4 March 2024

LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTE

Results and Perspectives in Particle Physics

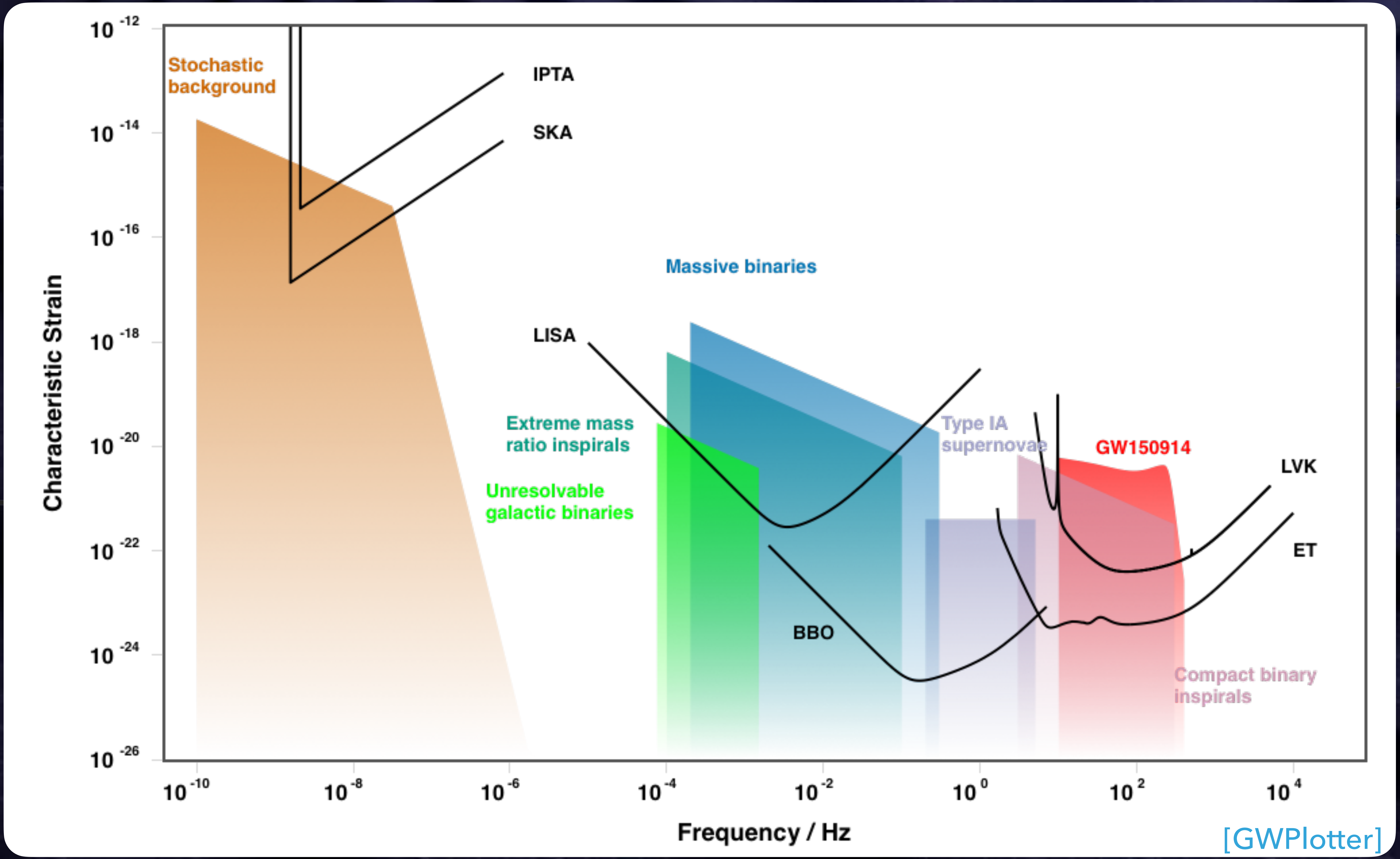
GW Signals From Primordial Phase Transitions

Davide Racco

ETH zürich

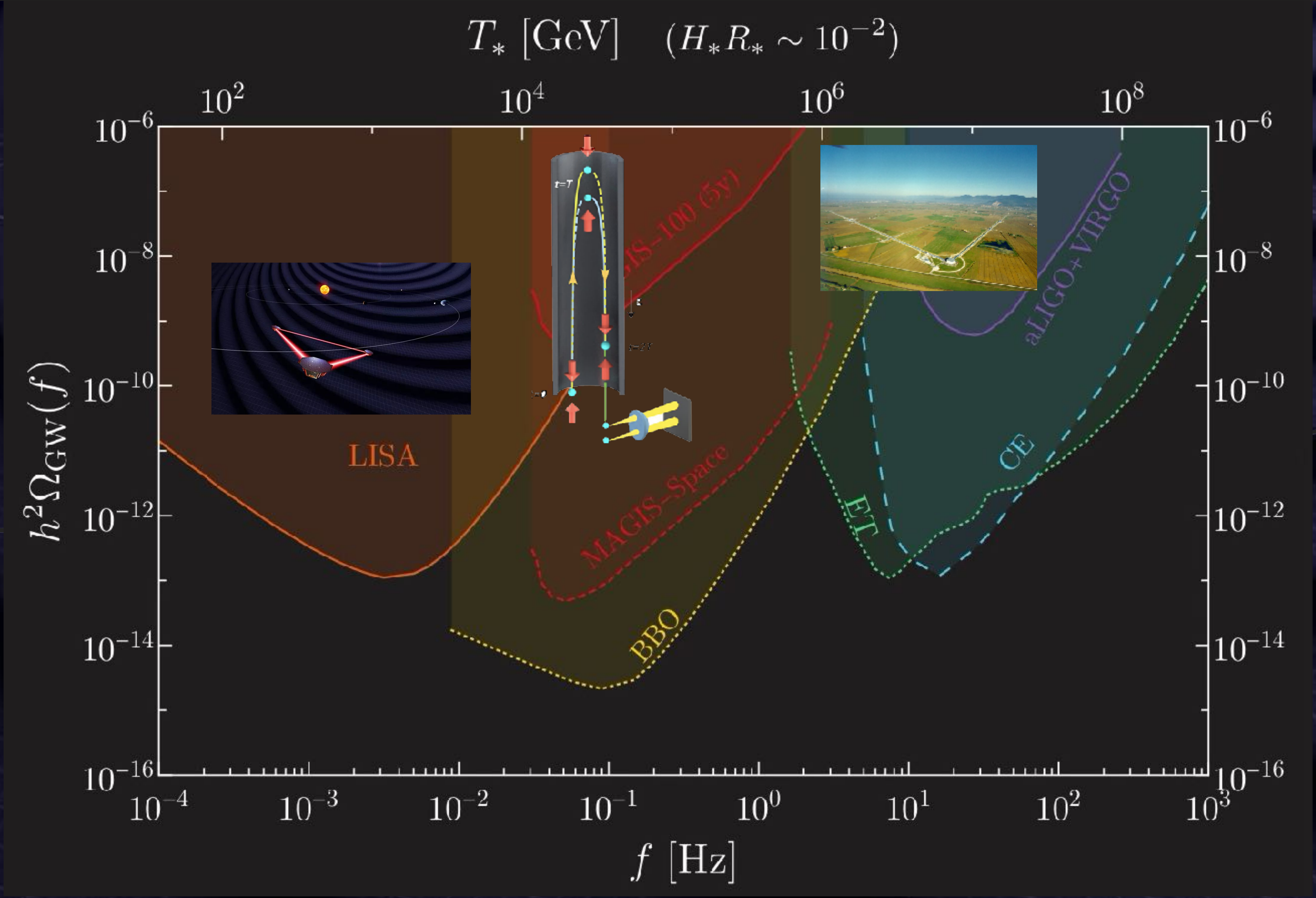
Universität Zürich UZH

GRAVITATIONAL WAVE ASTRONOMY ERA



[GWPlotter]

SEARCH FOR PRIMORDIAL GW BACKGROUNDS



- GWs from primordial source **local** in *space* and *time*
- Phase transitions, preheating, peak in $\mathscr{P}_\zeta$ …

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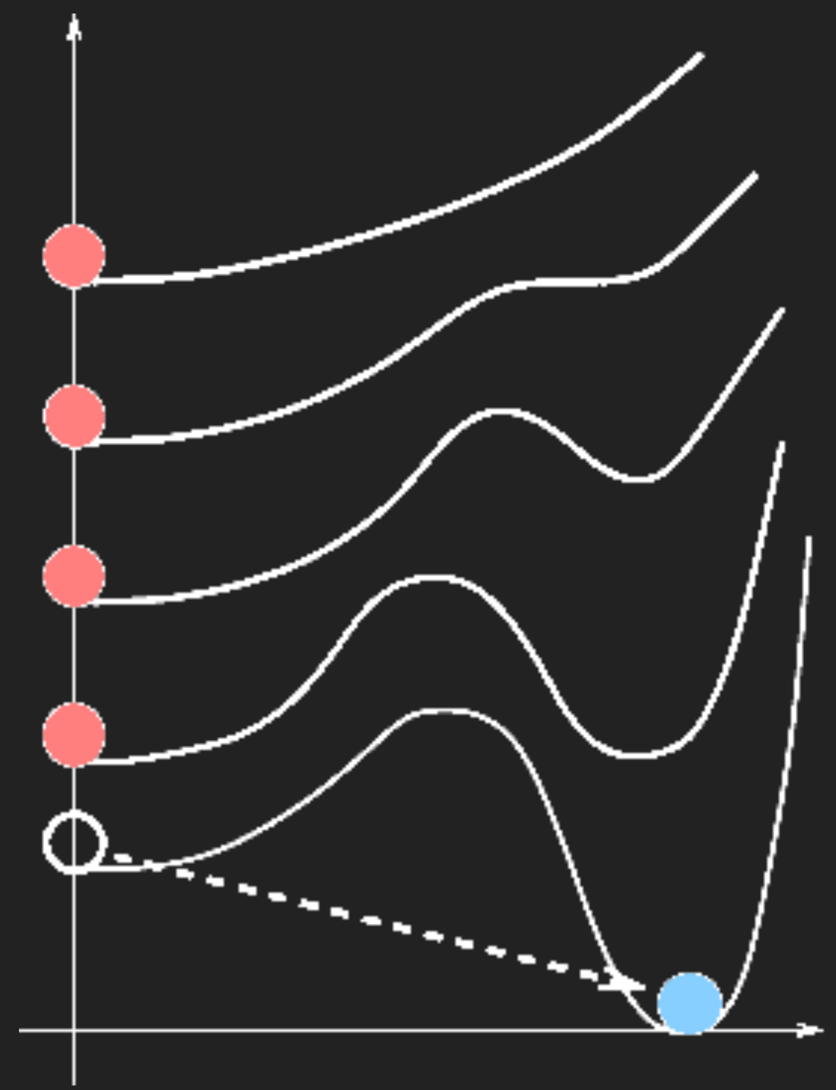
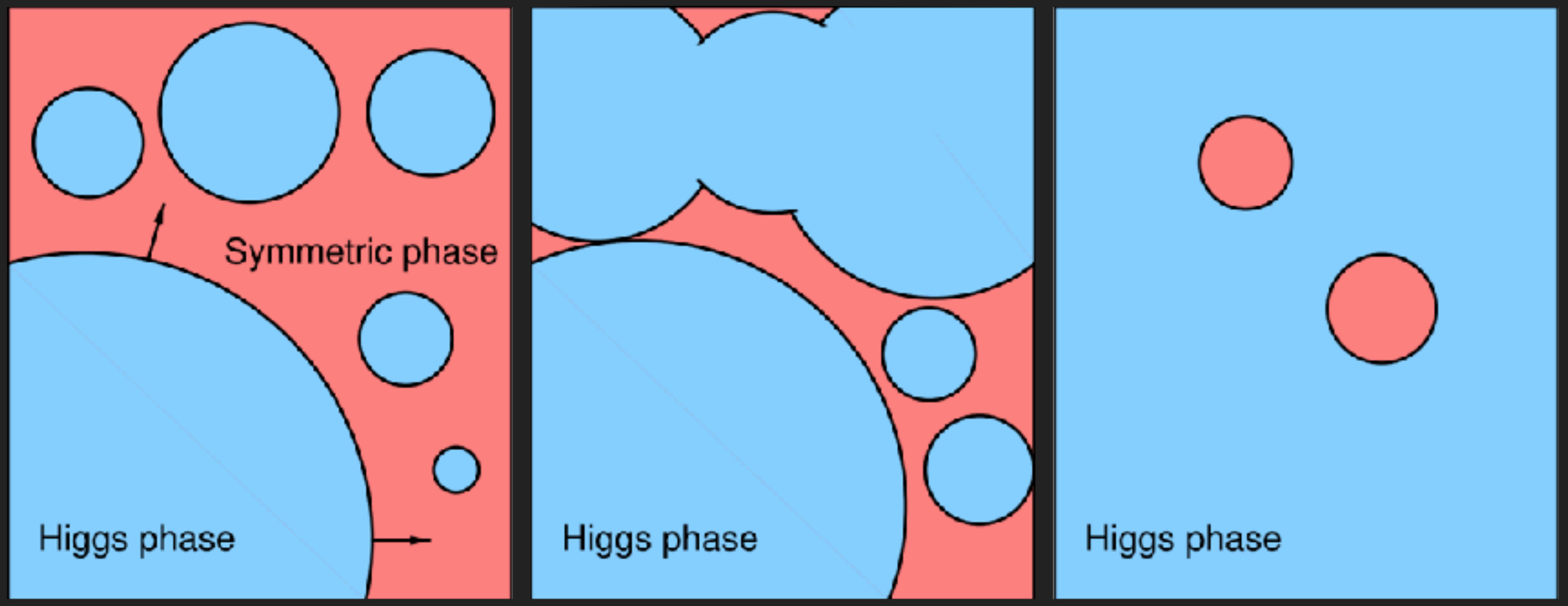
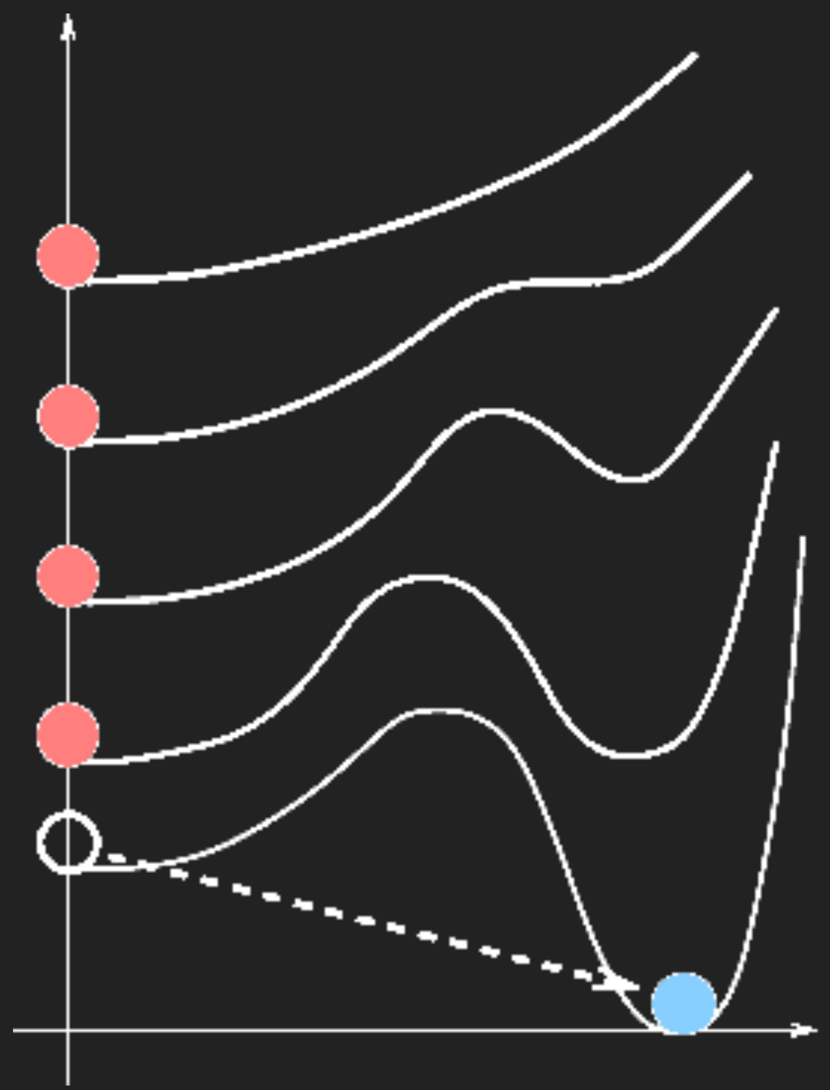
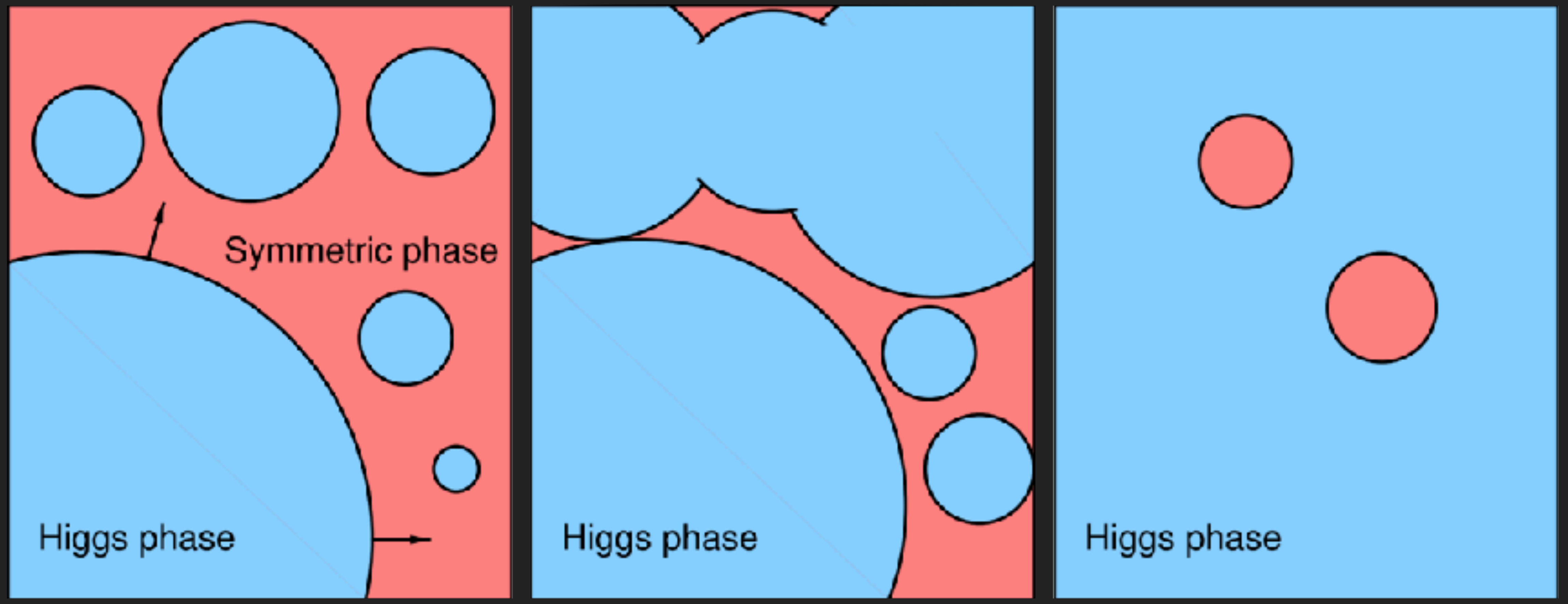


