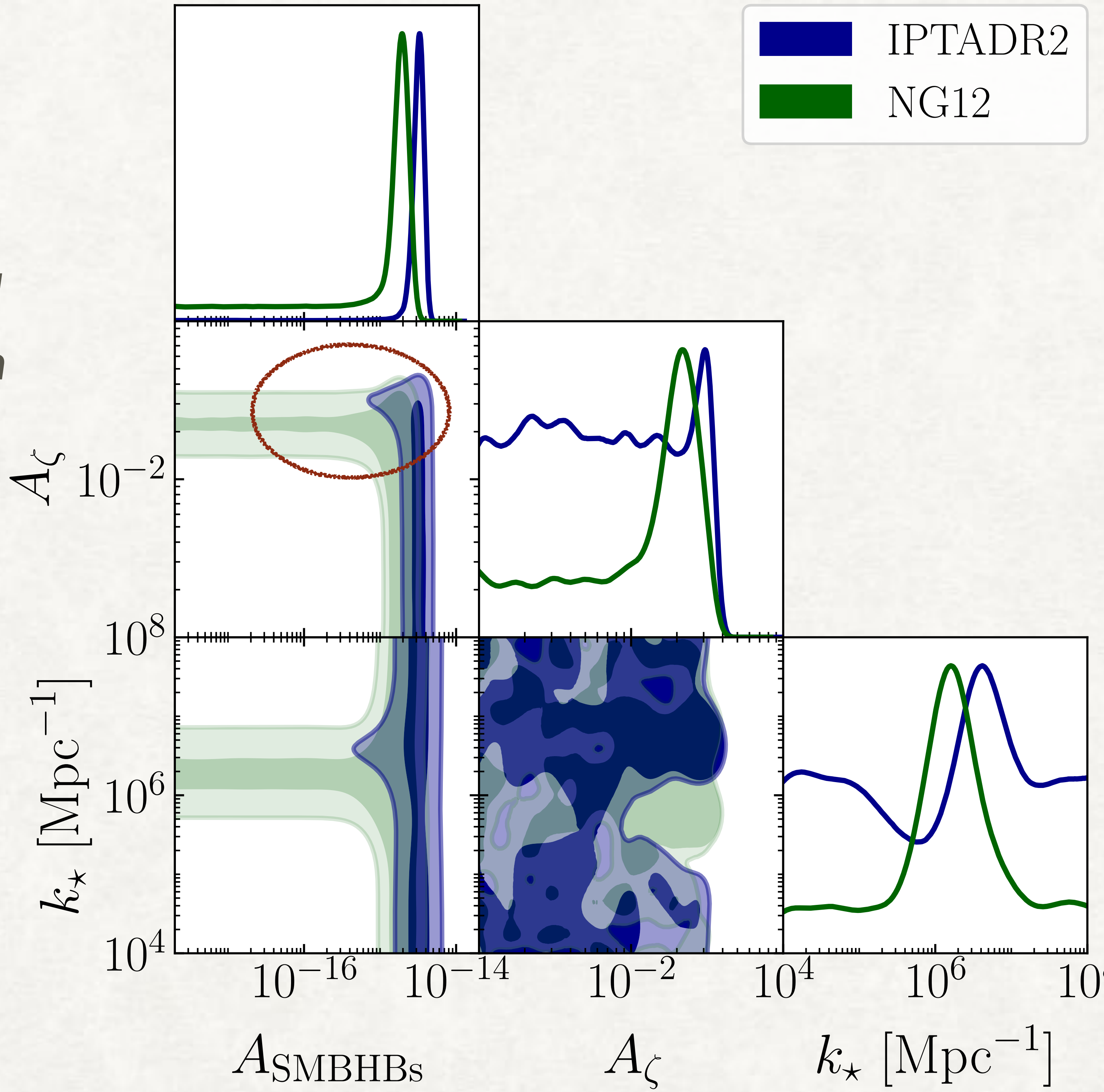
See also talk by Dani!

PTA interpretation in terms of SIGW faces challenge!

DETECTION ANALYSIS INCLUDING SMBHBS & PRIOR

$\Delta = 1$

Prior from PBH overproduction included!



SMBHBs signal modeled as power law with

$\gamma = 13/3$

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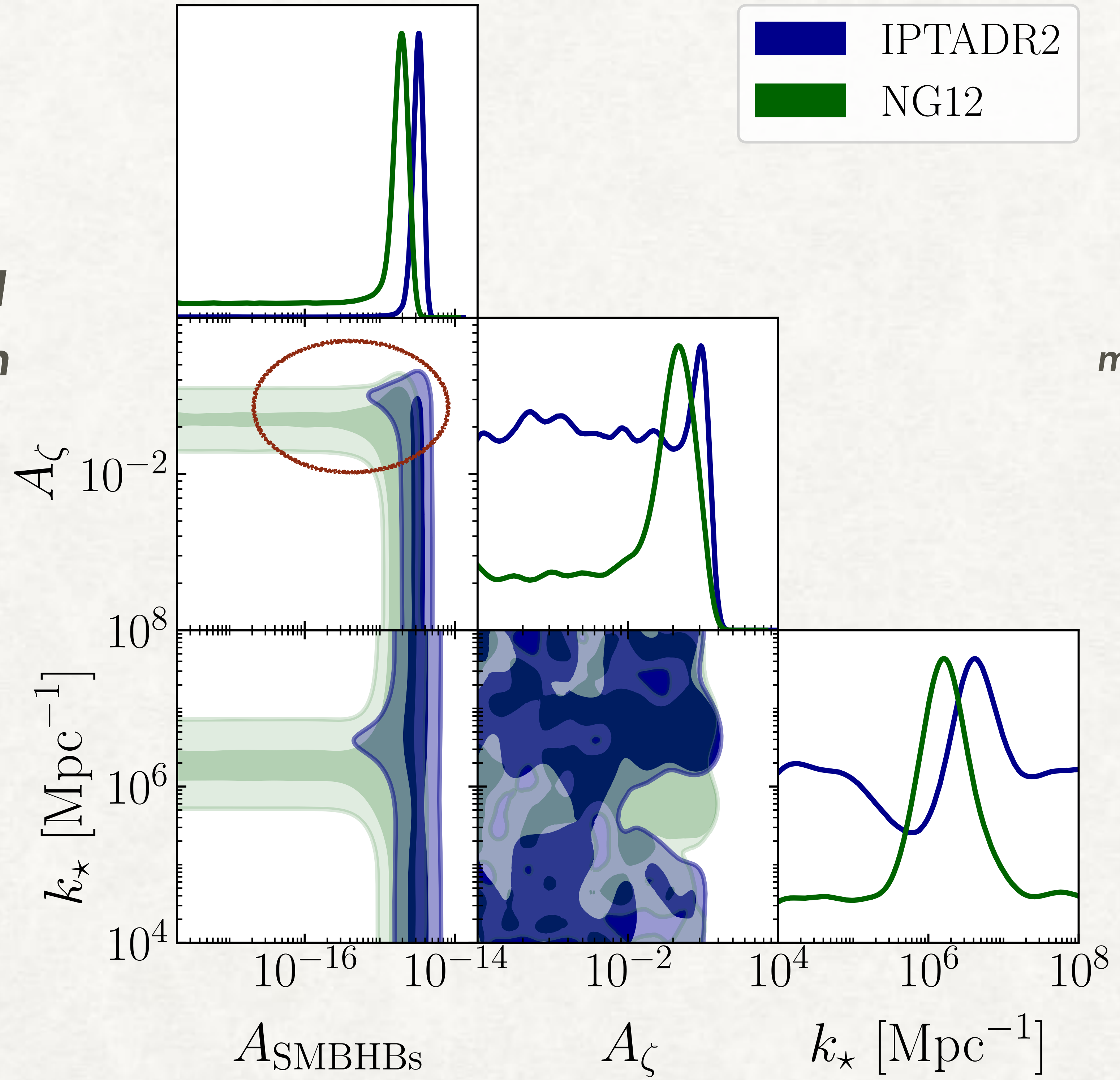

SMBHBs signal modeled as power law with

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*Upper prior on PBH overproduction severely constrains interpretation of **IPTA DR2**!*

DETECTION ANALYSIS INCLUDING SMBHBS

$\Delta = 1$

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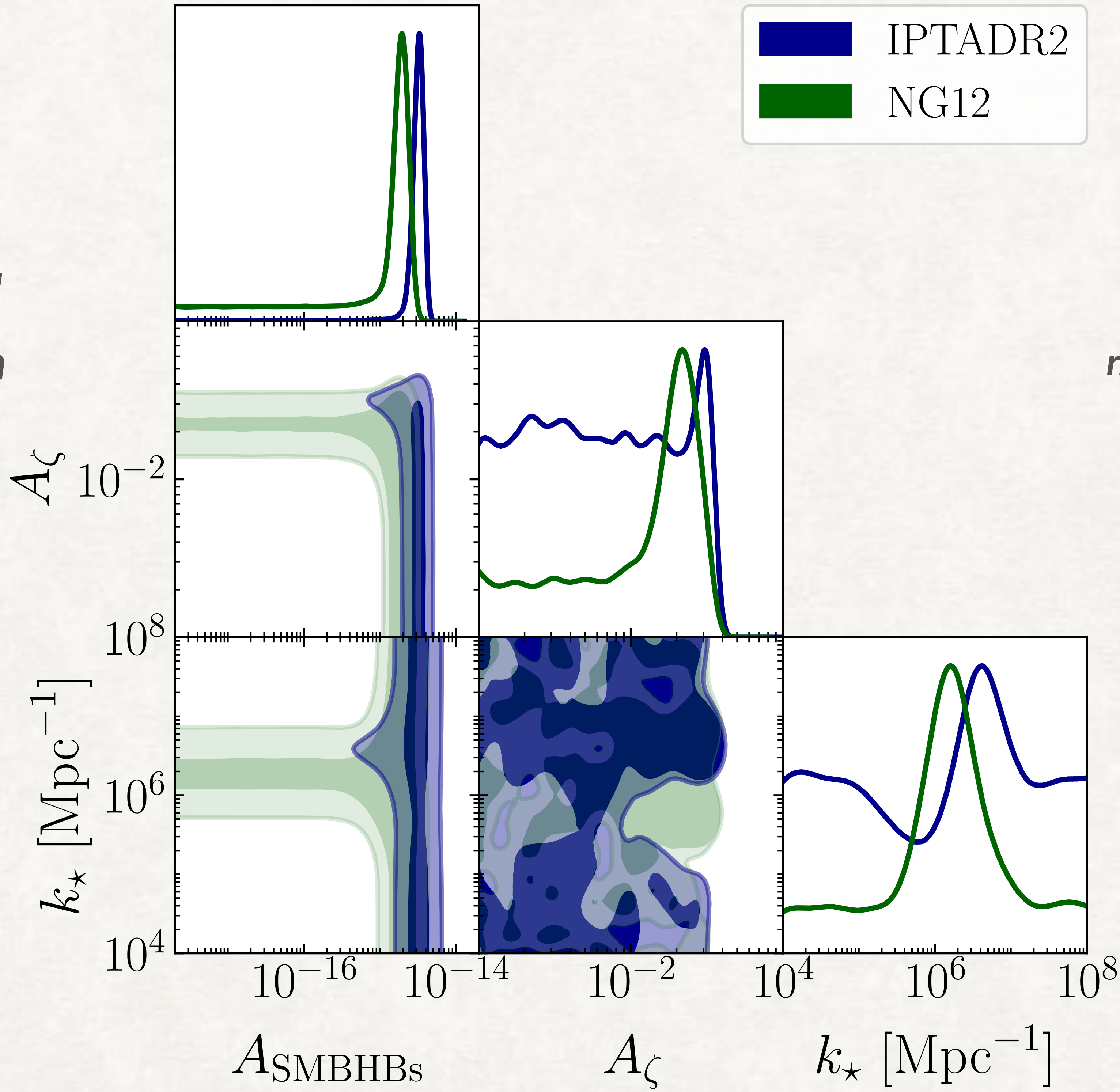