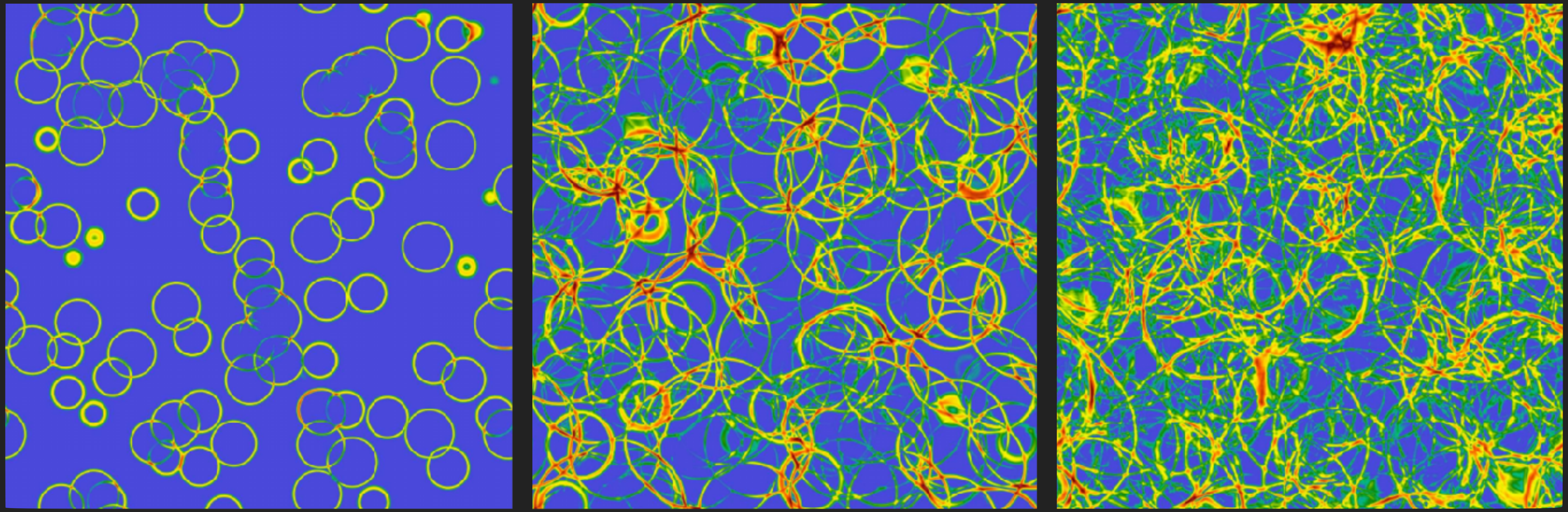


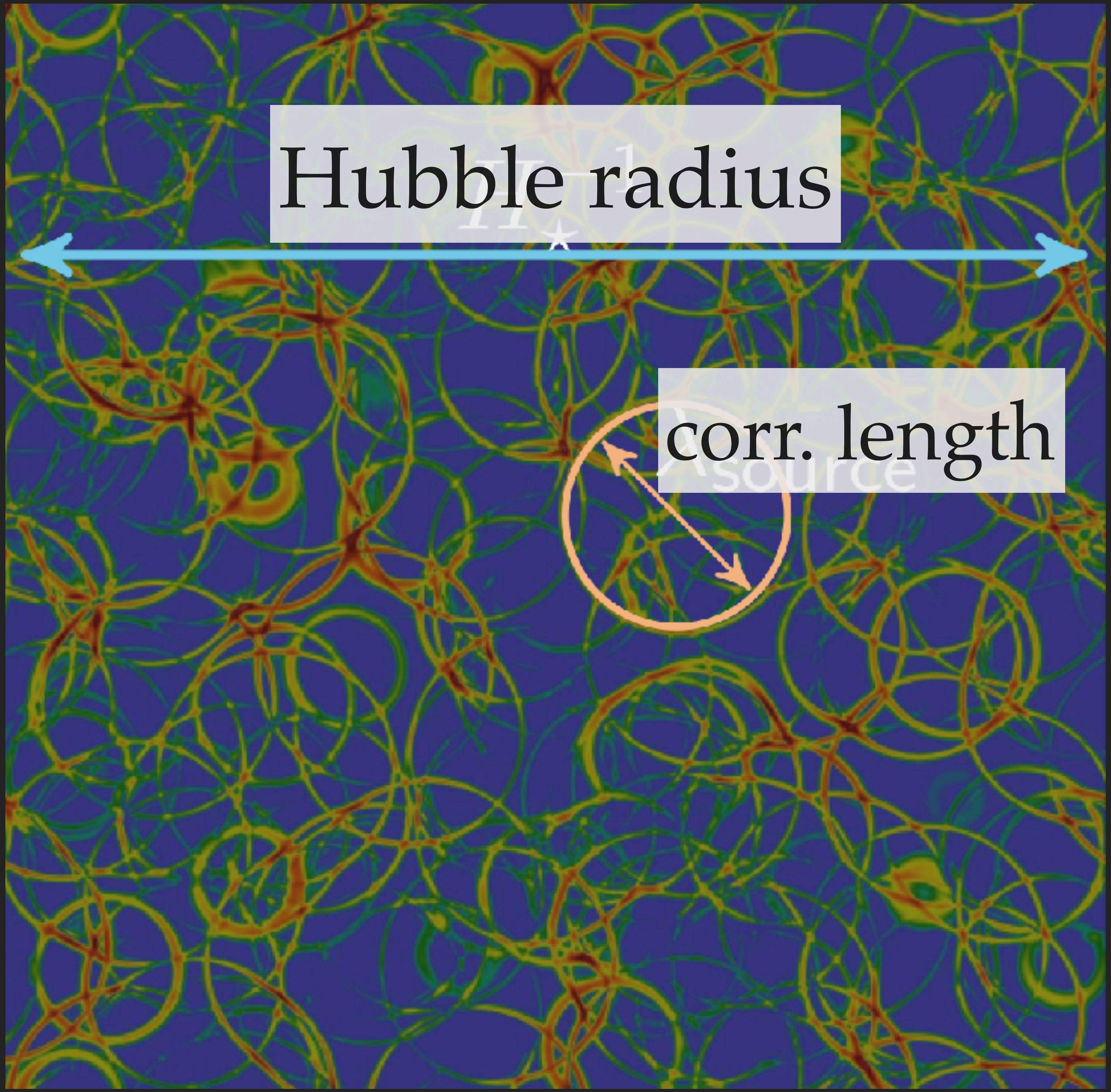
- GWs from primordial source **local** in *space* and *time*
- Phase transitions, preheating, peak in $\mathscr{P}_\zeta$ …

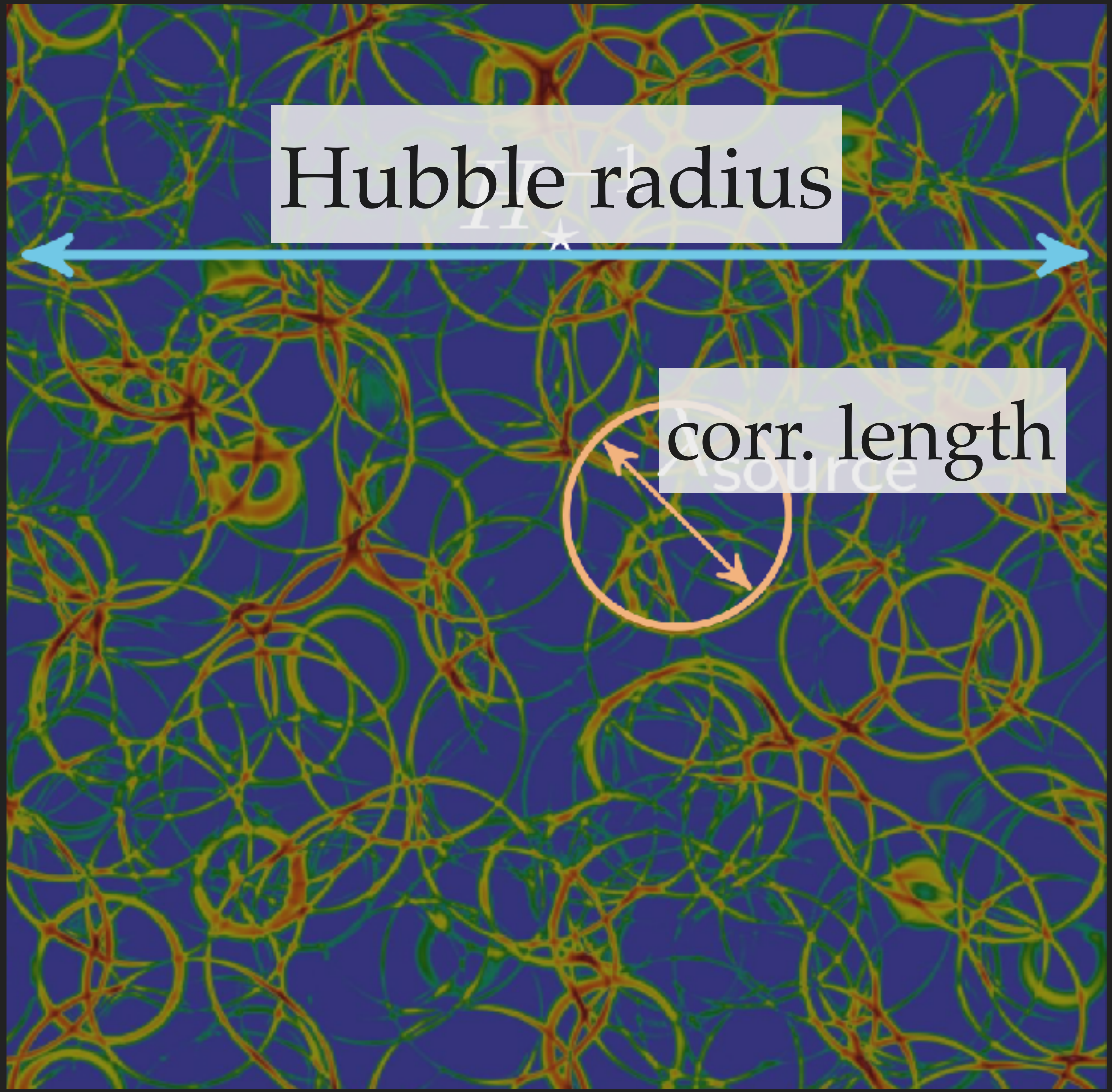




['15 Hindmarsh+]



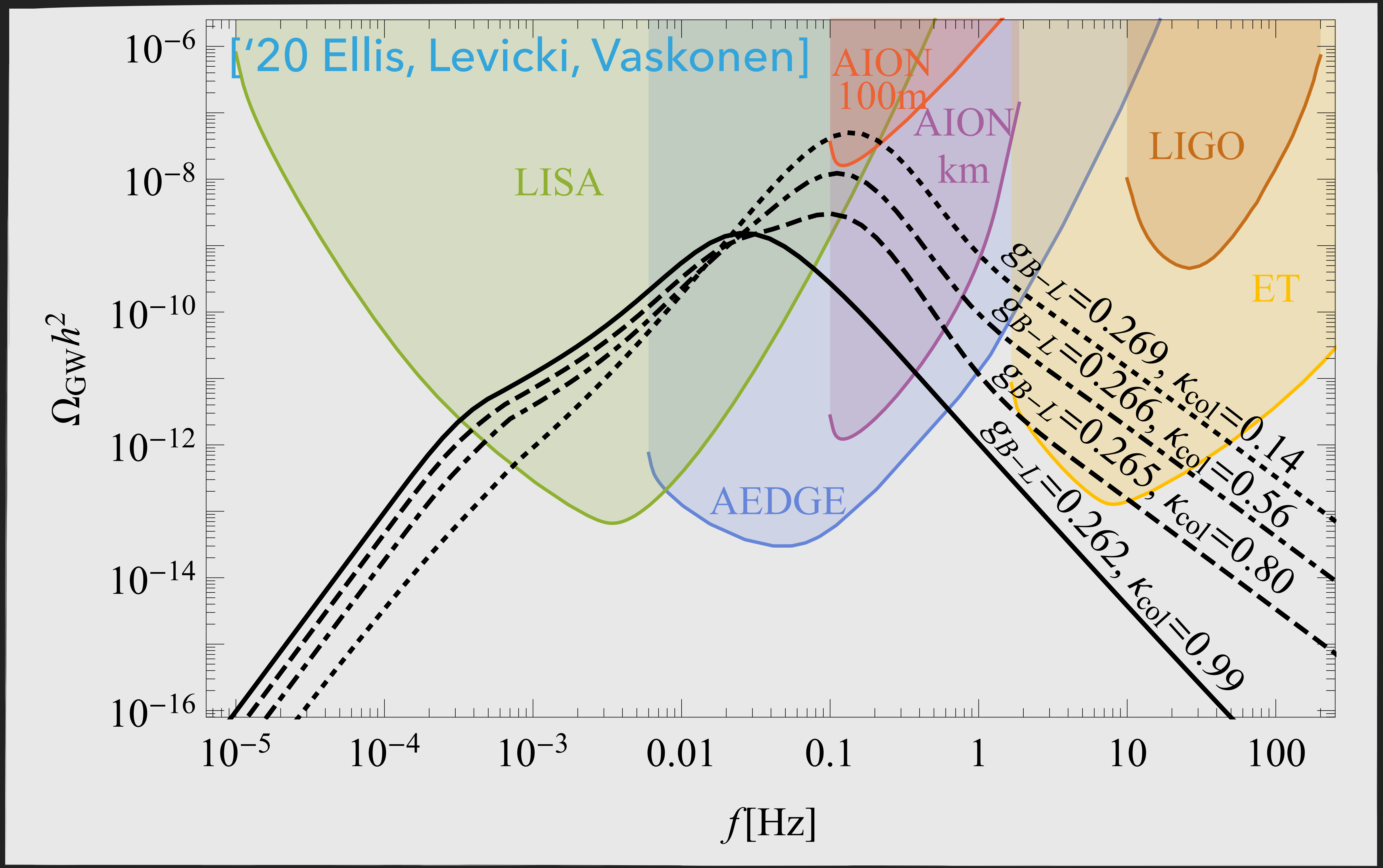

Hubble radius
corr. length



$$\langle \Pi(0)\, \Pi(d \gg \lambda_{\mathsf{source}}) \rangle = 0 \quad \Longrightarrow$$

$$\langle \widetilde{\Pi}(k)\, \widetilde{\Pi}(-k) \rangle \xrightarrow{k \ll \lambda_{\mathsf{source}}^{-1}} \text{constant}$$

UNIVERSALITY OF THE CAUSALITY TAIL



['03 Seto, Yokoyama;
'05 Boyle, Steinhardt;
'06 Watanabe, Komatsu;
'09 Caprini, Durrer, Konstandin, Servant;
'18 Caprini, Figueroa;
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'18 Cui, Lewicki, Morrissey, Wells;
'19 D'Eramo, Schmitz;
…]

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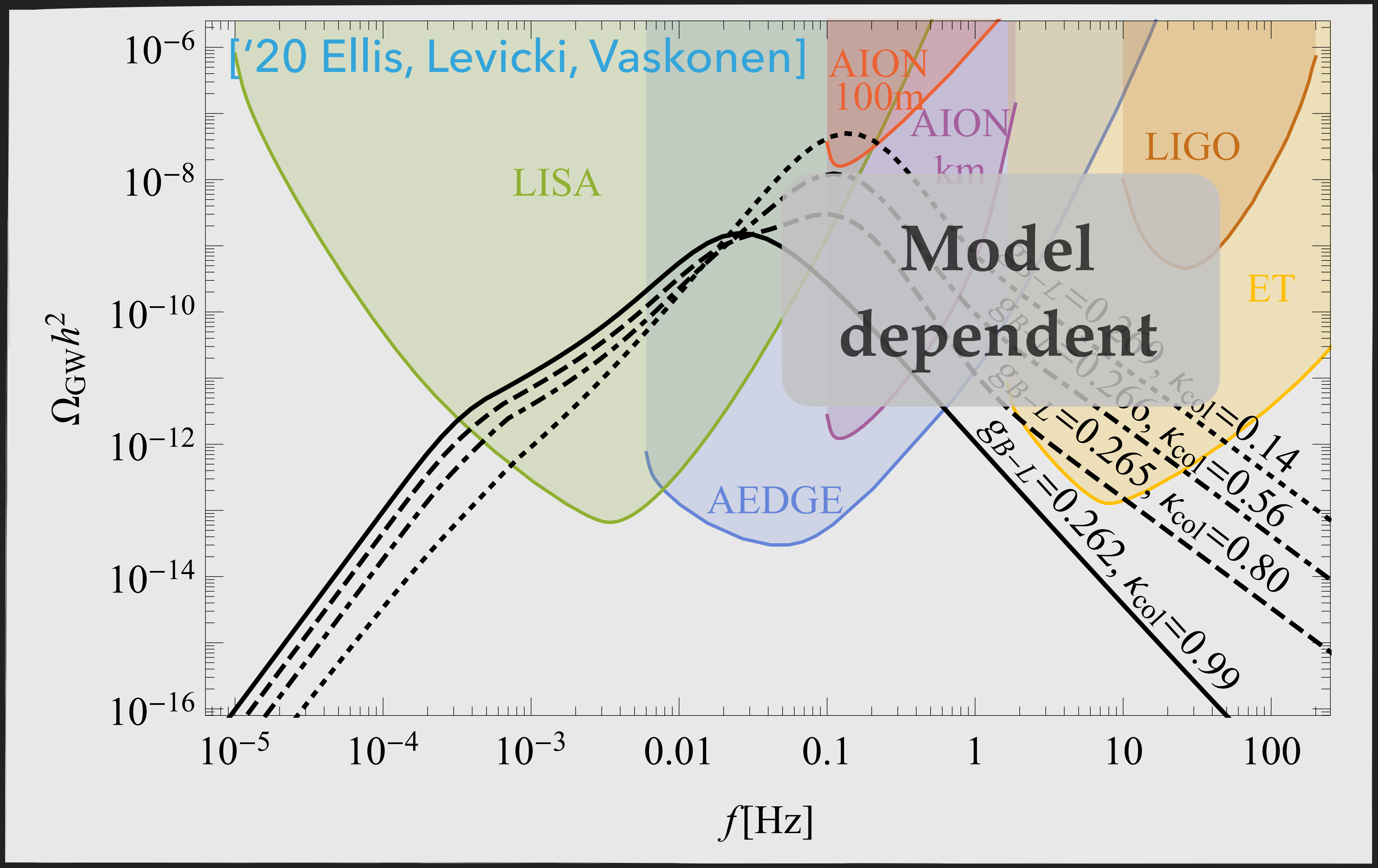

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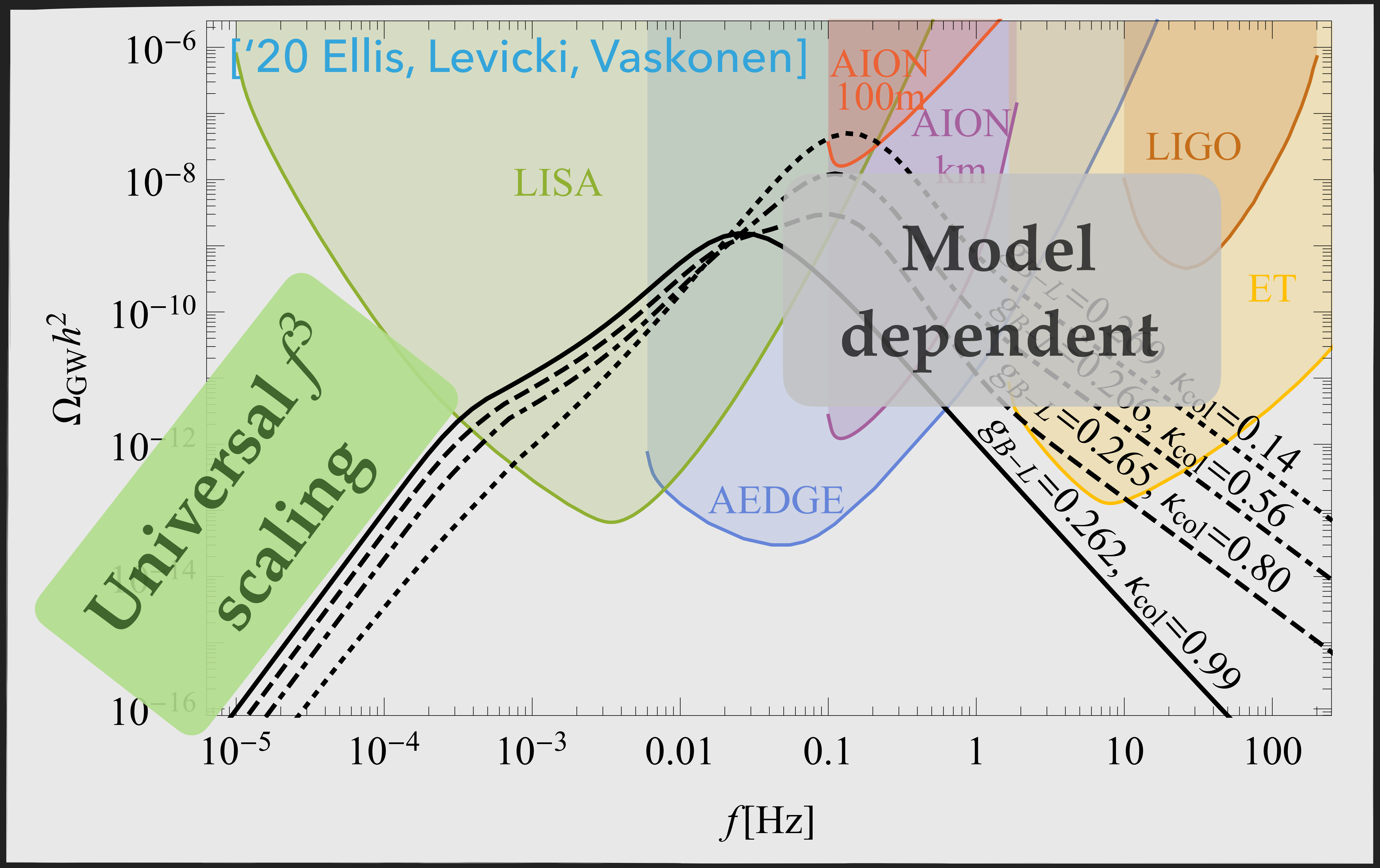

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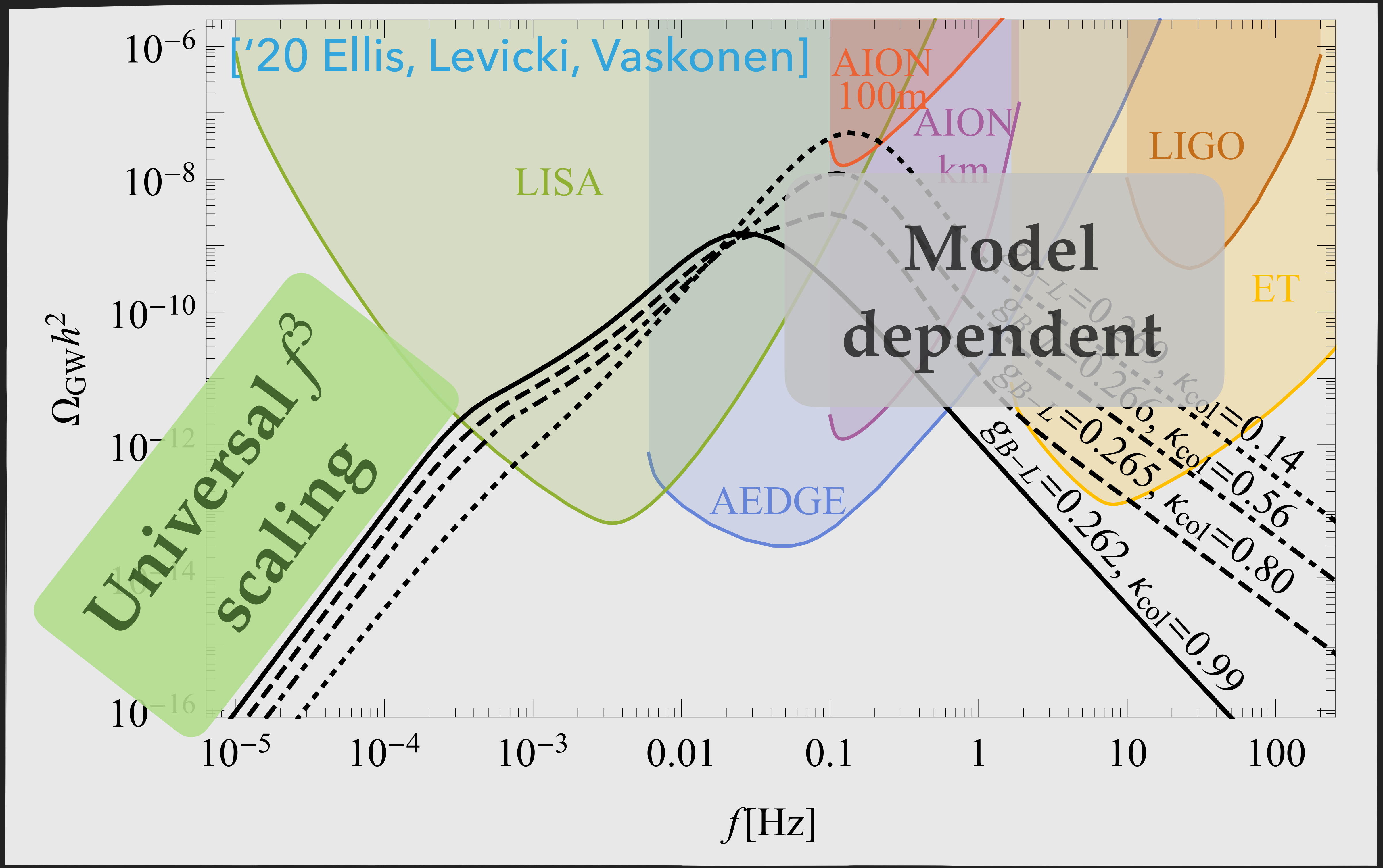

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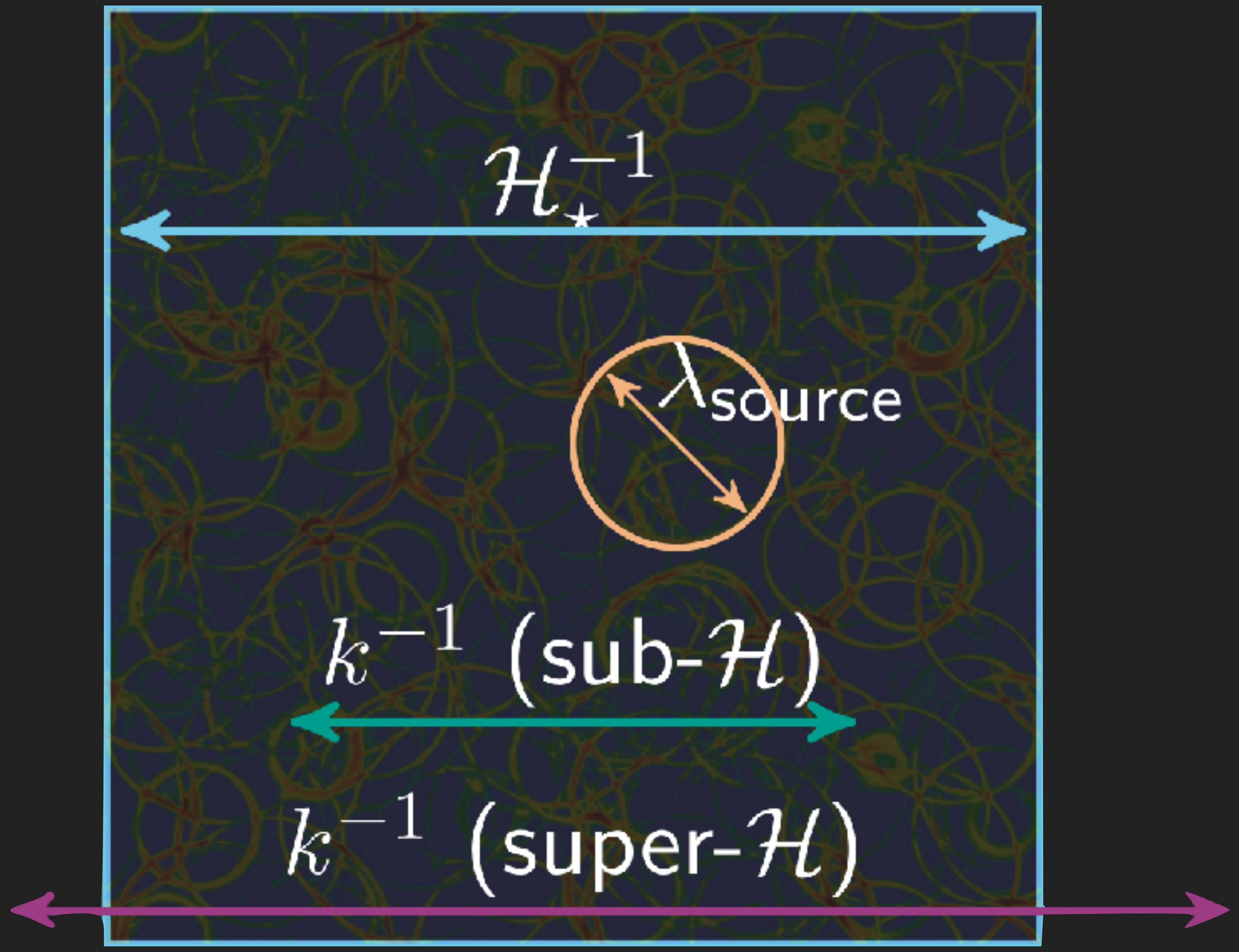
...]

Causality tail

- Low-f spectrum GWs ⇔ universal (model-independent) probe of the Universe wavelength $k^{-1} \gg$ corr. length λ_{source}