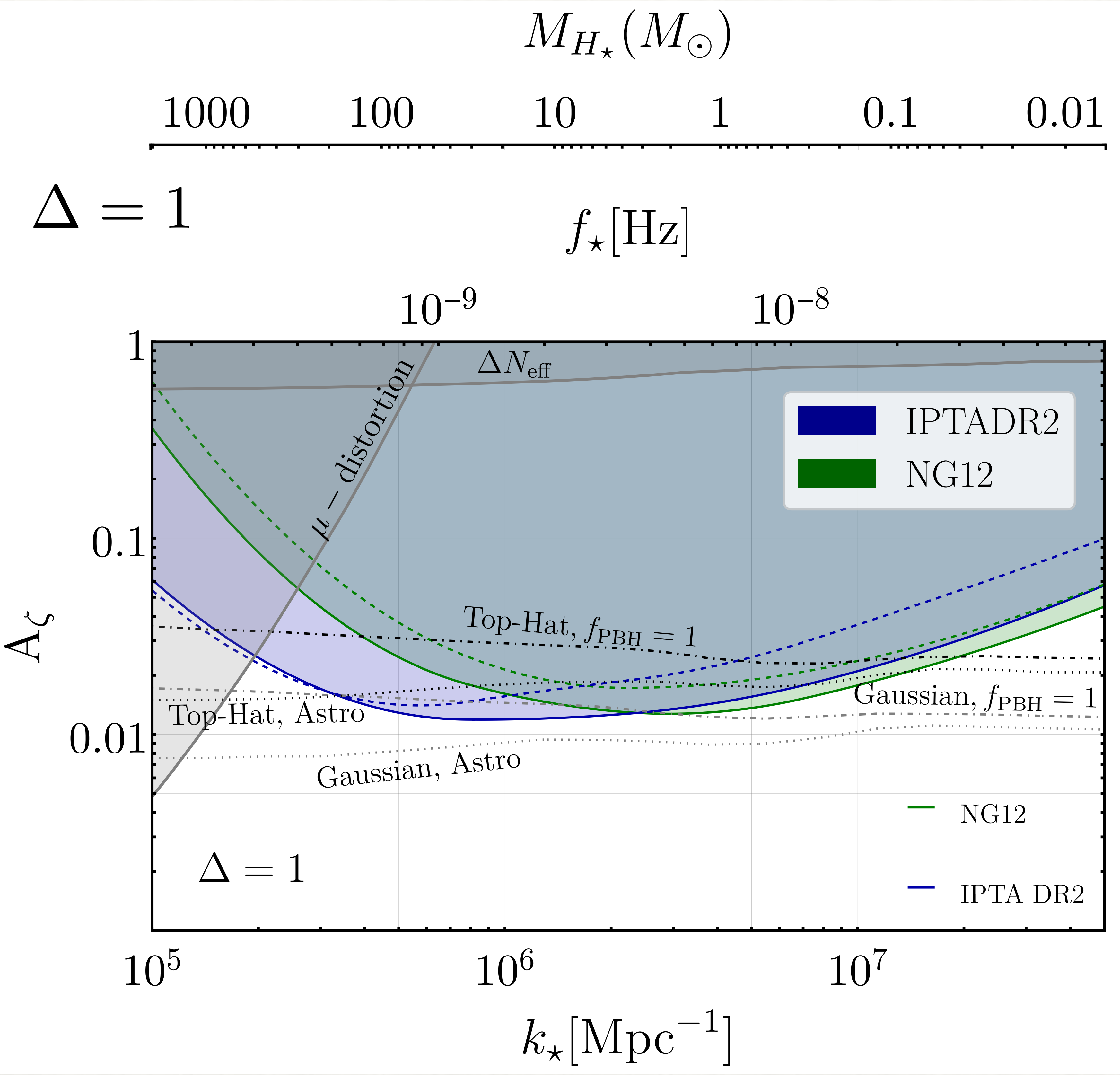
SMBHBs signal modeled as power law with

$\gamma = 13/3$

$$\mathcal{B}(\mathrm{SMBHB\ vs\ SIGW}) \simeq 10^2$$

CONSTRAINT ANALYSIS

*Other constraints shown only for comparison, **ours are independent!***



Here we include a signal from SMBHBs (different strategy from NG15)

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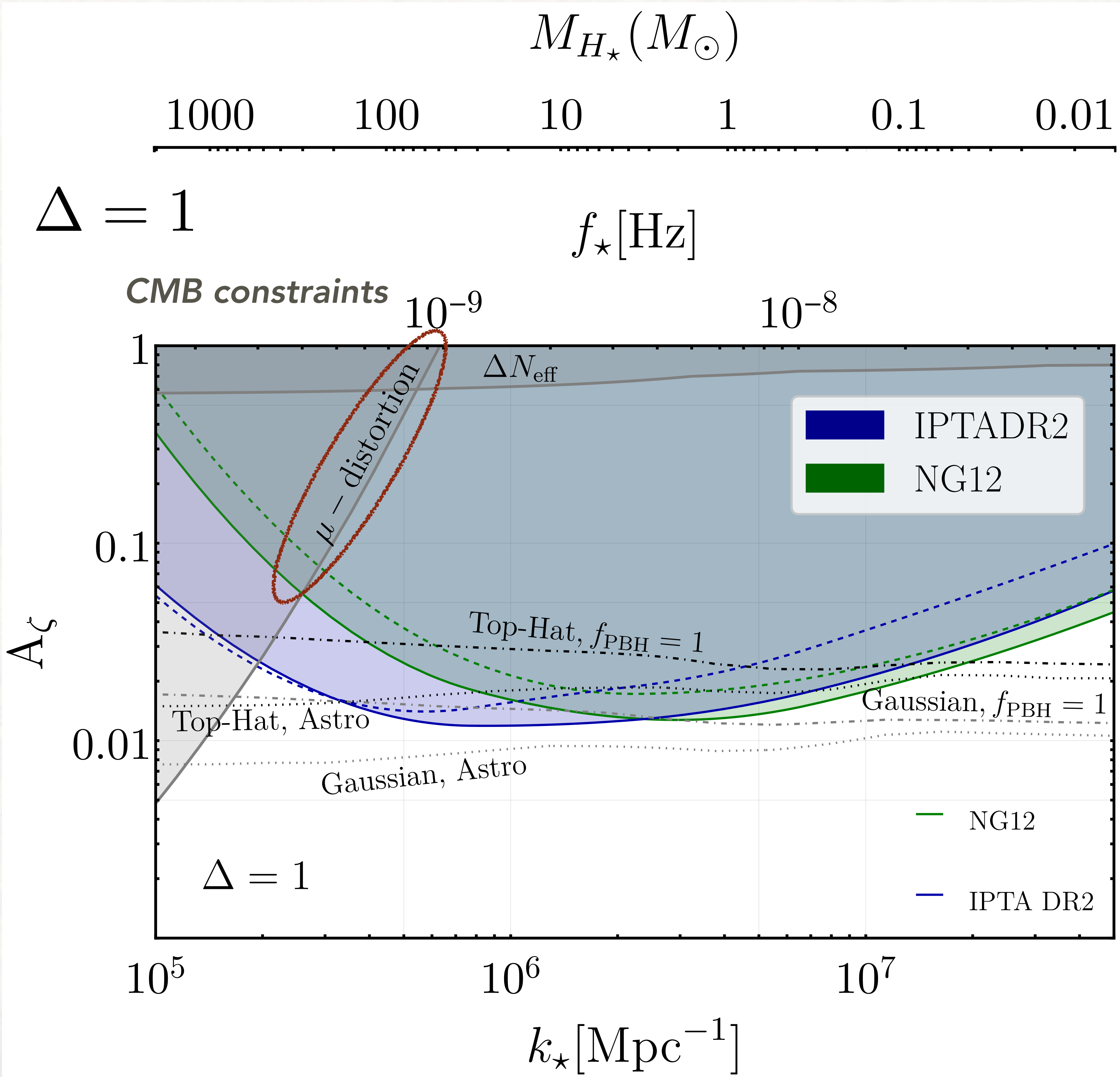