period $f^{-1} \gg$ duration of phase transition β^{-1}

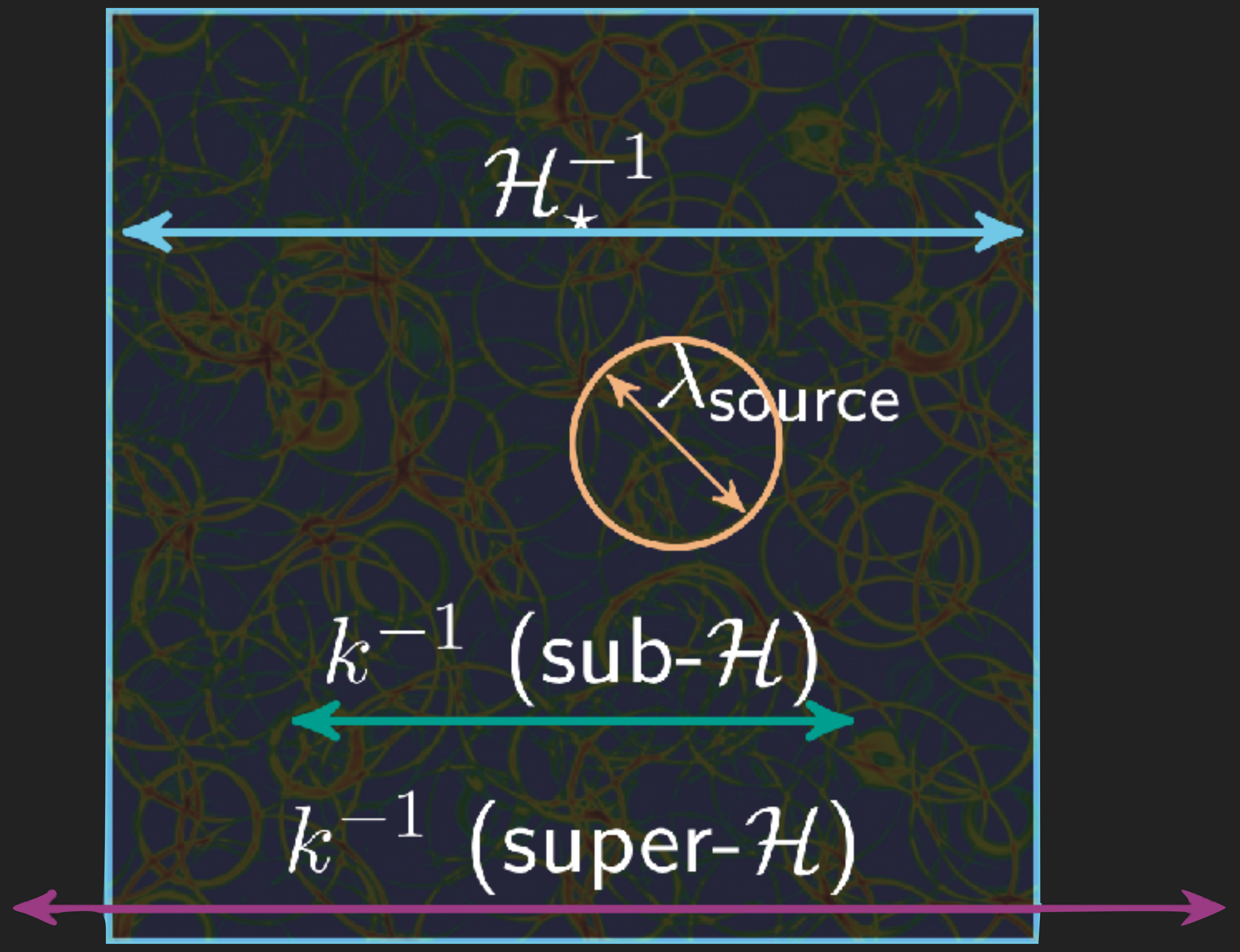


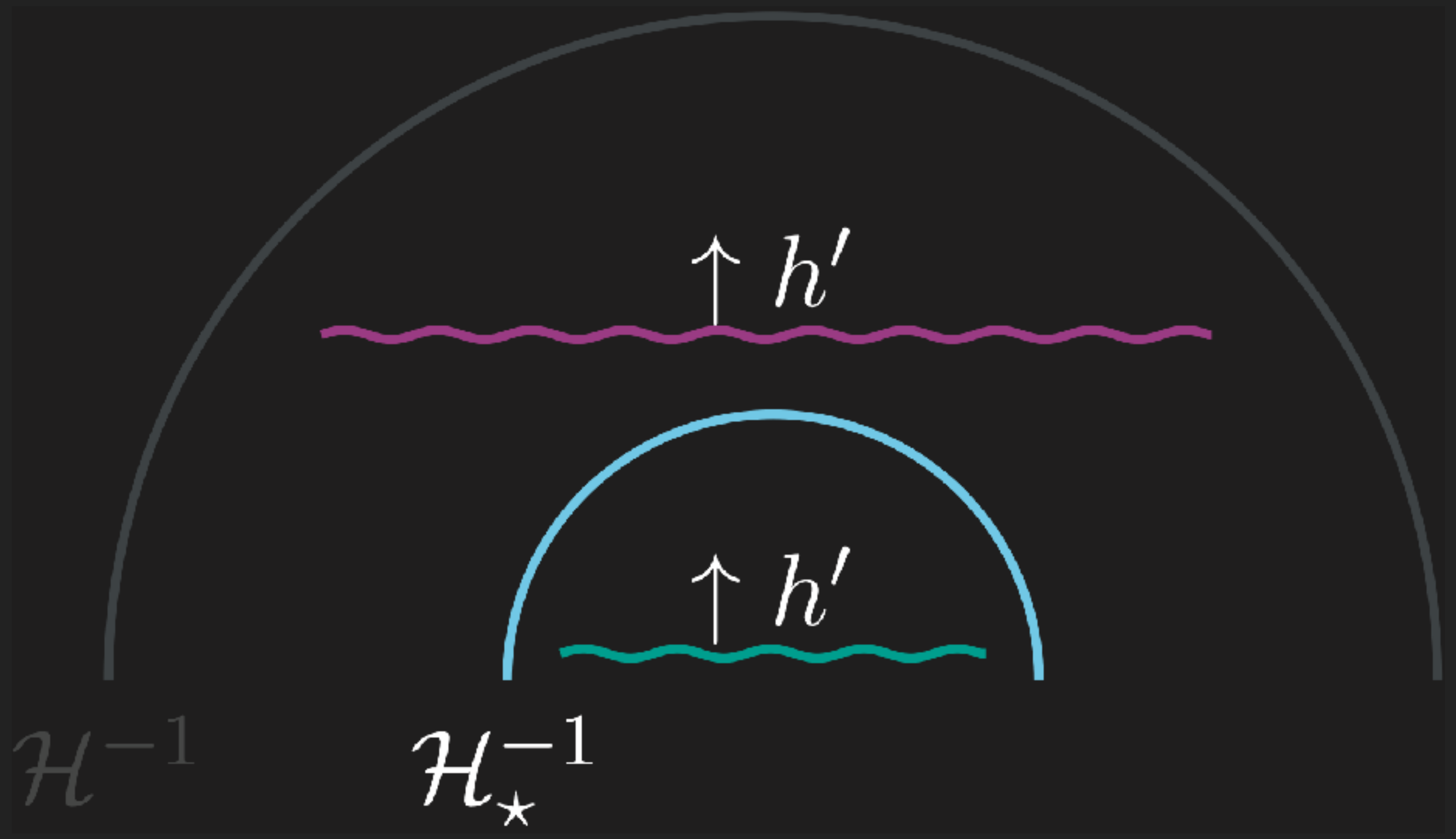
['20 Hook, Marques-Tavares, **DR**]

wavelength $k^{-1} \gg$ corr. length λ_{source}

period $f^{-1} \gg$ duration of phase transition β^{-1}

$$h'' + \boxed{2\mathcal{H}\, h'} + \boxed{k^2 h} = 0$$





['20 Hook, Marques-Tavares, **DR**]

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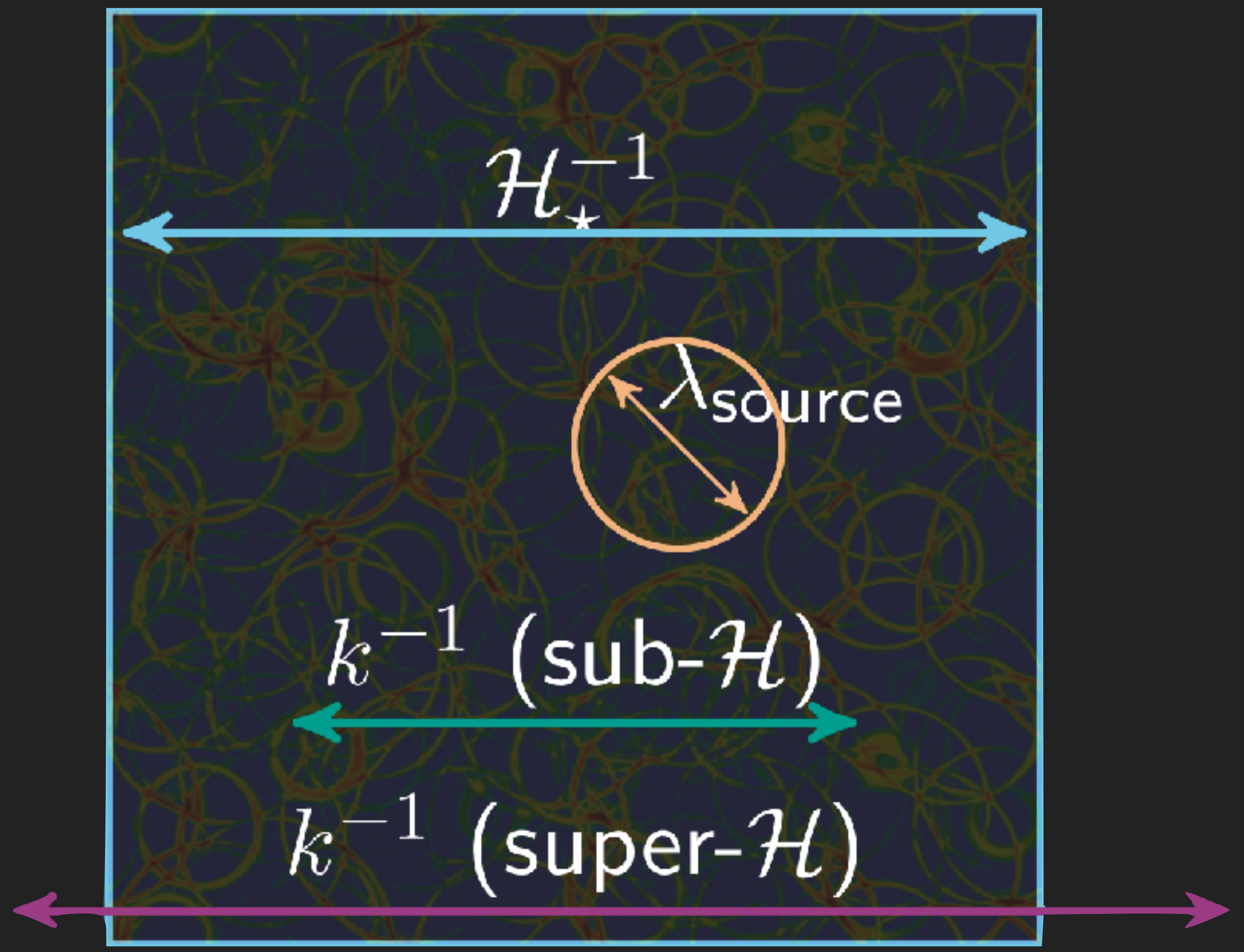

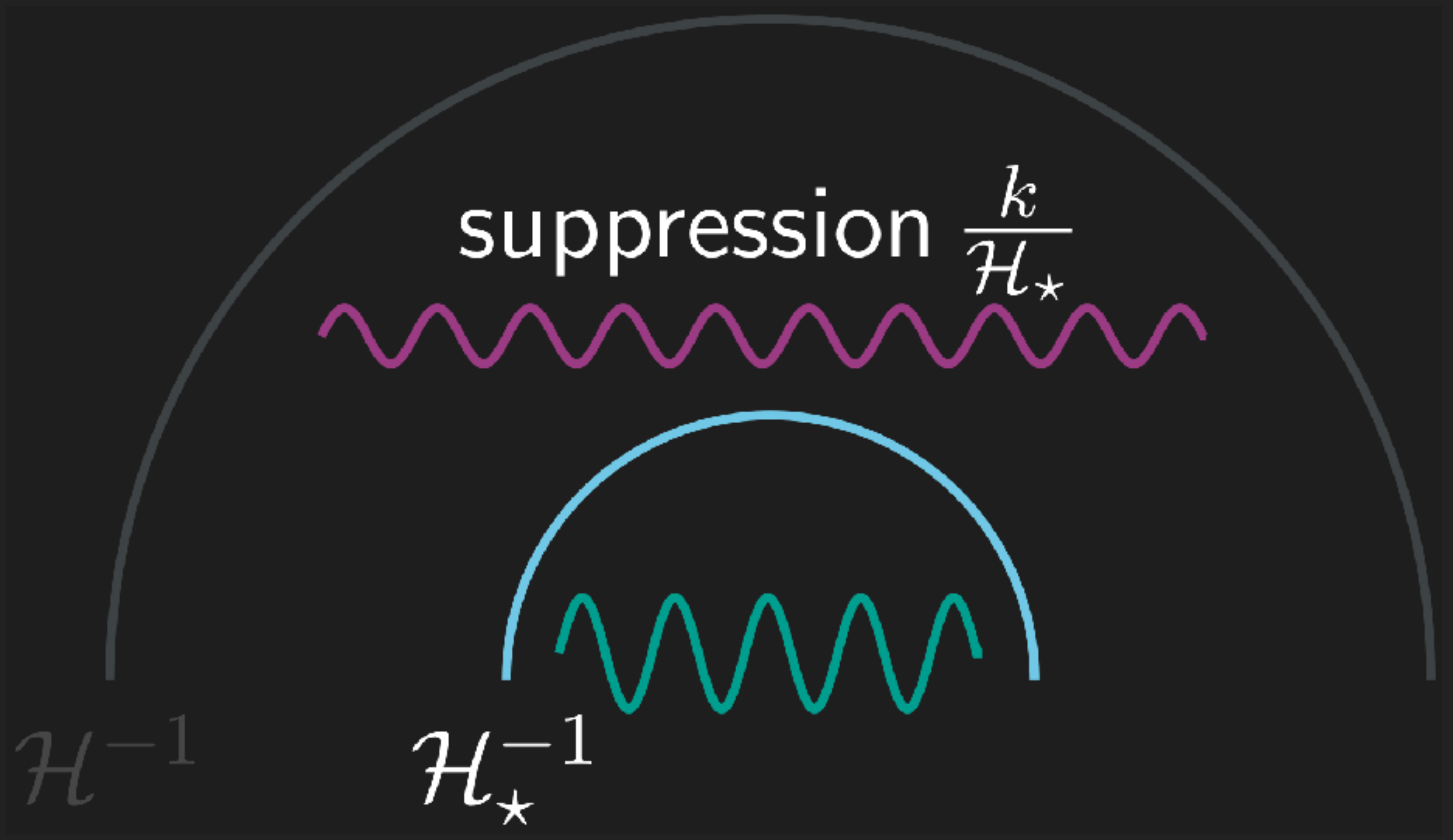

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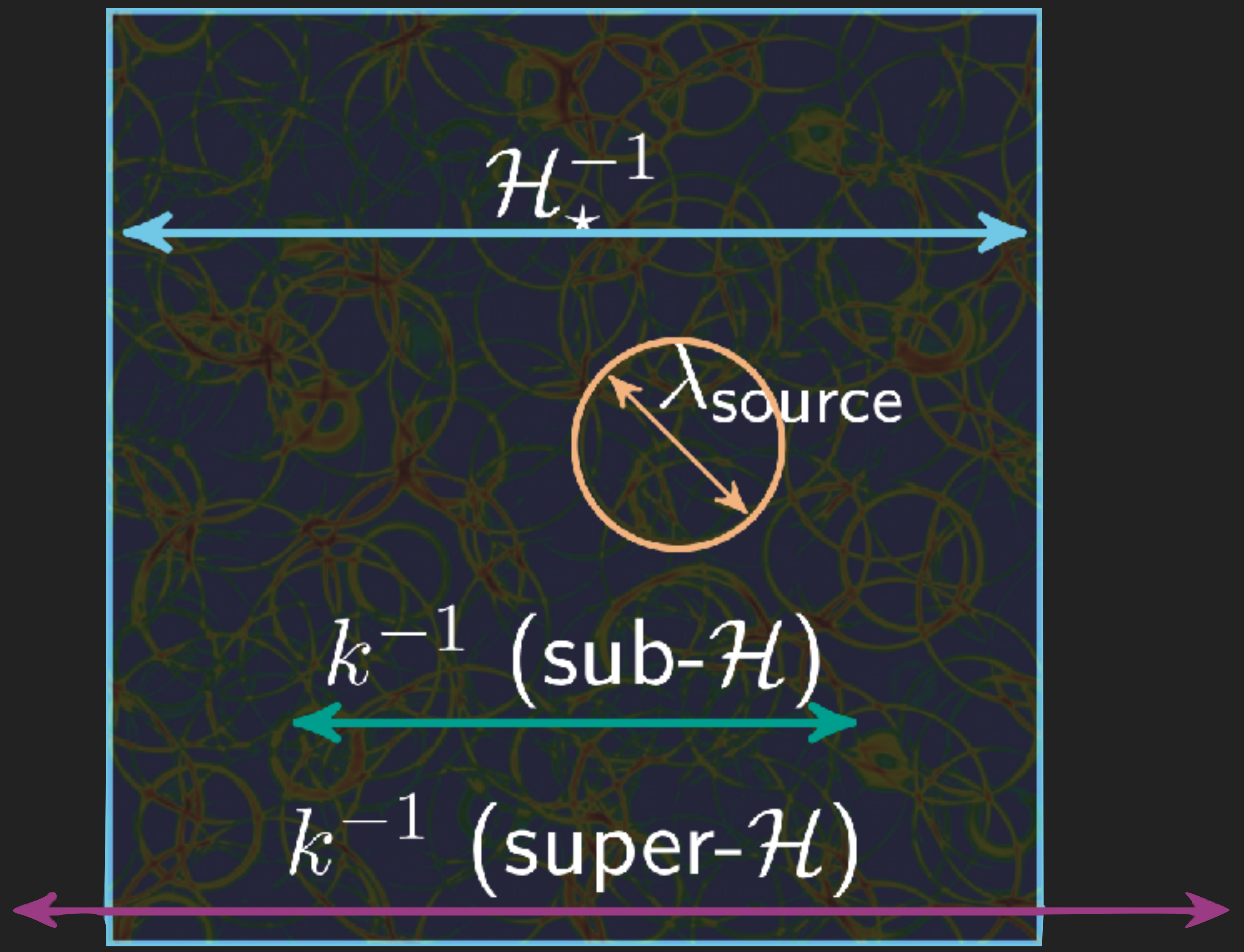
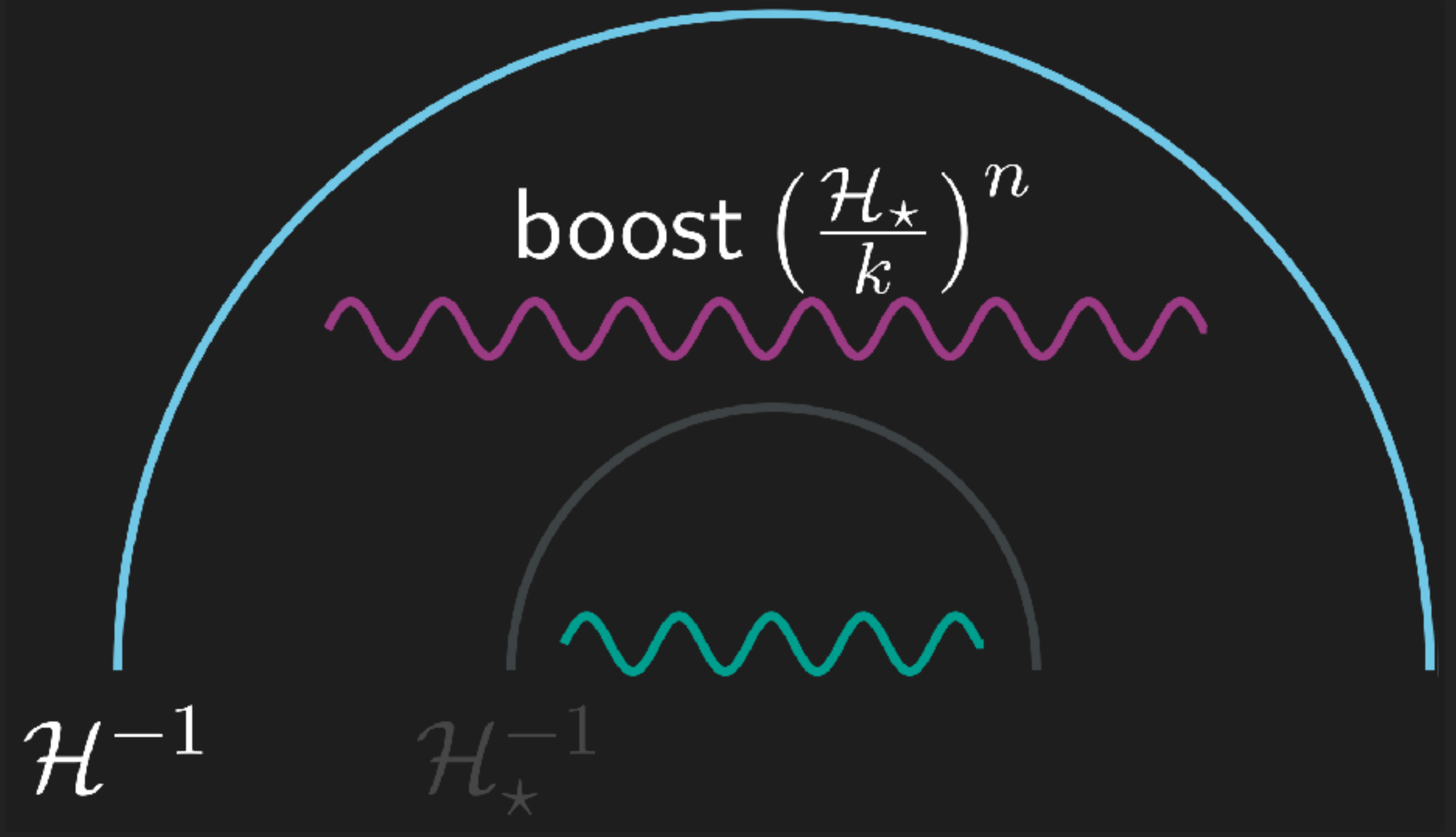
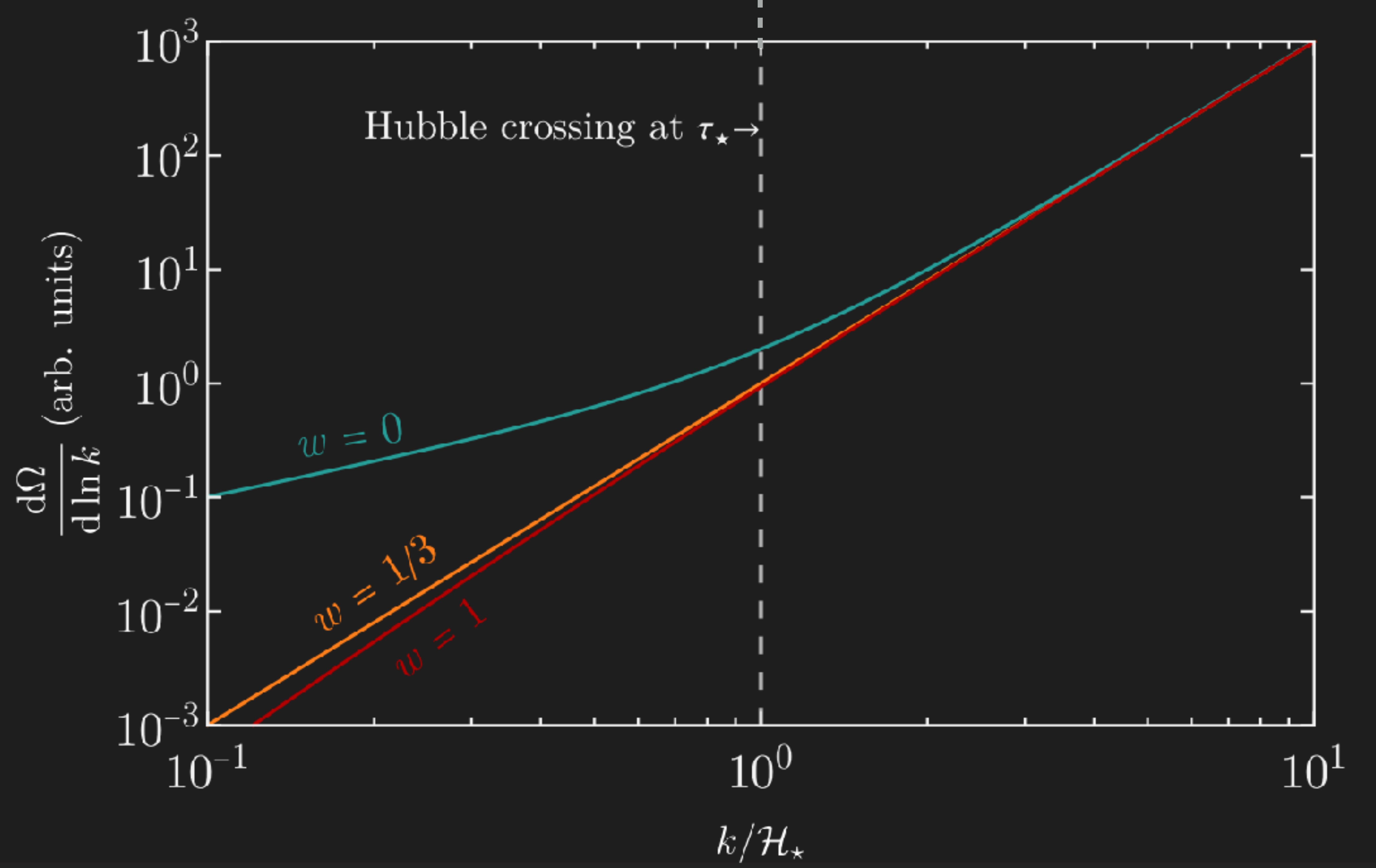




DEPENDENCE OF CAUSALITY TAIL ON w

$$\Omega_{\rm GW} \sim \begin{cases} k^3 & \text{RD} \\ k & \text{MD} \end{cases} \text{(super-horizon)}$$

$$\Omega_{\rm GW} \sim k^3 \text{ (sub-horizon)}$$



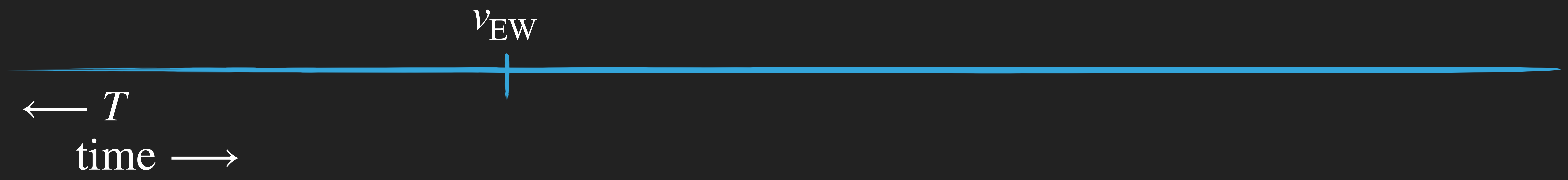
- Causality tail $\Leftrightarrow$ probe equation-of-state w

- SM particles are massless $\Rightarrow w = \frac{1}{3}$

$\longleftarrow T$

time $\longrightarrow$

- SM particles are massless $\Rightarrow w = \frac{1}{3}$
- Heavy particle decays $\Rightarrow \Omega_{\mathrm{GW}} \sim g_\star(T)^{1/3}$

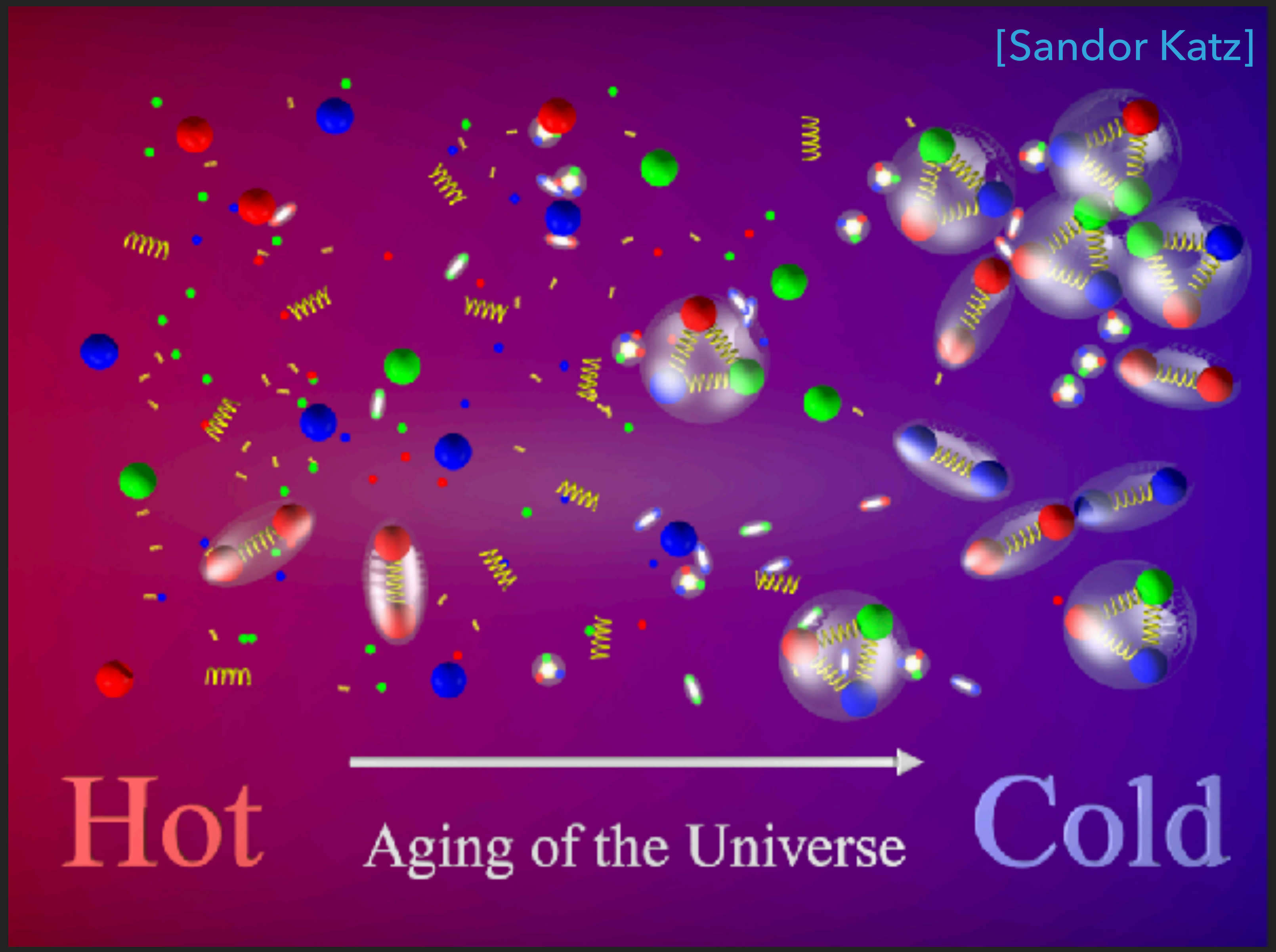


- SM particles are massless $\Rightarrow w = \frac{1}{3}$
- Heavy particle decays $\Rightarrow \Omega_{\mathrm{GW}} \sim g_\star(T)^{1/3}$
- QCD confines
- w deviates from $\frac{1}{3}$