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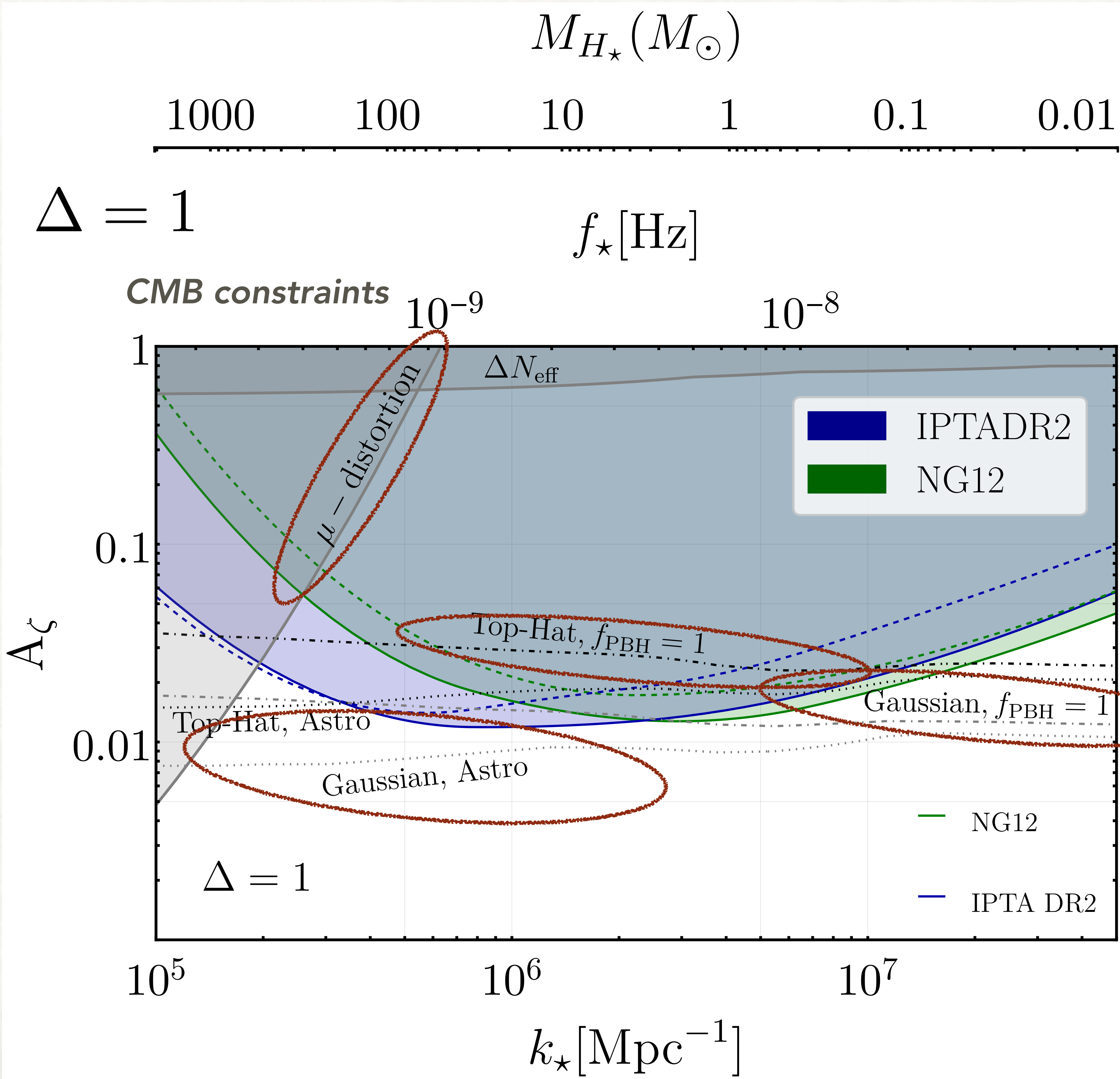

Constraints from PBHs

See talk by Valerie!

Stronger constraints for smaller widths

DIRECTIONS/OPPORTUNITIES FOR PARTICLE PHYSICS/COSMOLOGY @ PTAS

R.Z. Ferreira, A. Notari, O. Pujolàs, FR *2204.04228*

Motivated models for signal interpretation

Cosmic Domain Walls

CHALLENGE OF EARLY UNIVERSE INTERPRETATION FROM TRANSIENT SOURCES

$t_\star \equiv$ *Time/length scale of the source*

$t_\star^{-1}$

$$\Omega_{\rm gw} h^2 \simeq 10^{-8} \left(\frac{10.75}{g_*(T_\star)}\right)^{\frac{1}{3}} \left(\frac{\alpha_\star/(1+\alpha_\star)}{0.1}\right)^2 \epsilon\left(\frac{t_\star^{-1}}{H_\star}, \cdots\right) \mathcal{S}(f/f_\star)$$

$$\epsilon_\star \propto \left(\frac{H_\star}{t_\star^{-1}}\right)^p \leq 1$$

$$\epsilon_\star \lesssim 10^{-2}$$

See also talk by Eric!

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Suppression factor:
sub-Hubble time/length-scale of source + velocity + …

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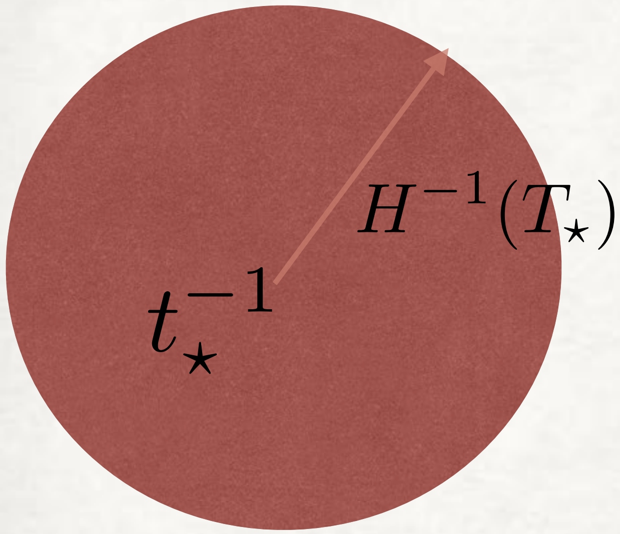

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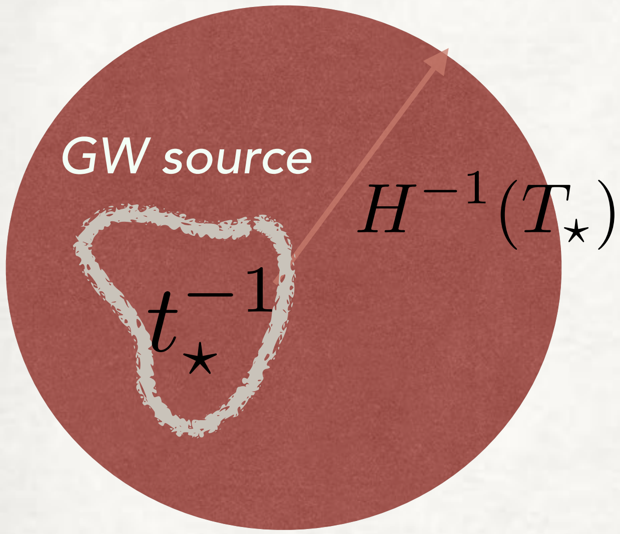

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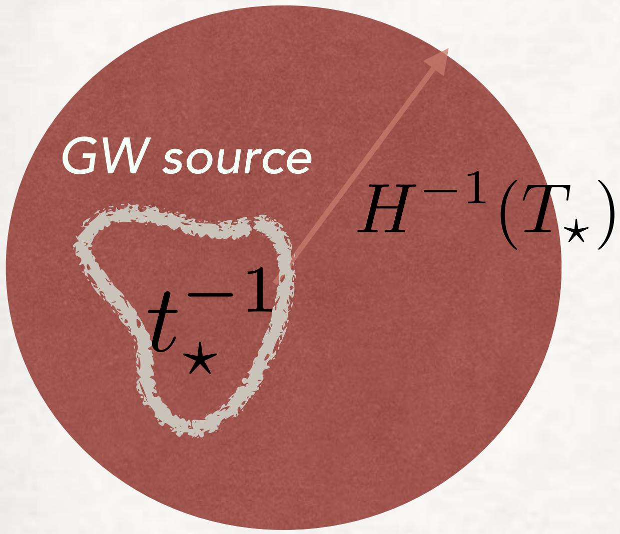

$t_\star \equiv$ *Time/length scale of the source*

How much of the Universe is in the source

Spectral shape

$$\Omega_{\rm gw} h^2 \simeq 10^{-8} \left(\frac{10.75}{g_*(T_\star)}\right)^{\frac{1}{3}} \left(\frac{\alpha_\star/(1+\alpha_\star)}{0.1}\right)^2 \epsilon(\frac{t_\star^{-1}}{H_\star}, \cdots) \mathcal{S}(f/f_\star)$$

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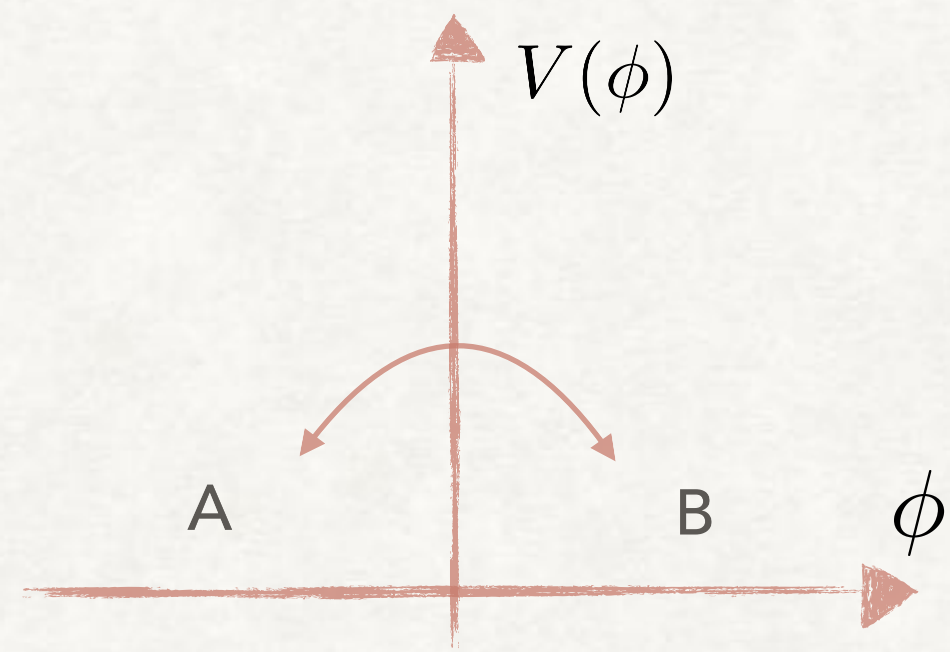
AN “ATTRACTIVE” POSSIBILITY: DOMAIN WALLS