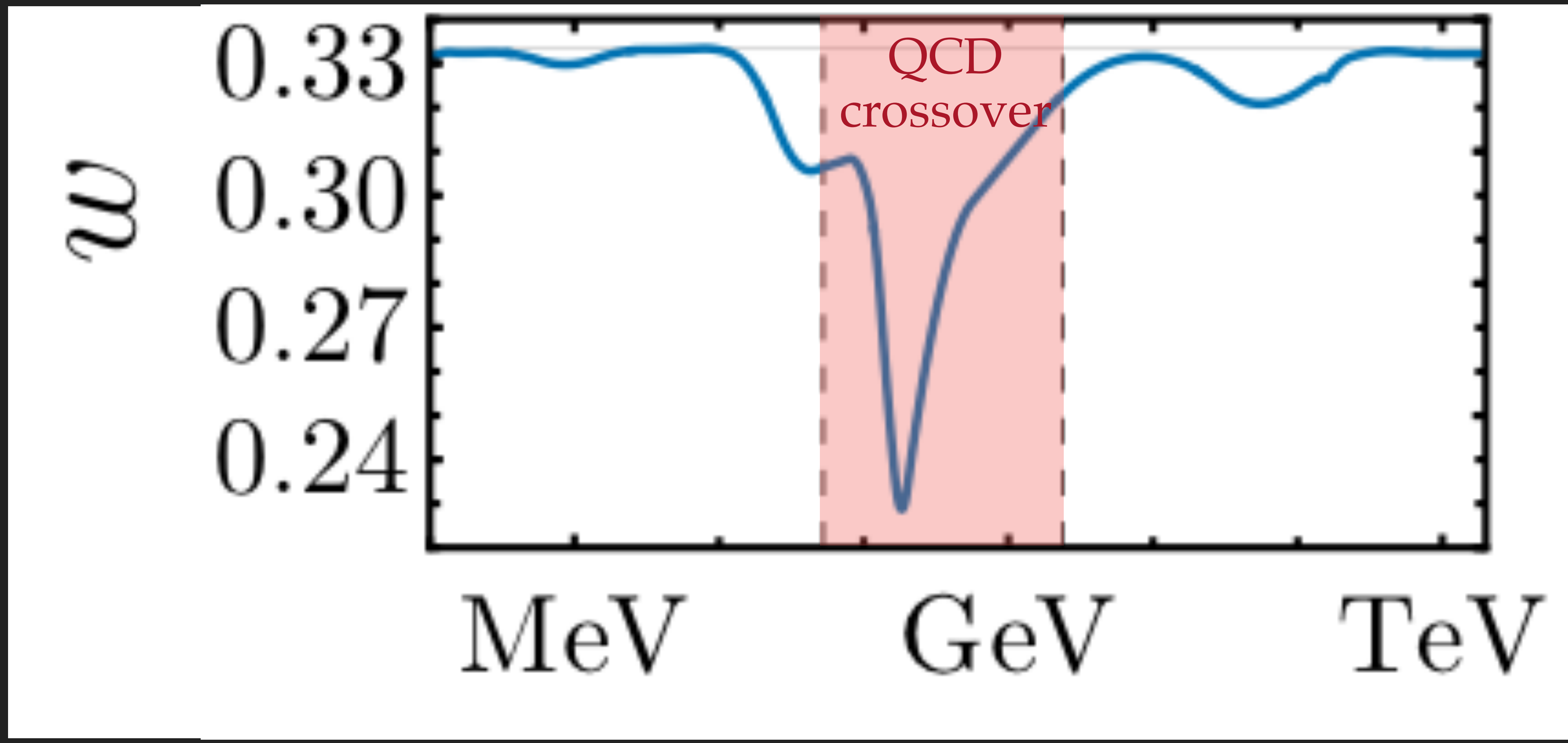
v_{EW} Λ_{QCD}

$\longleftarrow T$

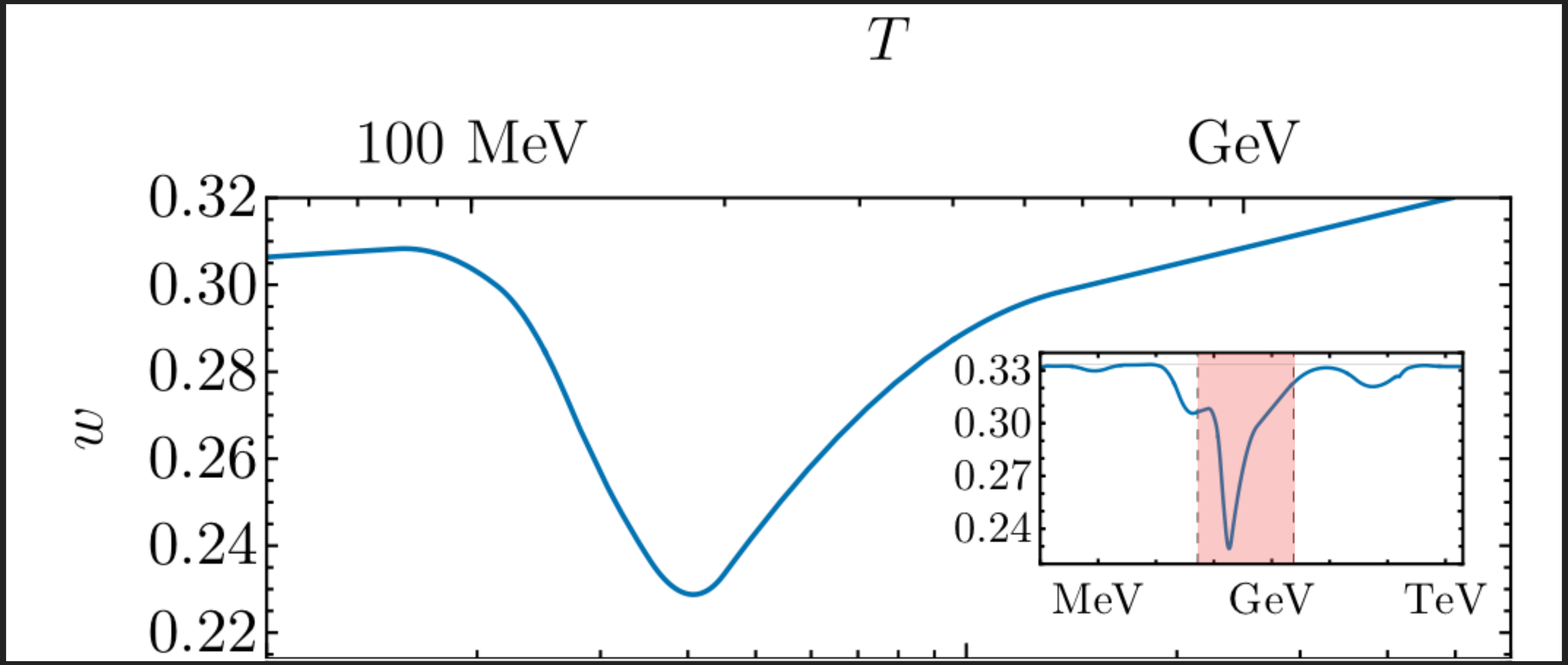
time $\longrightarrow$



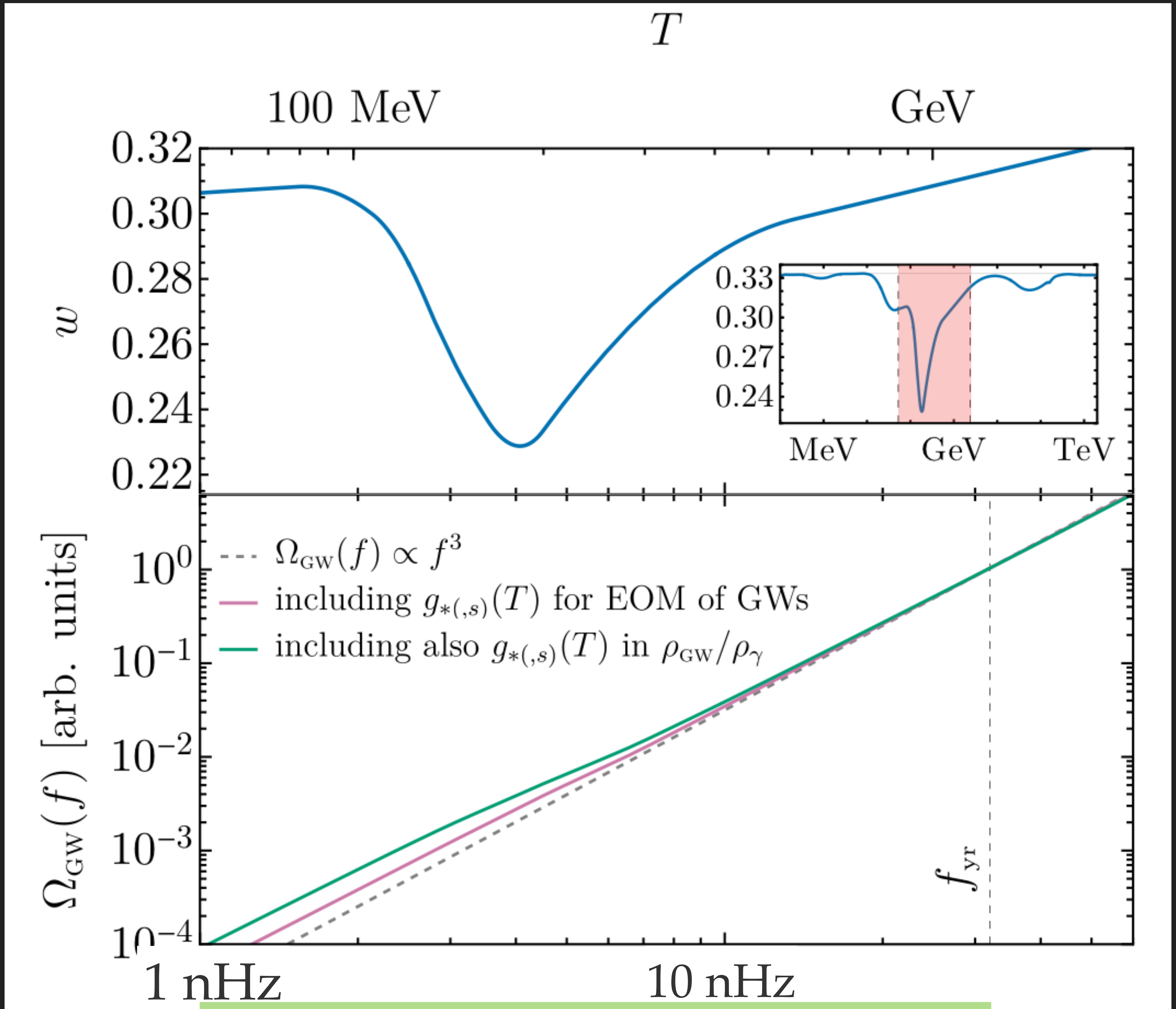
STANDARD MODEL EFFECT ON THE CAUSALITY TAIL



STANDARD MODEL EFFECT ON THE CAUSALITY TAIL



['23 Franciolini, **DR**, Rompineve]

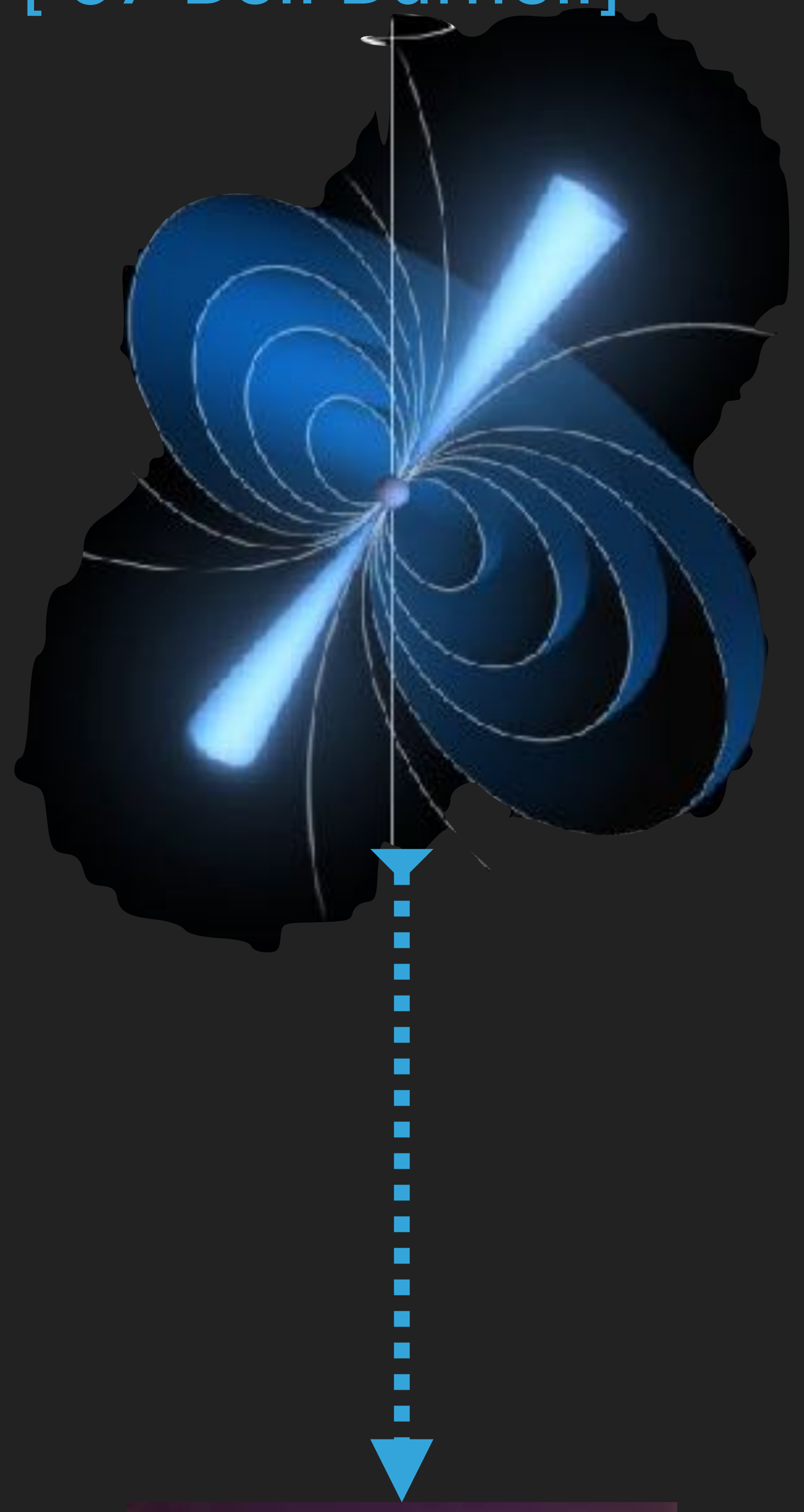


1-10 nHz → GW bkg at PTAs

PULSAR TIMING ARRAY MEASUREMENTS

['78 Sazhin; '79 Detweiler; '83 Hellings, Downs]

['67 Bell Burnell]



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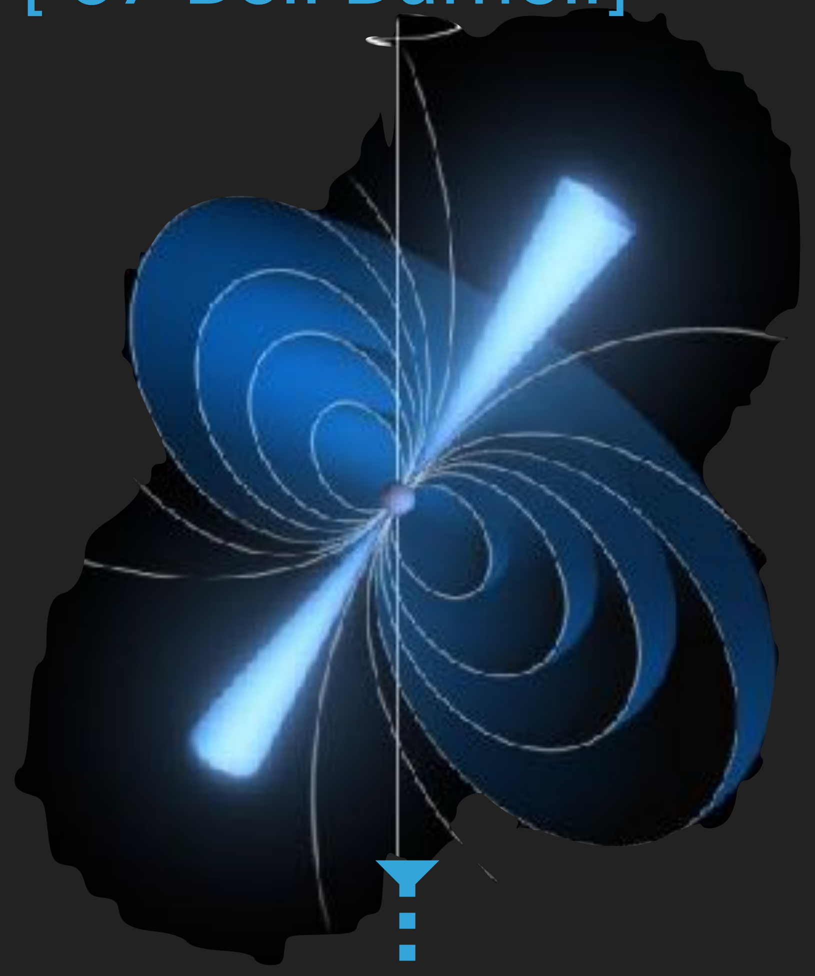

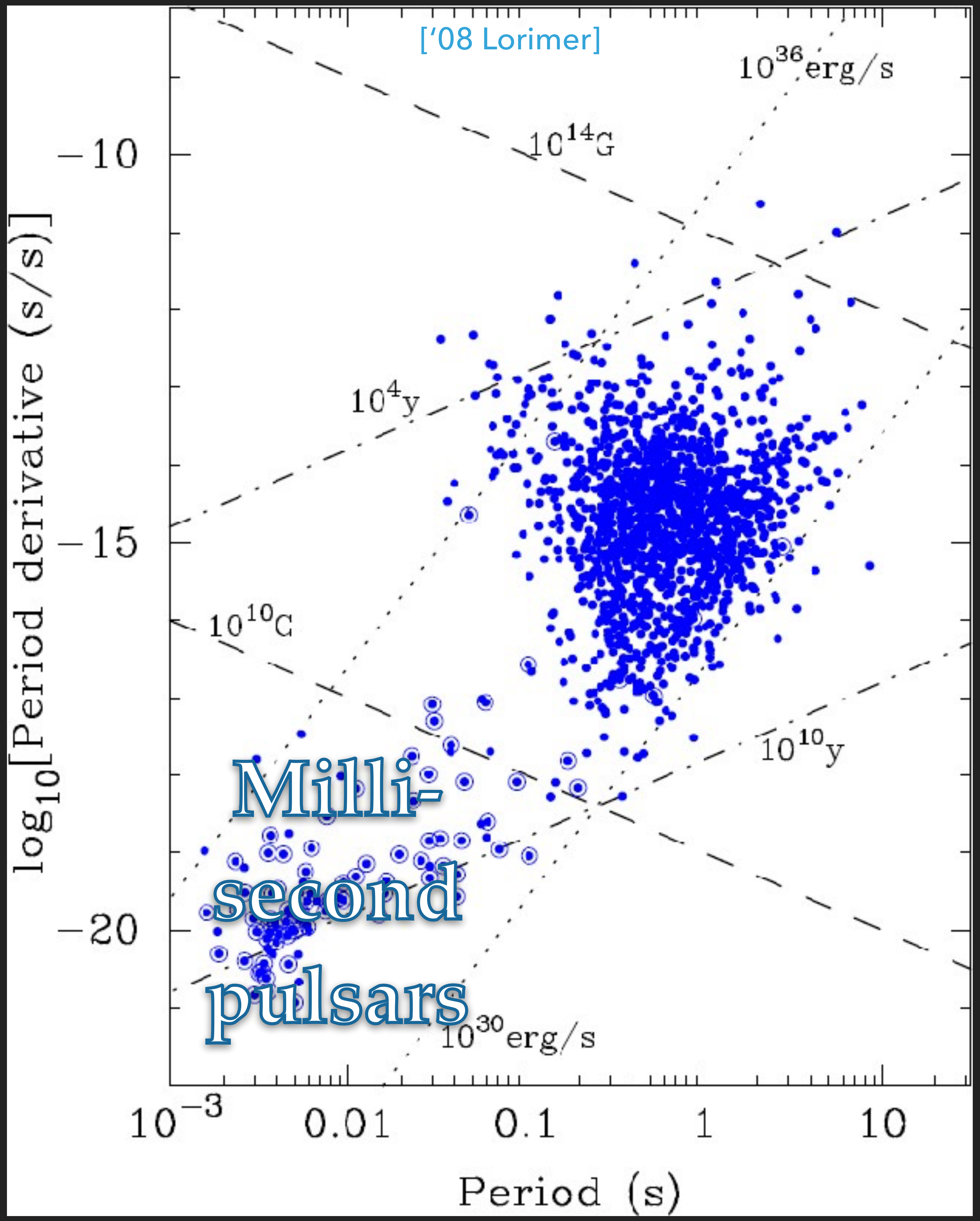

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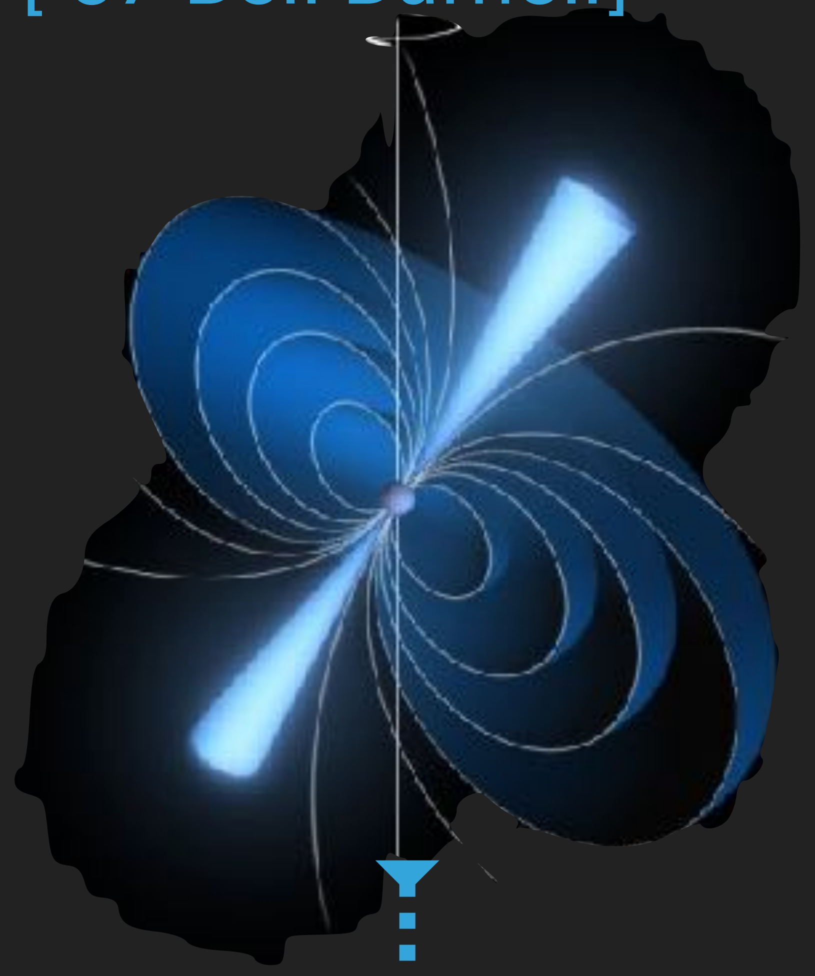

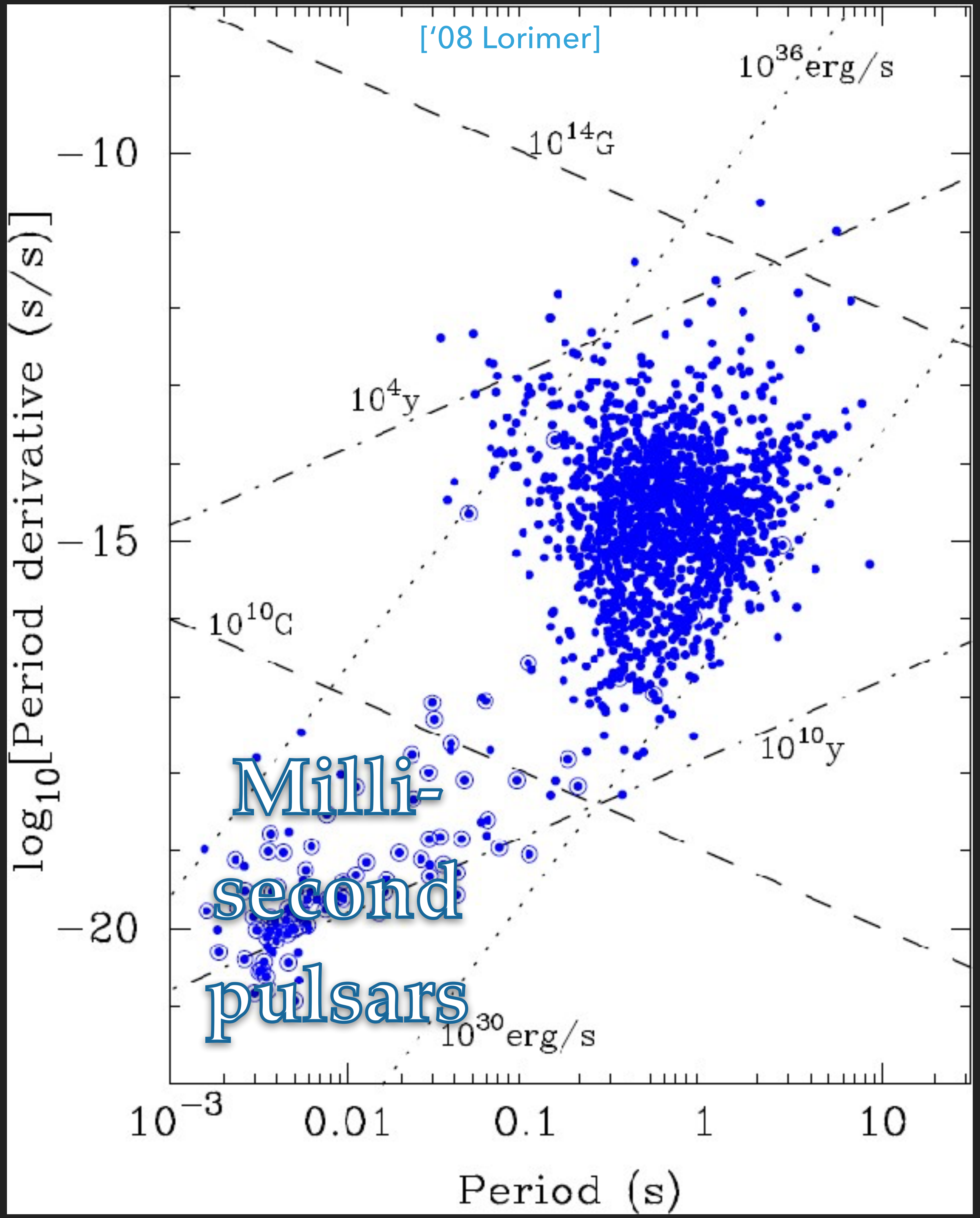

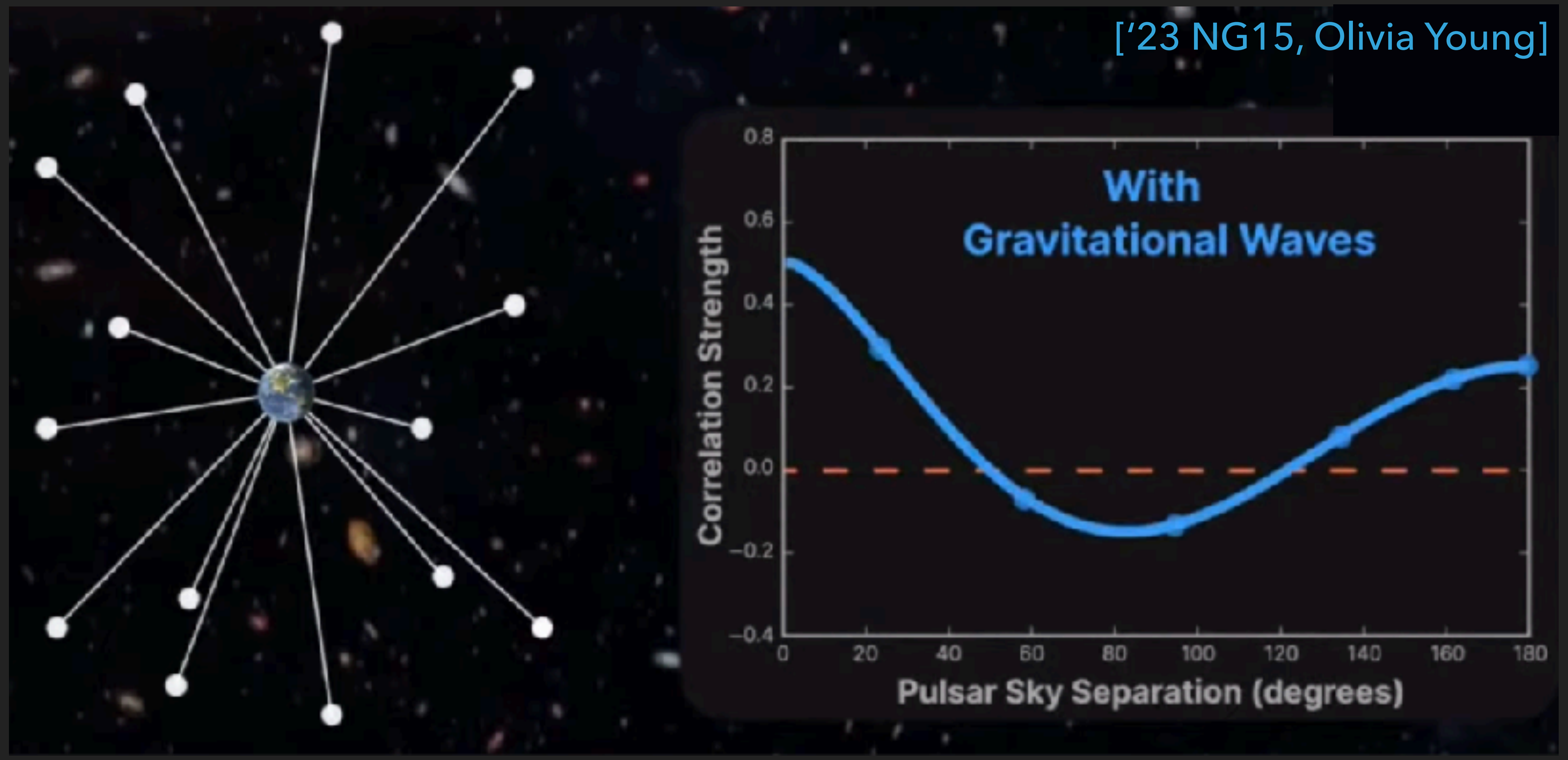

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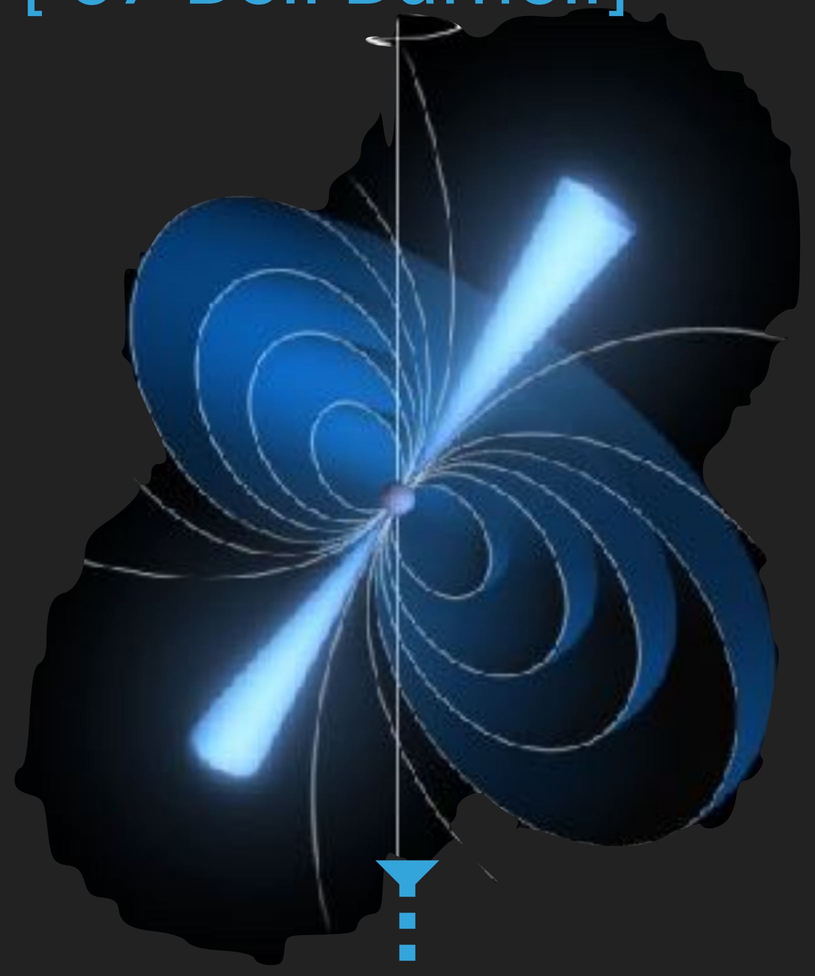
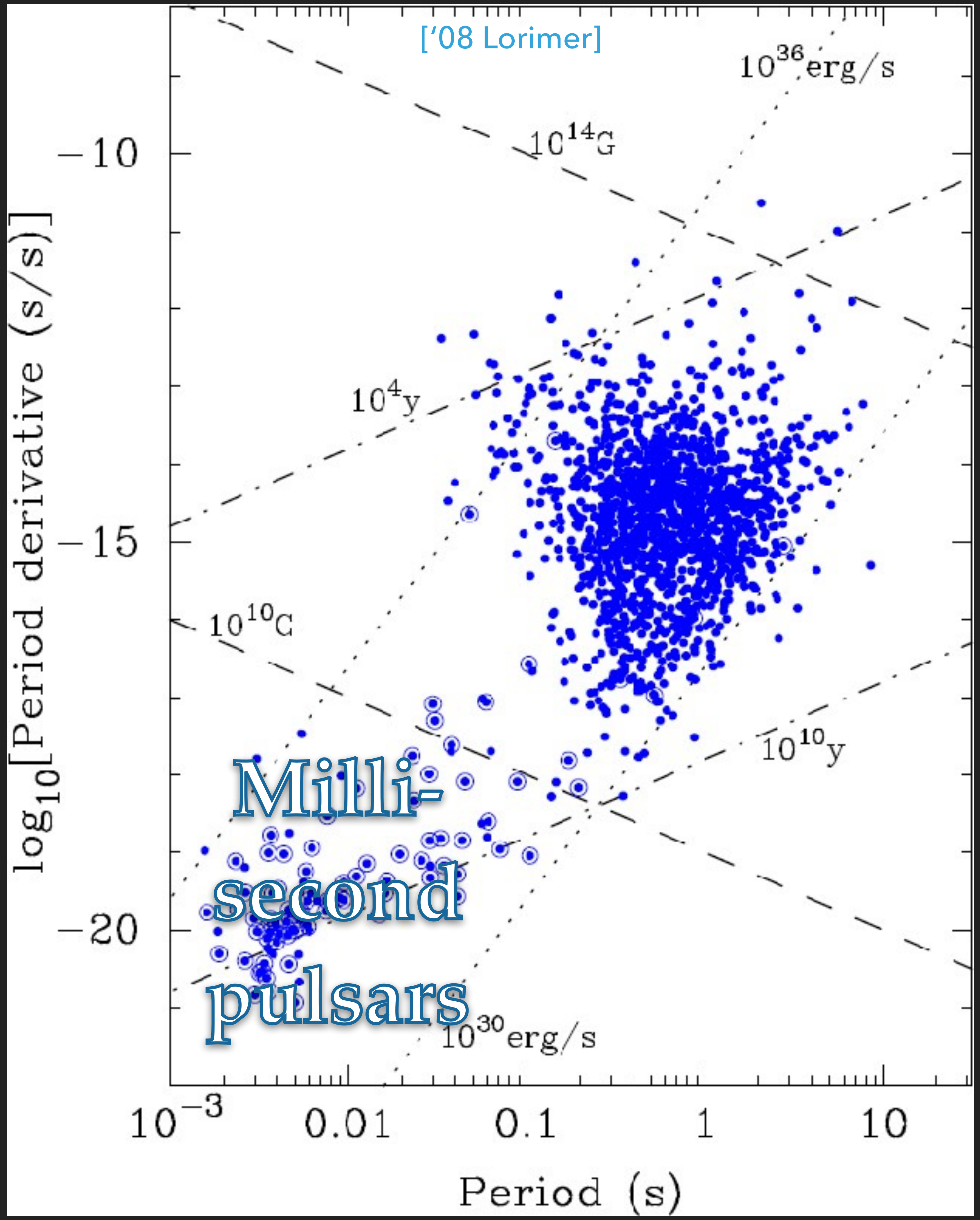
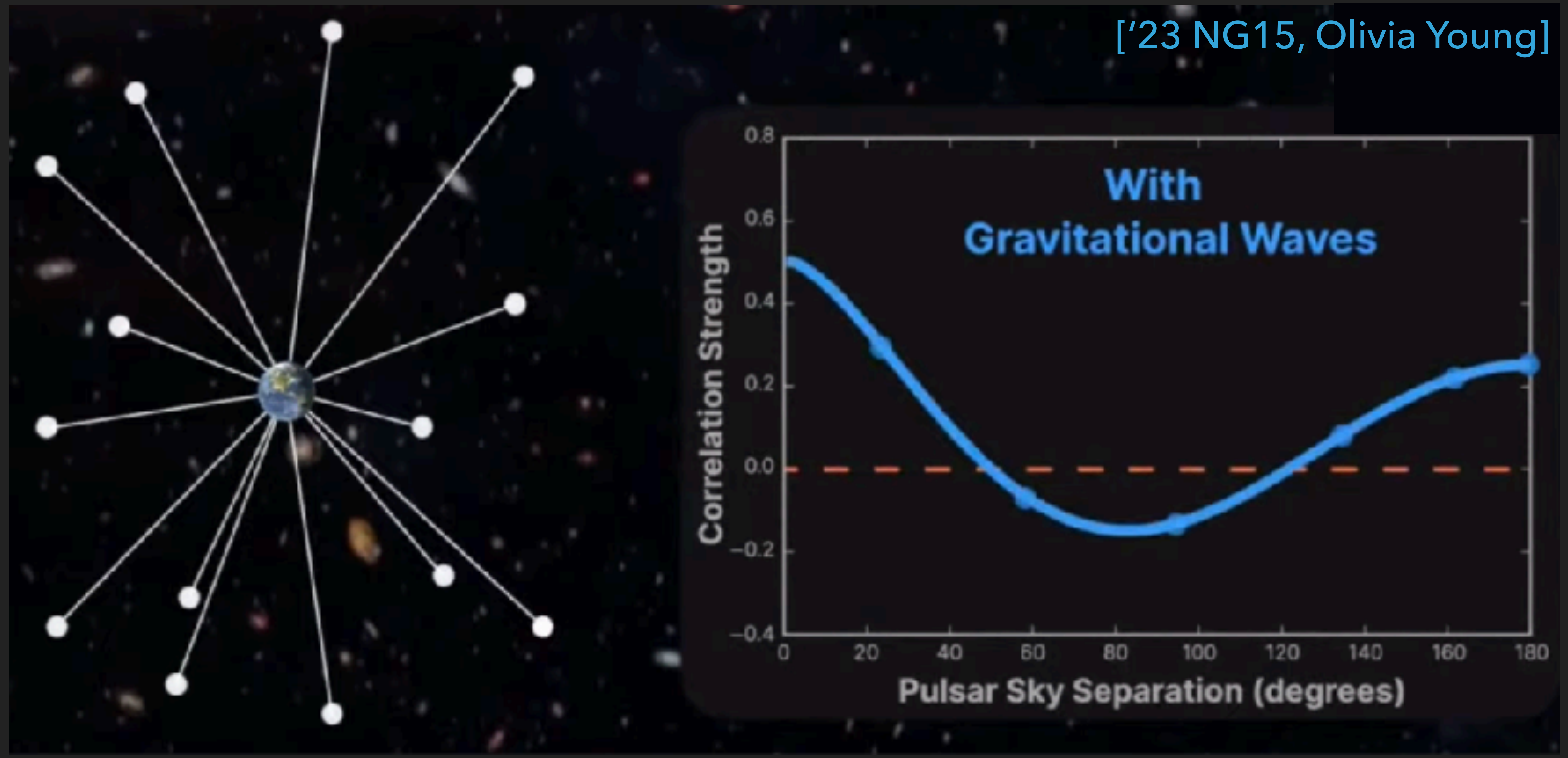
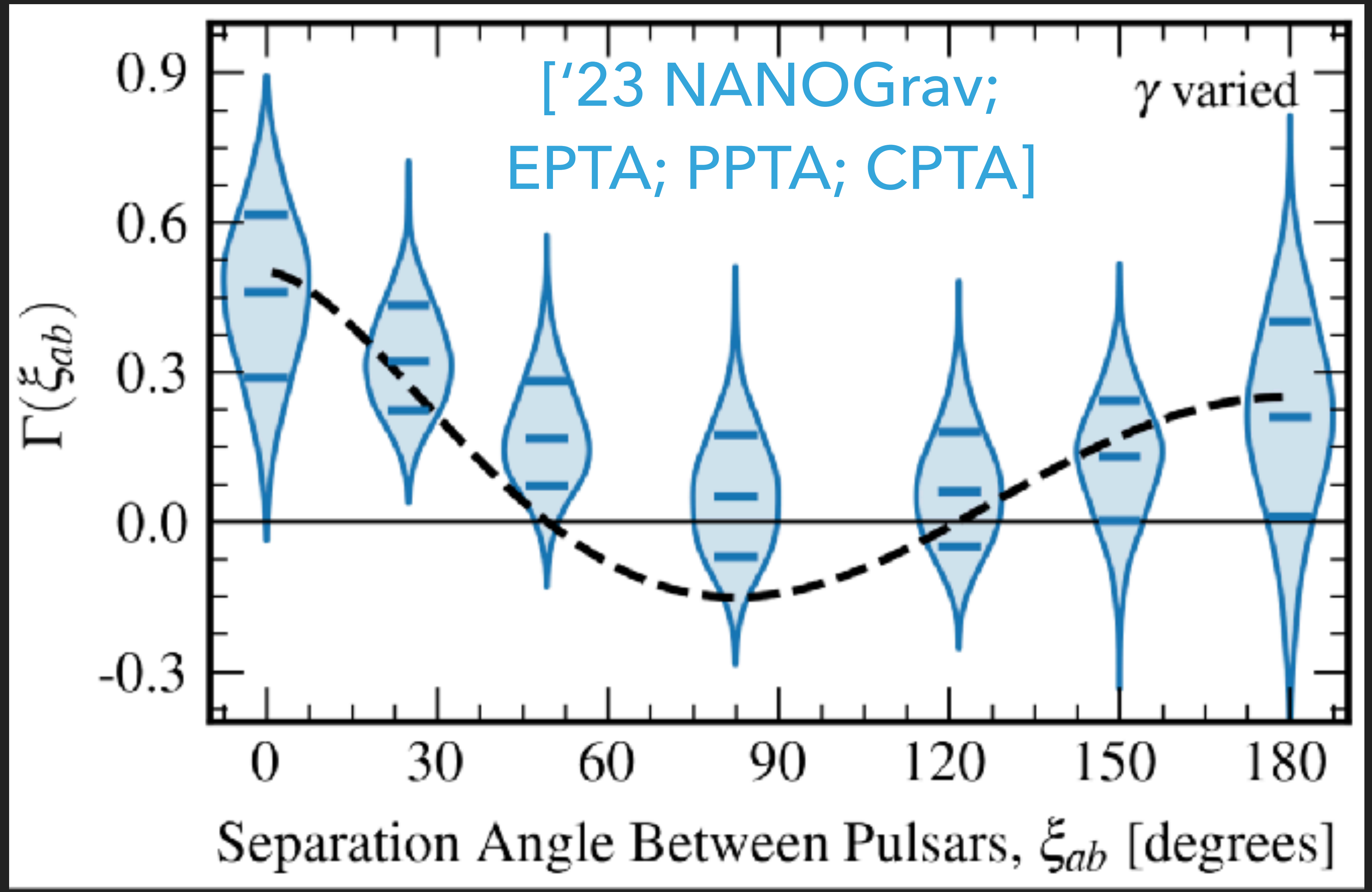
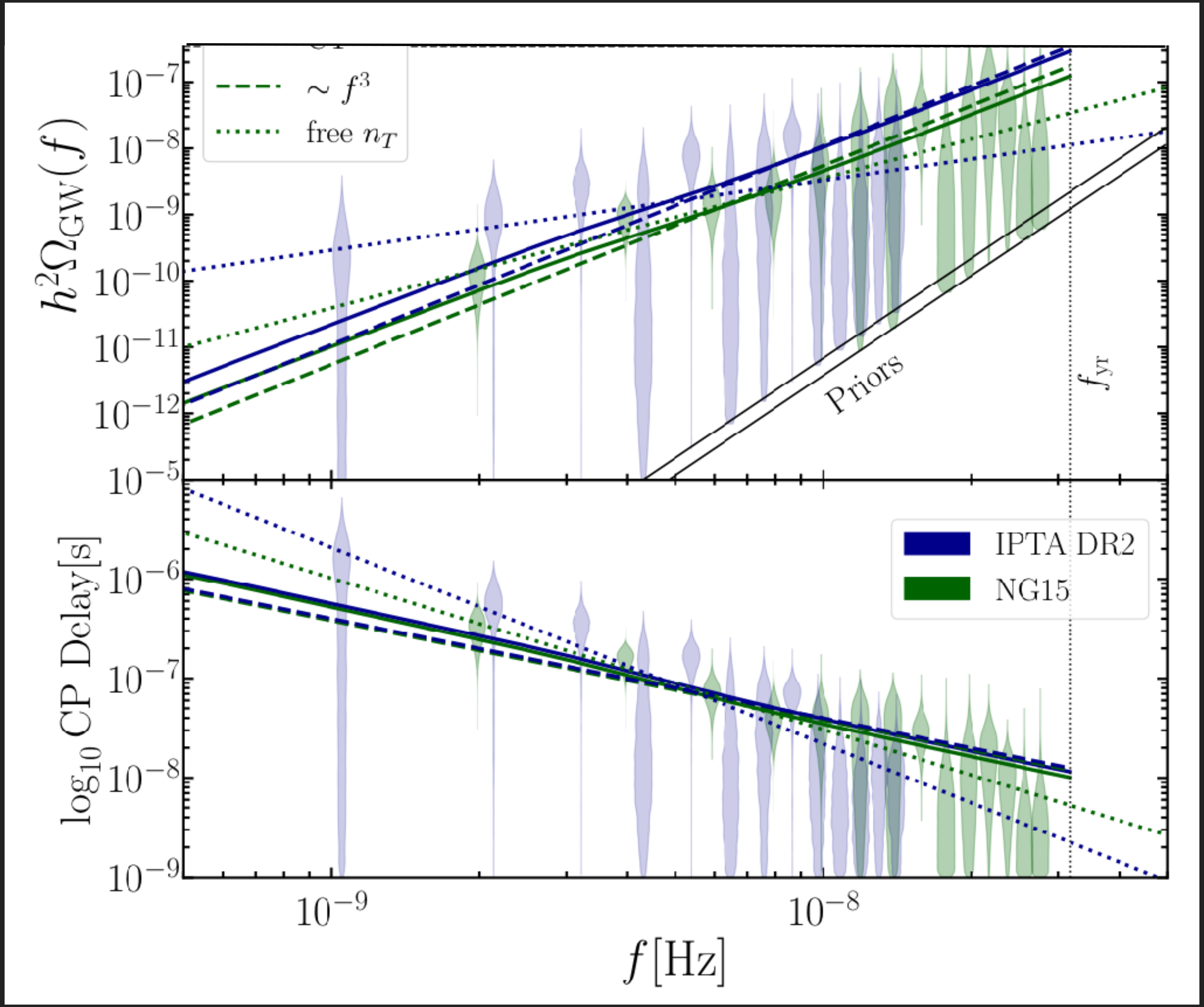