Two-dimensional defects associated to
*(spontaneous) breaking of **discrete symmetries***



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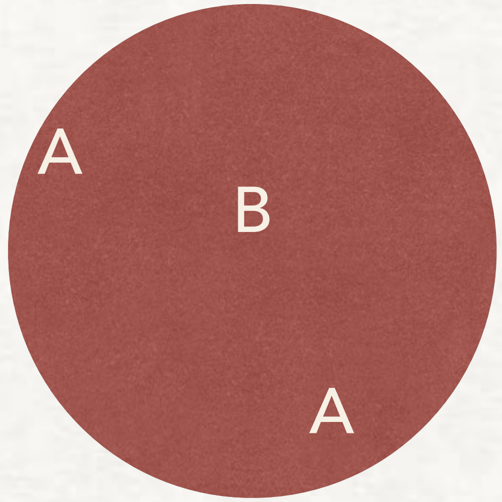

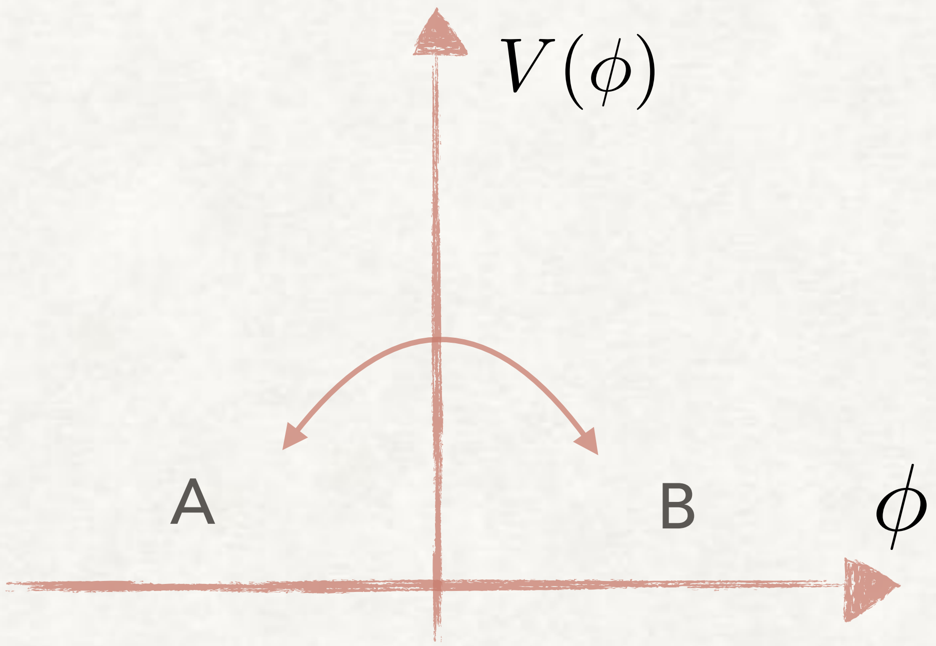

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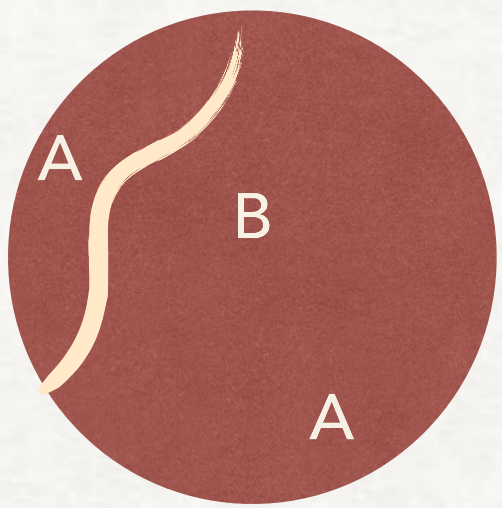

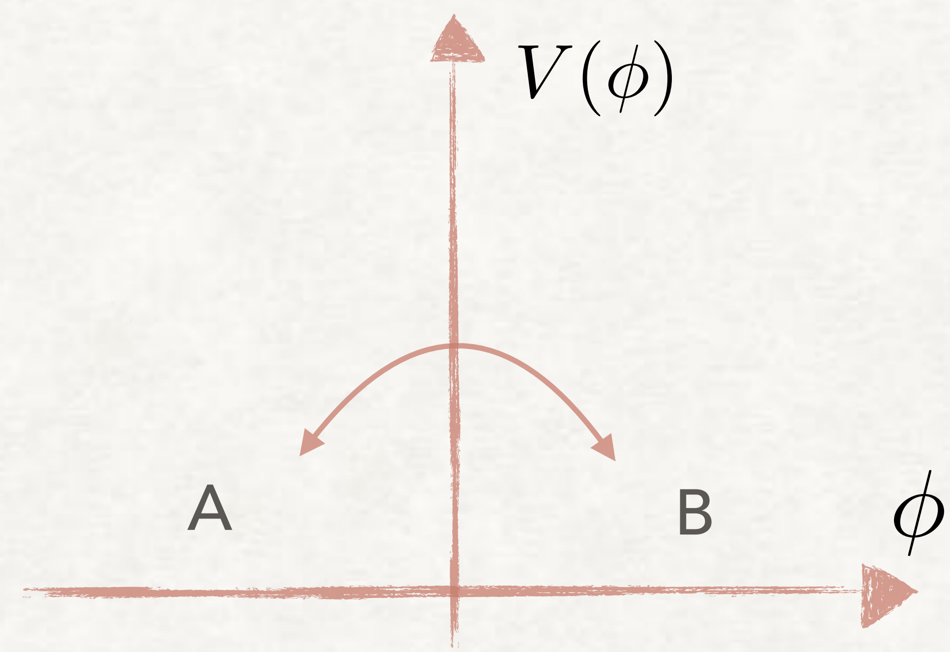

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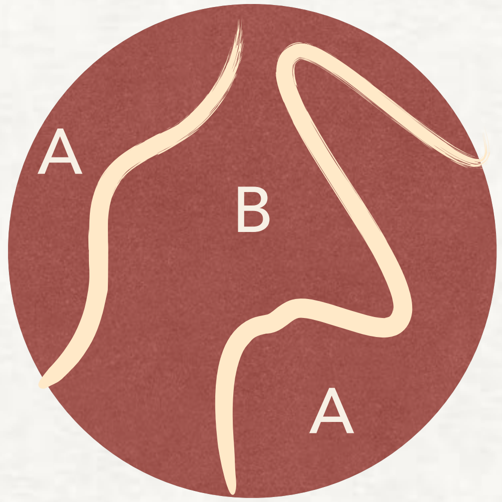

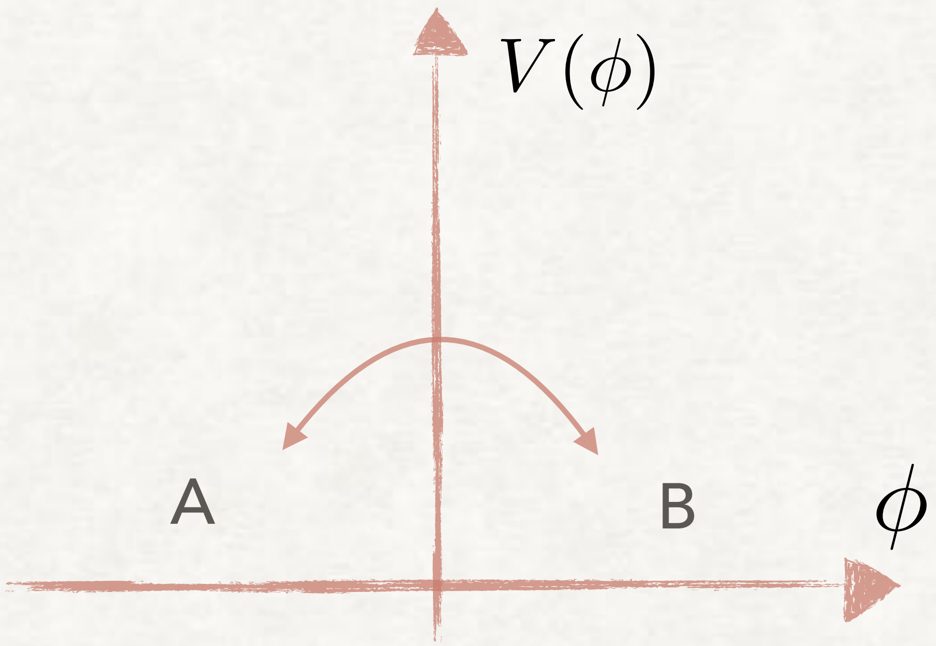

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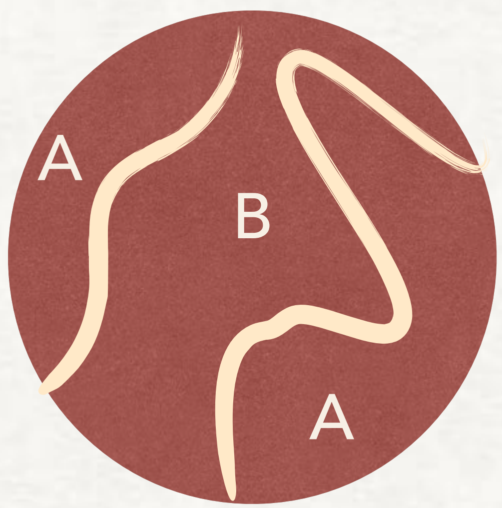

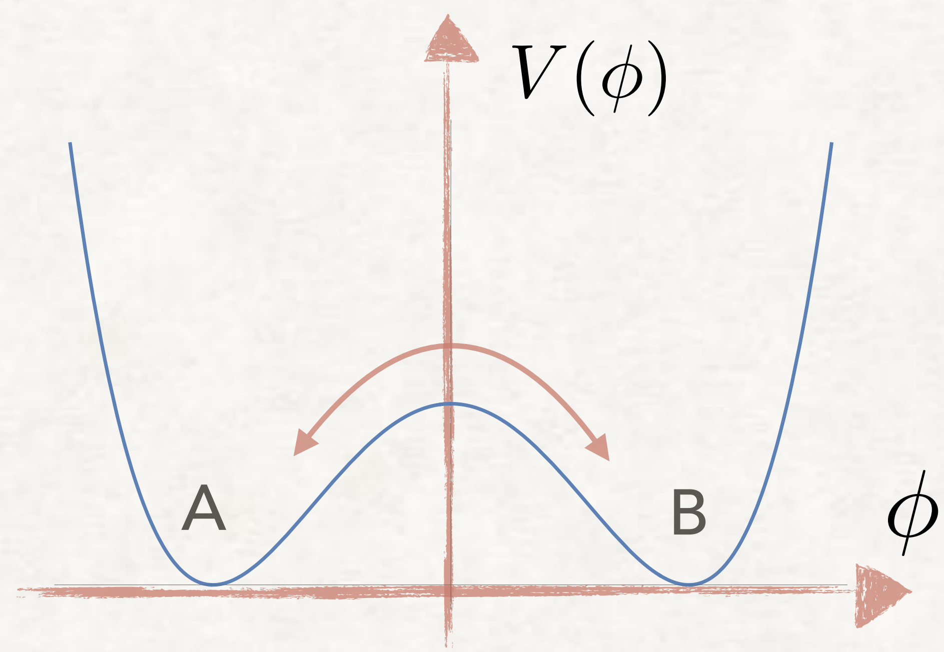

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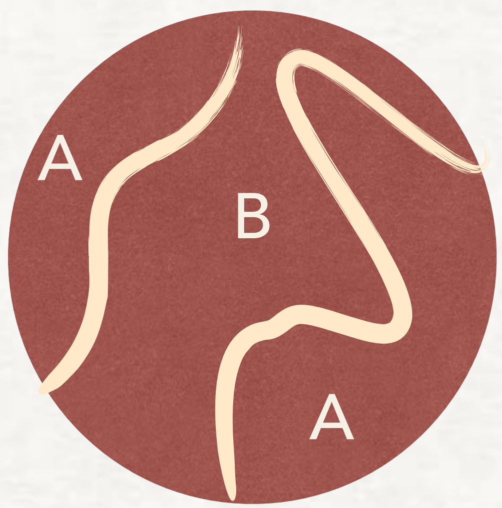
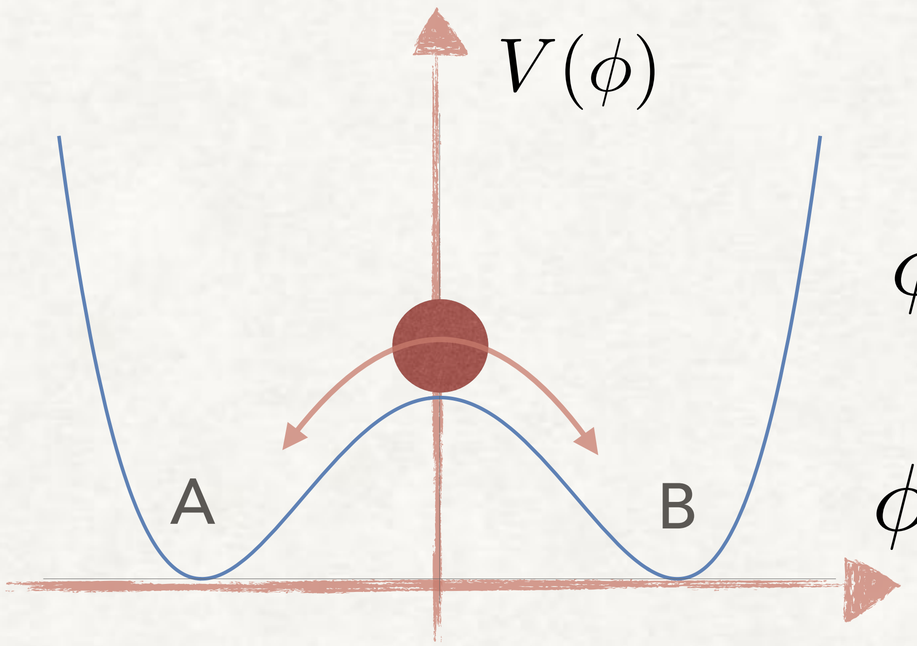




$\mathbb{Z}_2$

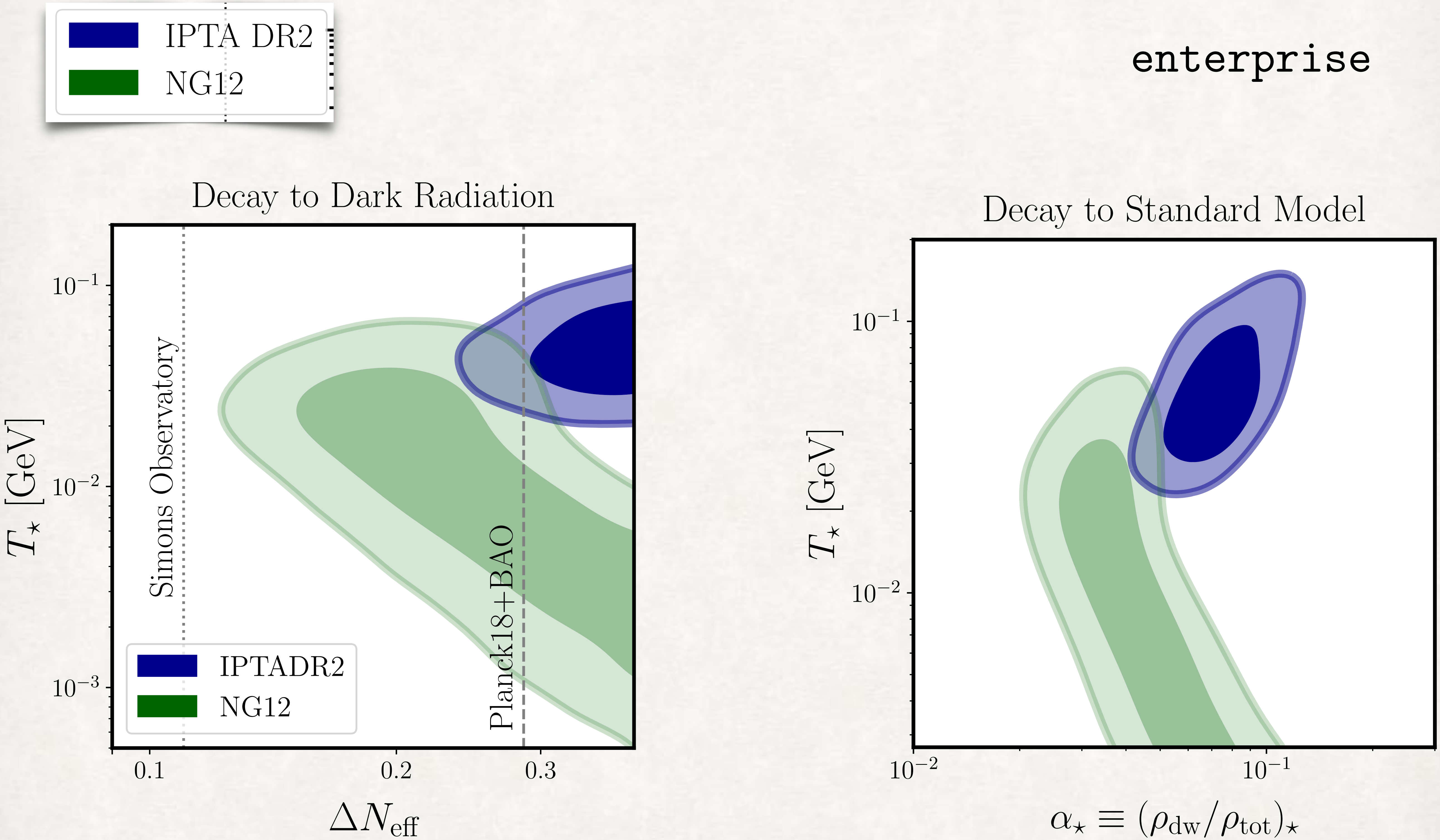
$\phi \to -\phi$

Crucial advantage: Scaling Regime

Wall network is dominated by fixed number (~1-few) of ***Hubble-sized*** *wall*

DOMAIN WALLS IN PTA DATASETS (2022)

enterprise



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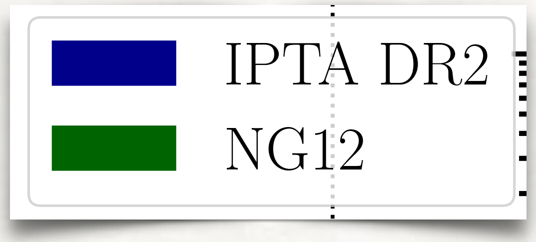

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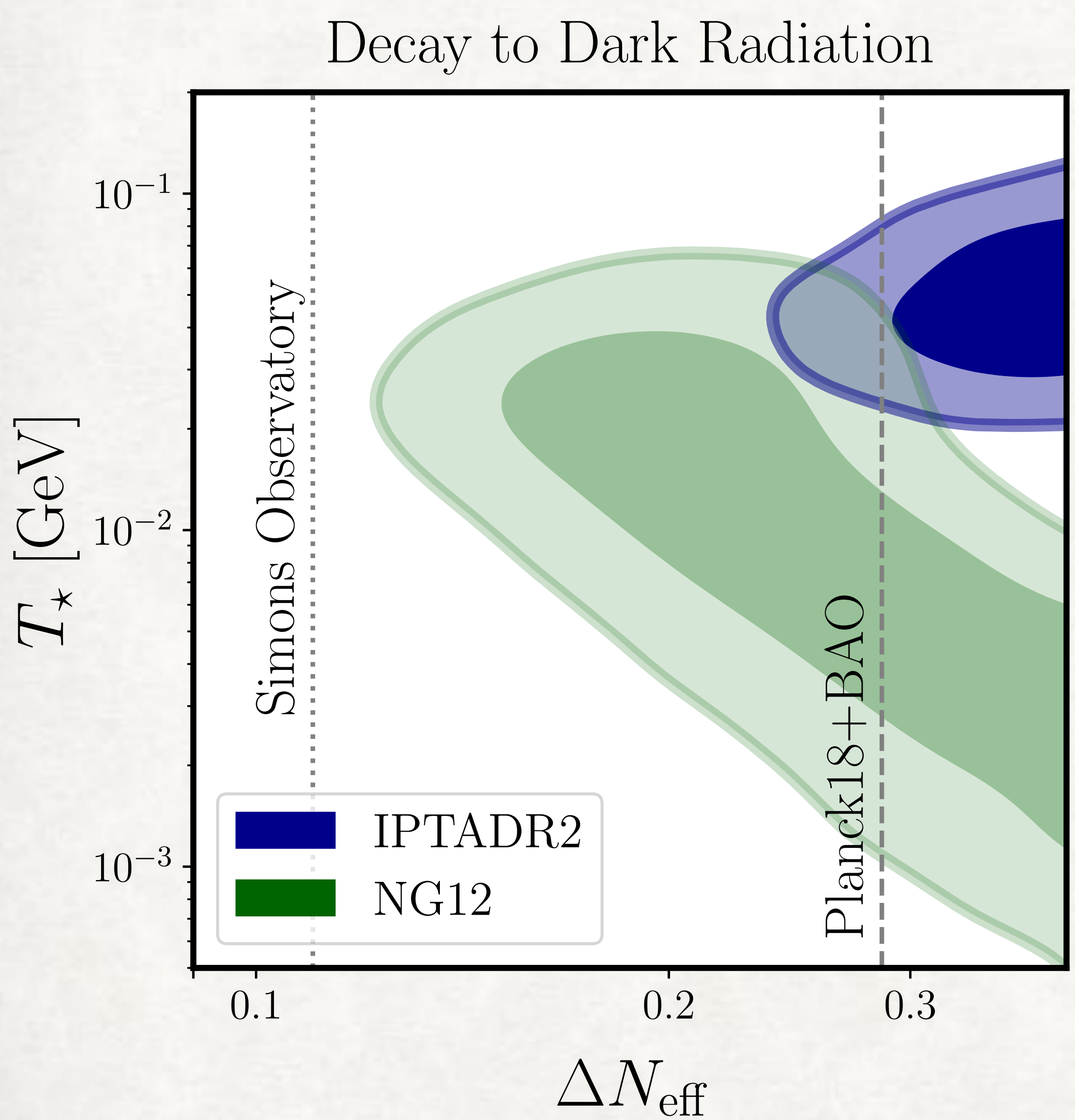
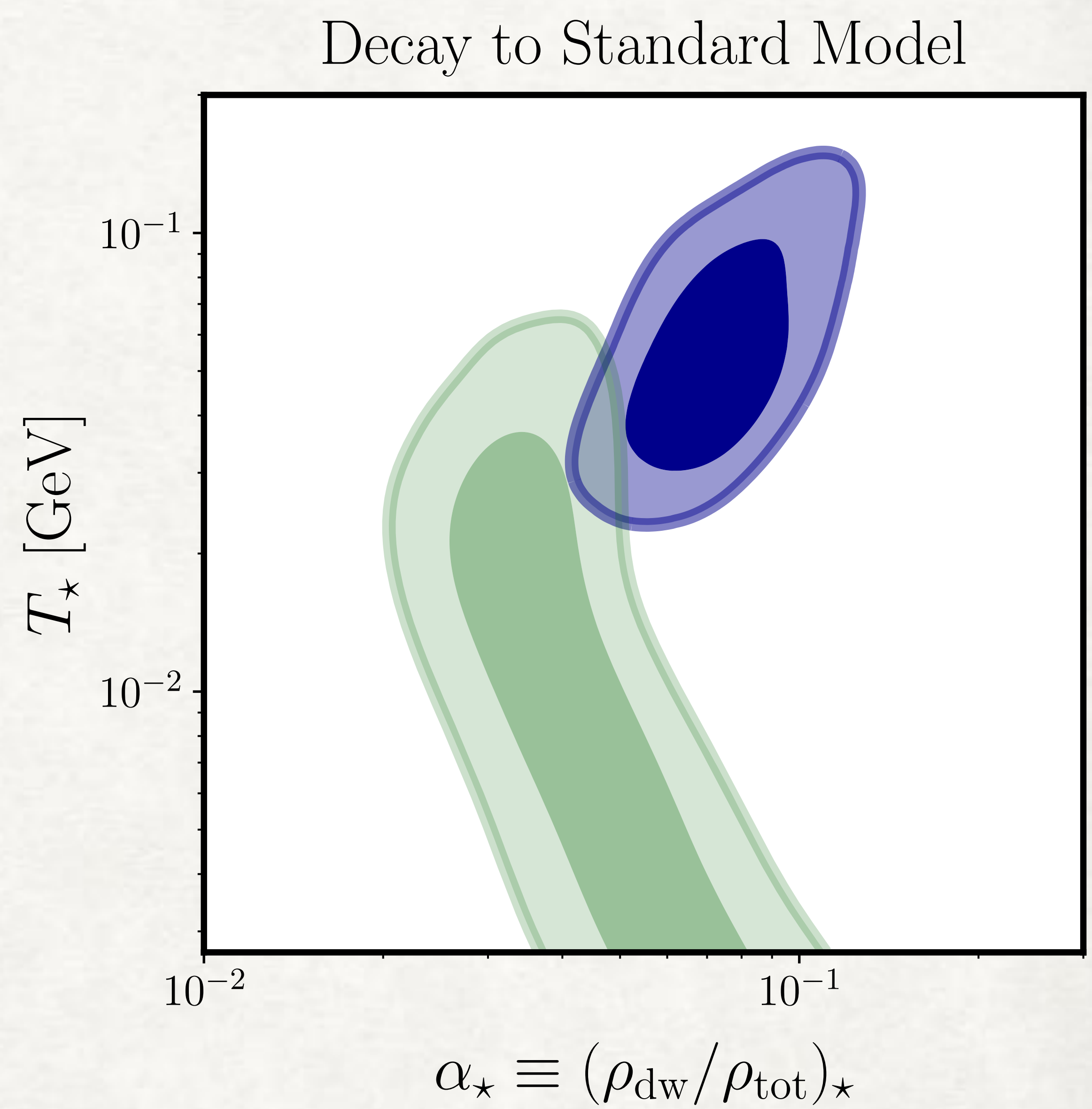
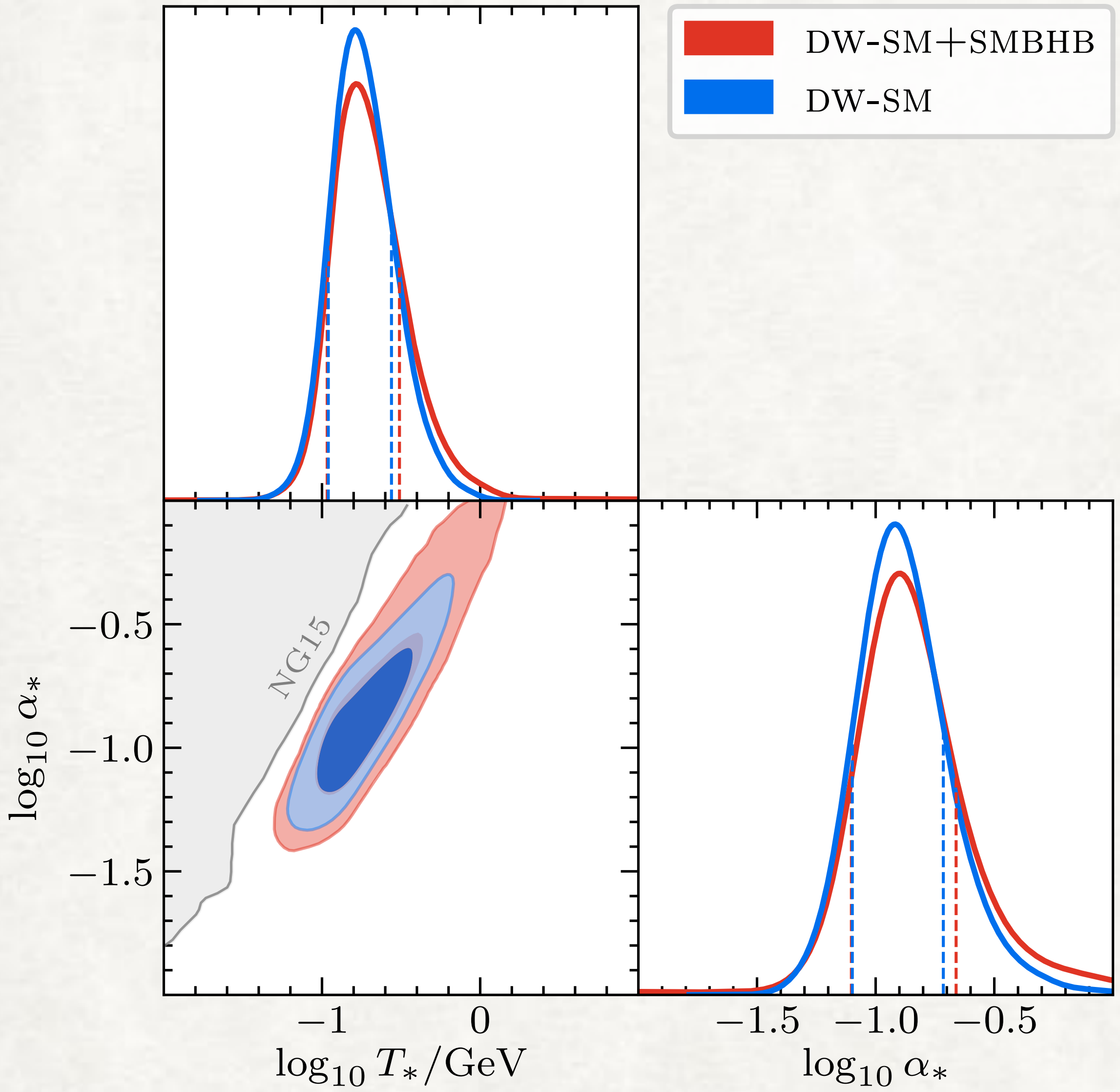
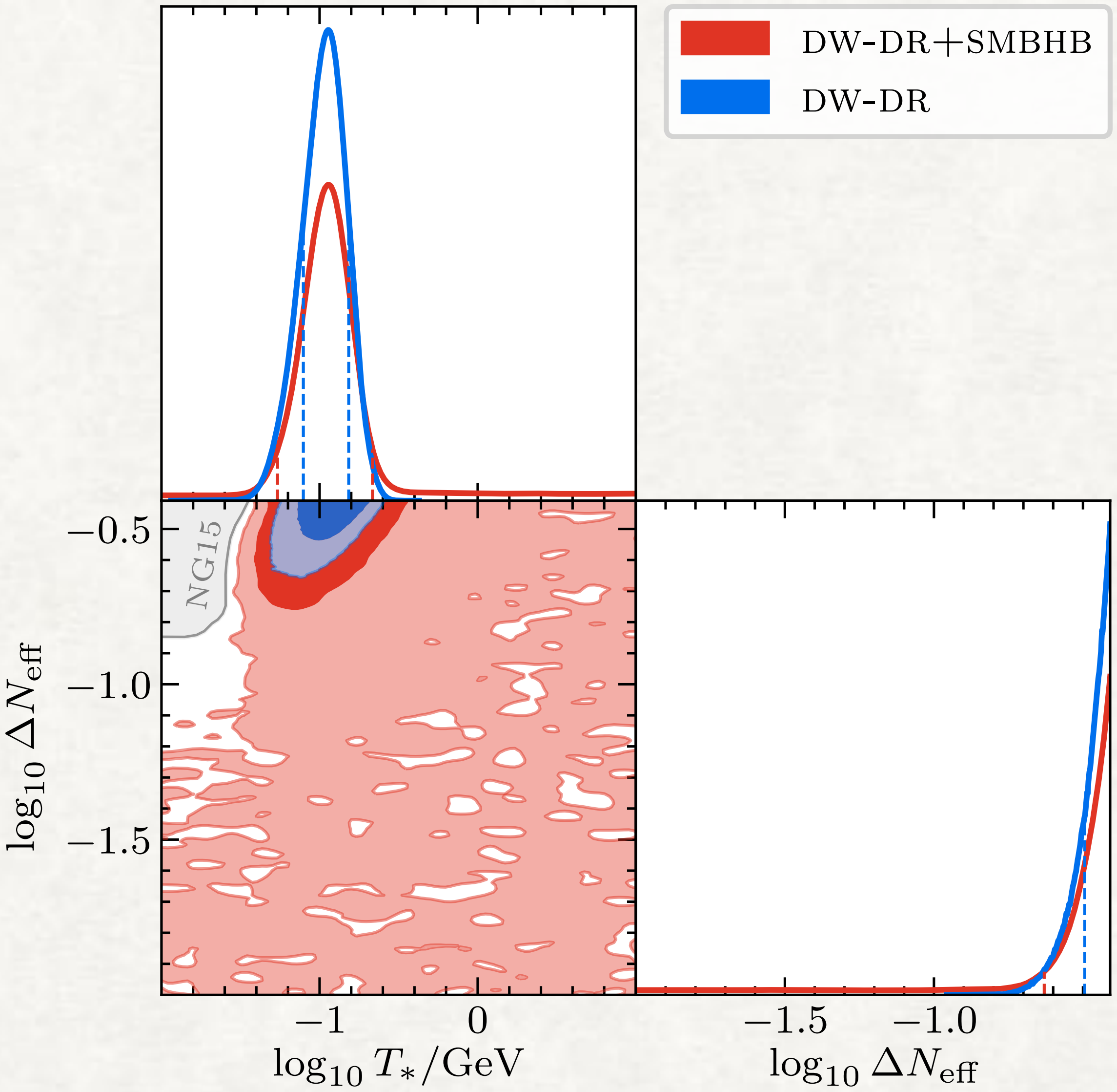




Prior from BBN included, CMB severely constrains "dark" scenario

DOMAIN WALLS IN NANOGRAV 15 (2023)





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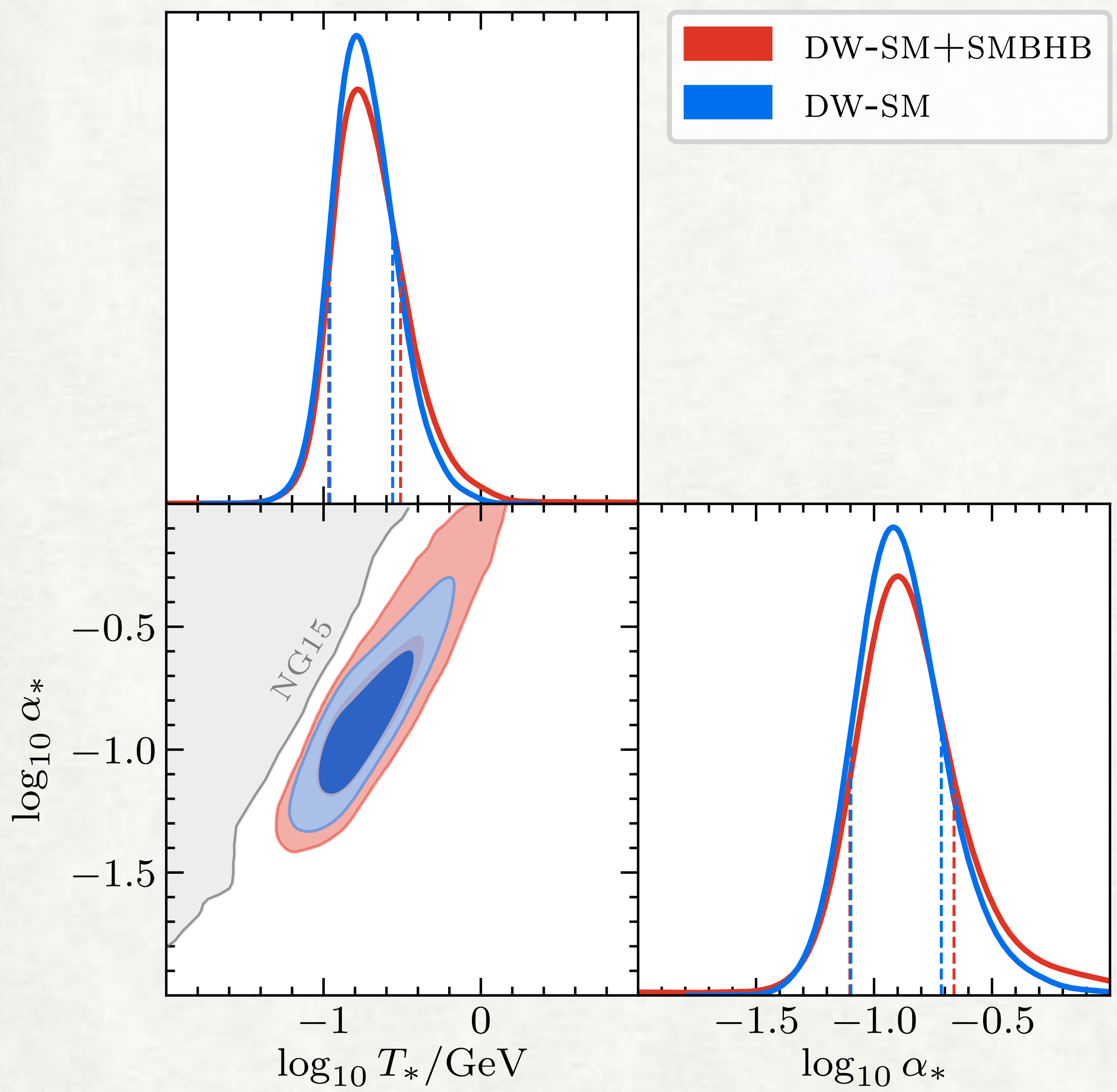
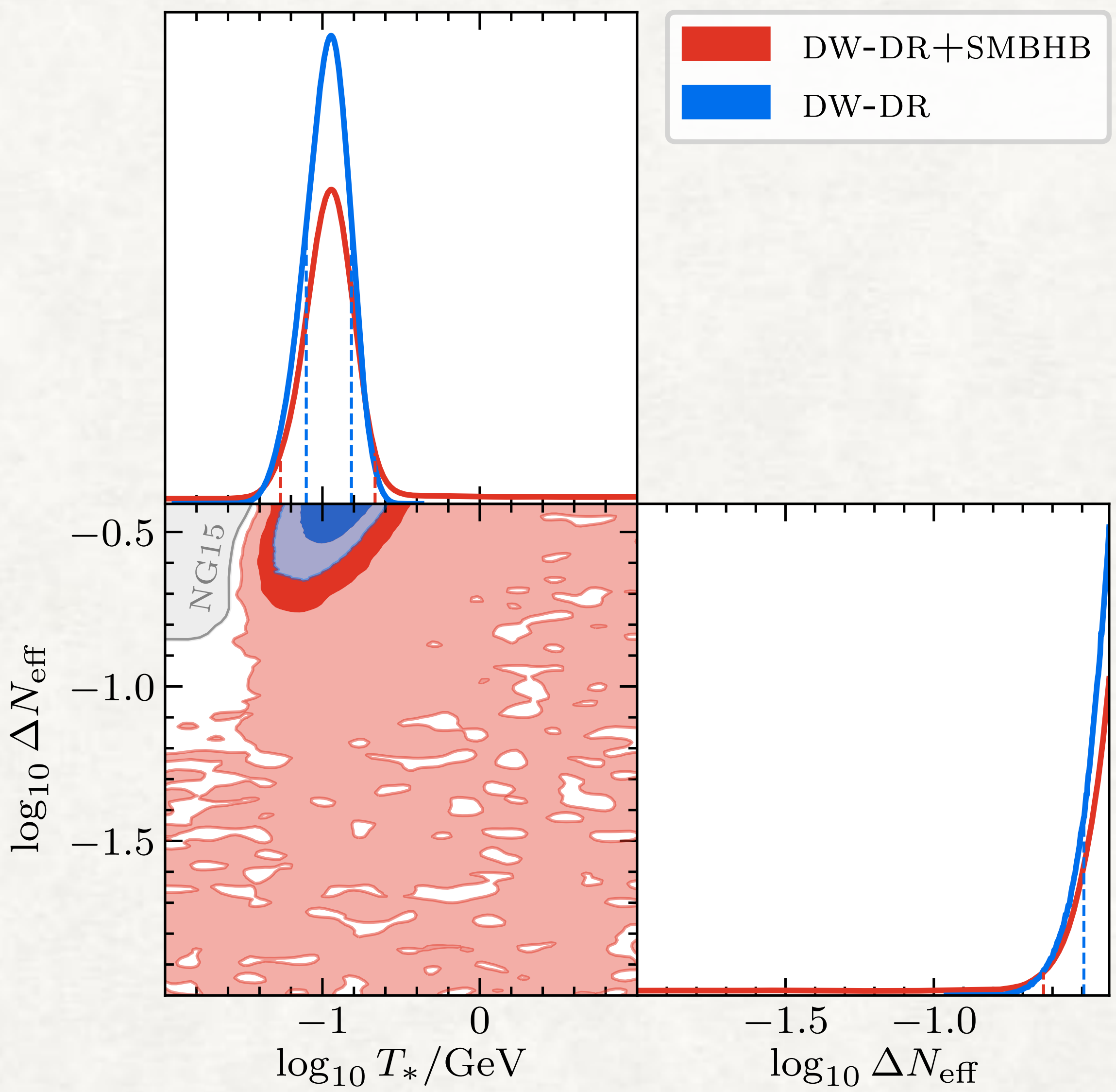


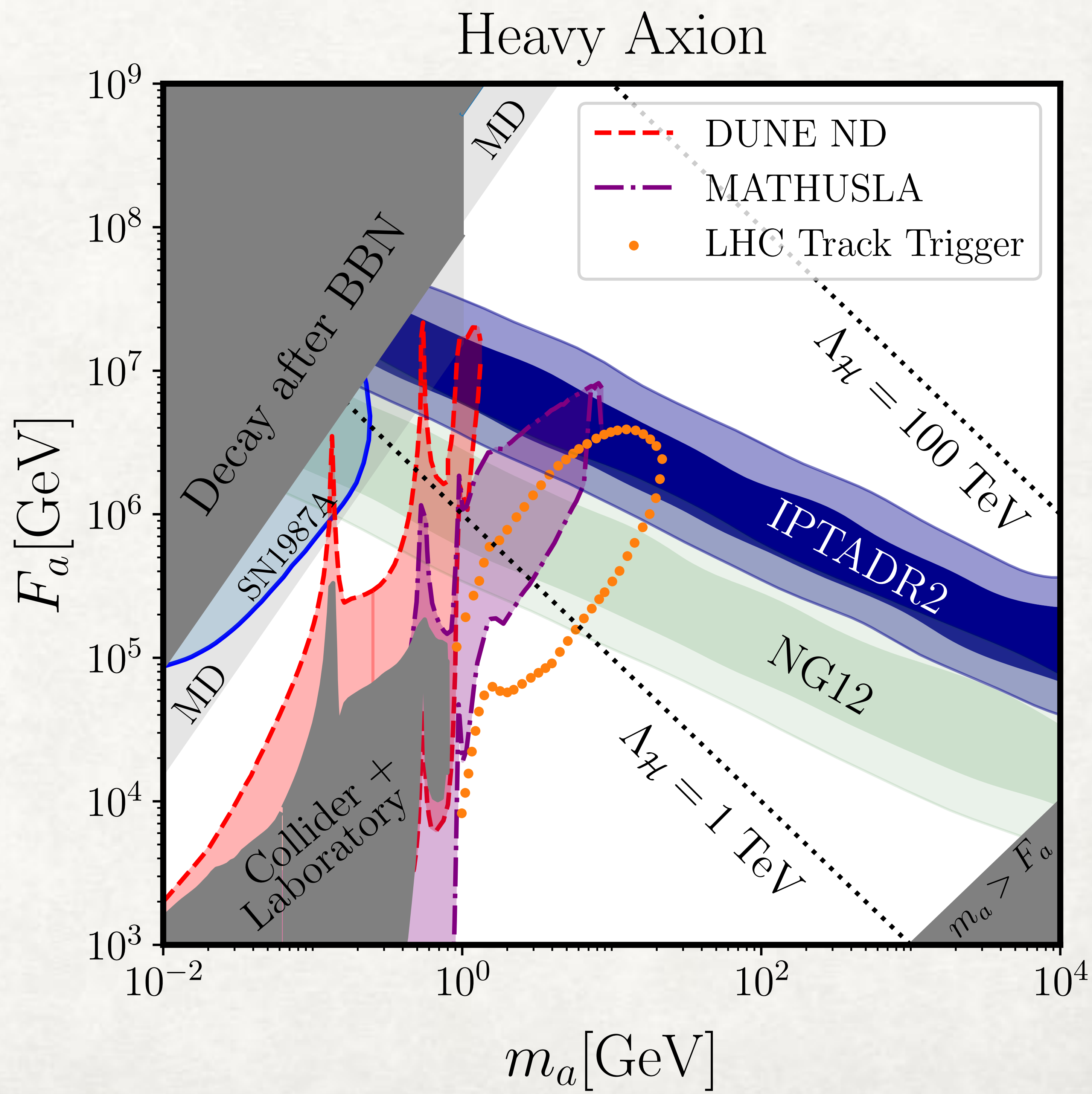


Similar to IPTA DR2 results

AN INTERESTING SCENARIO WITH COMPLEMENTARY PROBES

$$U(1) \to \mathbb{Z}_{N_{\rm dw}} \to I$$

$$\Lambda_{\mathcal{H}} \gg \Lambda_{\rm QCD}$$



AN INTERESTING SCENARIO WITH COMPLEMENTARY PROBES

$$U(1) \to \mathbb{Z}_{N_{\mathrm{dw}}} \to I$$

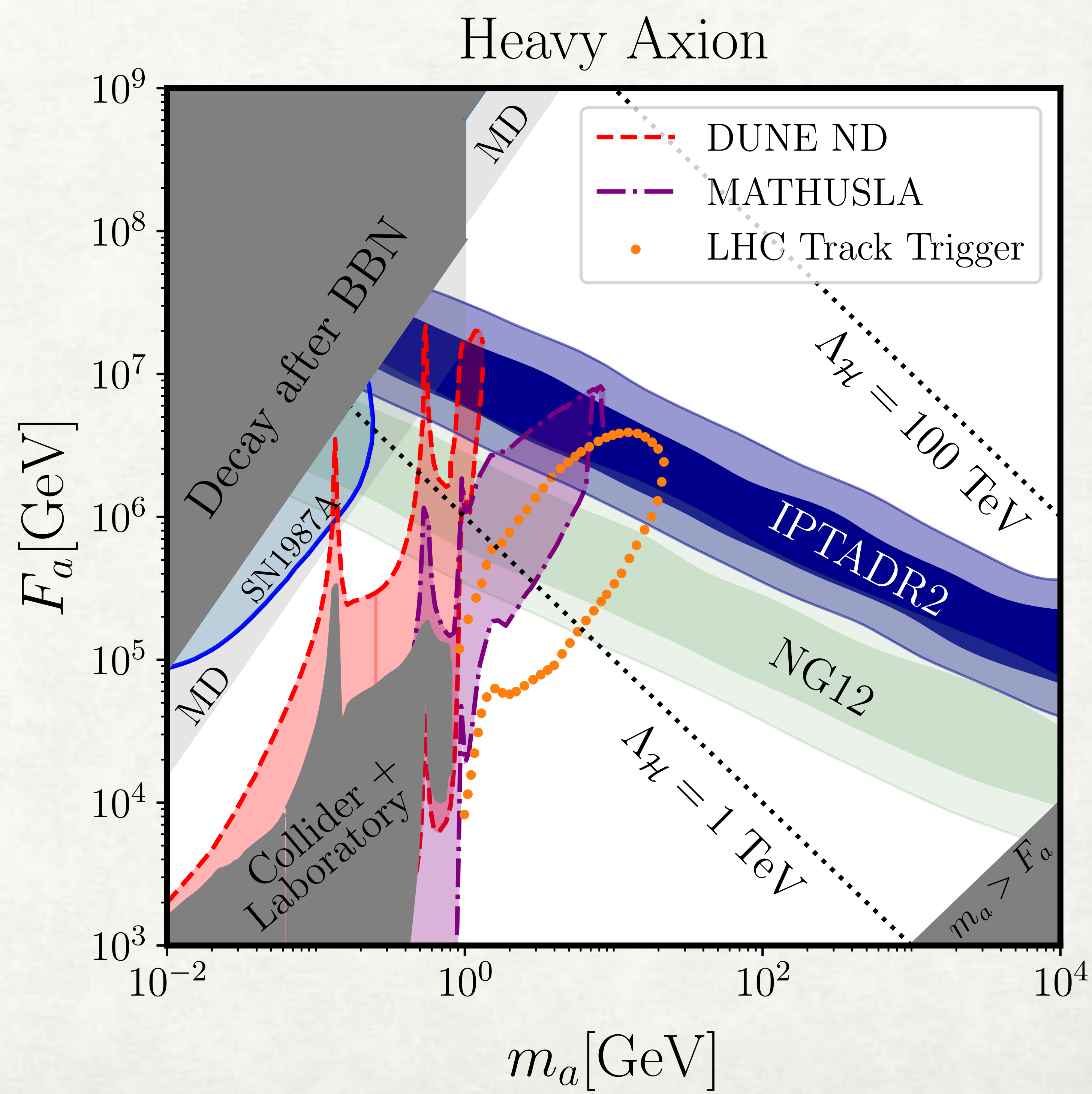
Analogous to QCD axion

But different confinement scale

$$\Lambda_{\mathcal{H}} \gg \Lambda_{\mathrm{QCD}}$$

If also coupled to QCD, complementary signatures at colliders! (& possibly inducing annihilation?)

***See also:** Higaki+ 16/ Blasi, Mariotti, Rase, Sevrin/Kitajima+/…*



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Low-frequency tail in the PTA band is distinctively affected by Standard Model physics.

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Interesting scenario for interpretation

Cosmic Domain Walls interesting because of scaling, complementary signals at lab/colliders for axion models