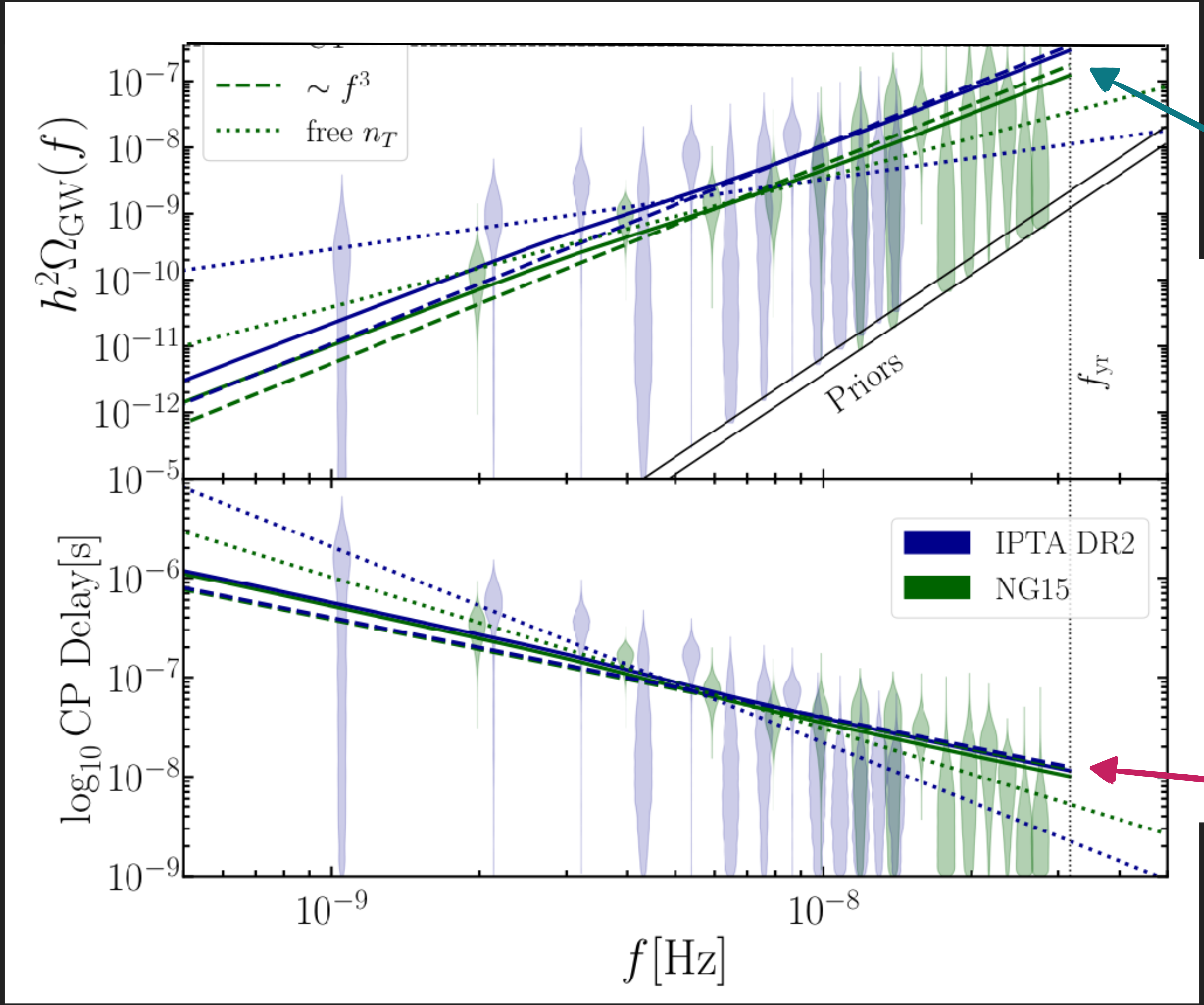


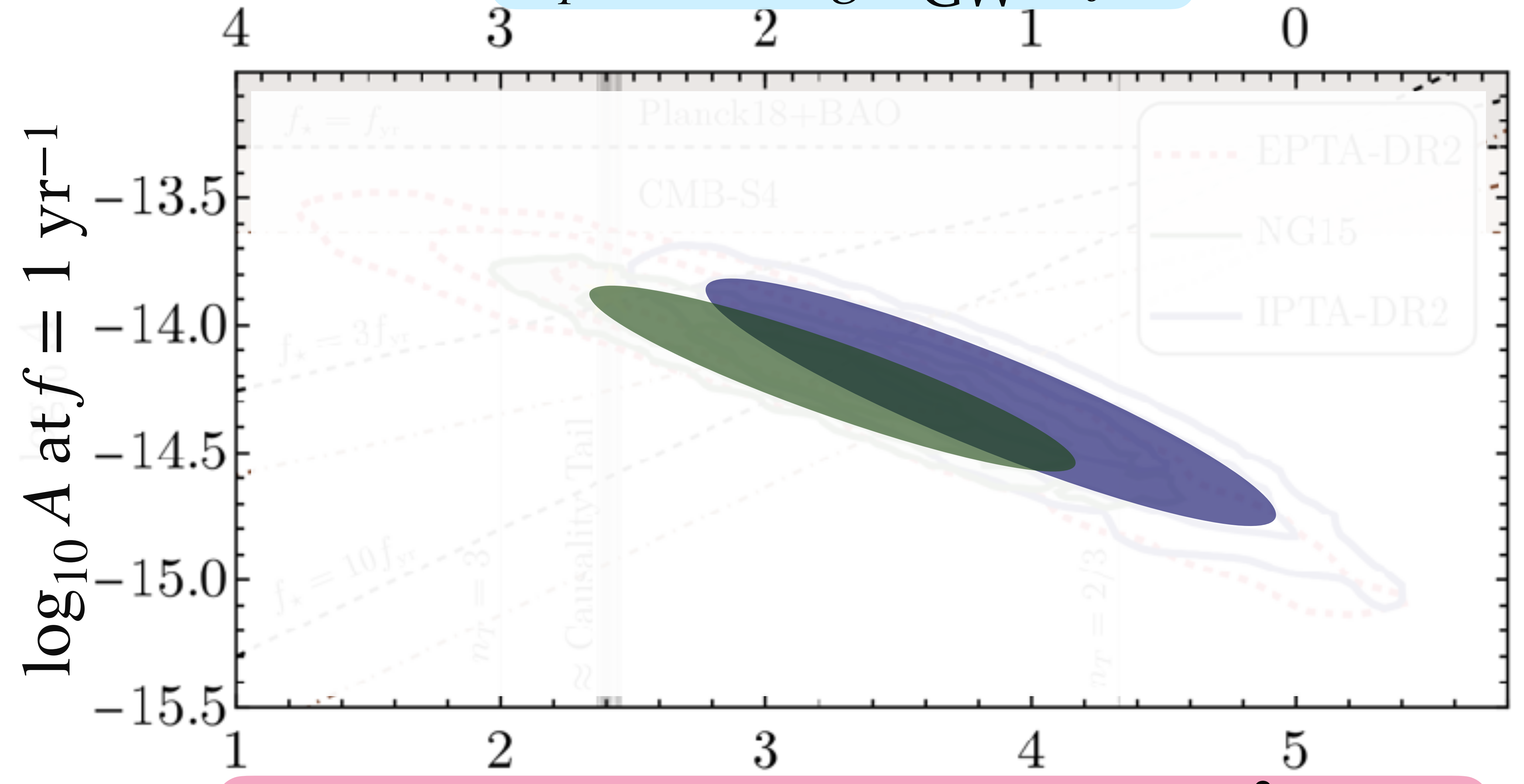


PULSAR TIMING ARRAY MEASUREMENTS: GW SPECTRUM



PULSAR TIMING ARRAY MEASUREMENTS: GW SPECTRUM





n_T : tilt of bkg $\Omega_{\rm GW} \sim f^{n_T}$

$\gamma = 5 - n_T$: tilt of timing residuals $\langle h(f)^2 \rangle \sim f^{-\gamma}$

- Earth motion

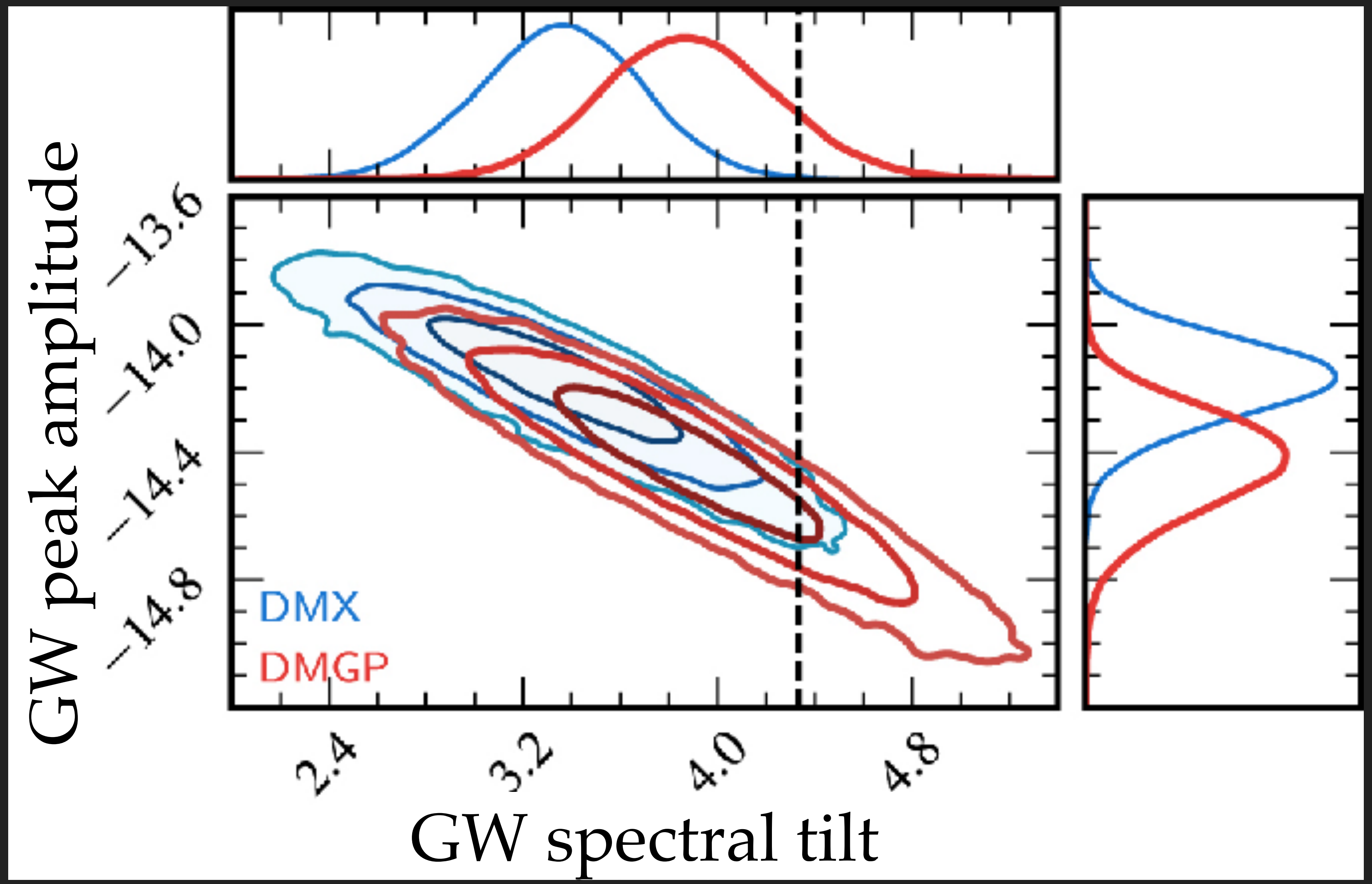
- Pulsar evolution: timing model

- Earth motion

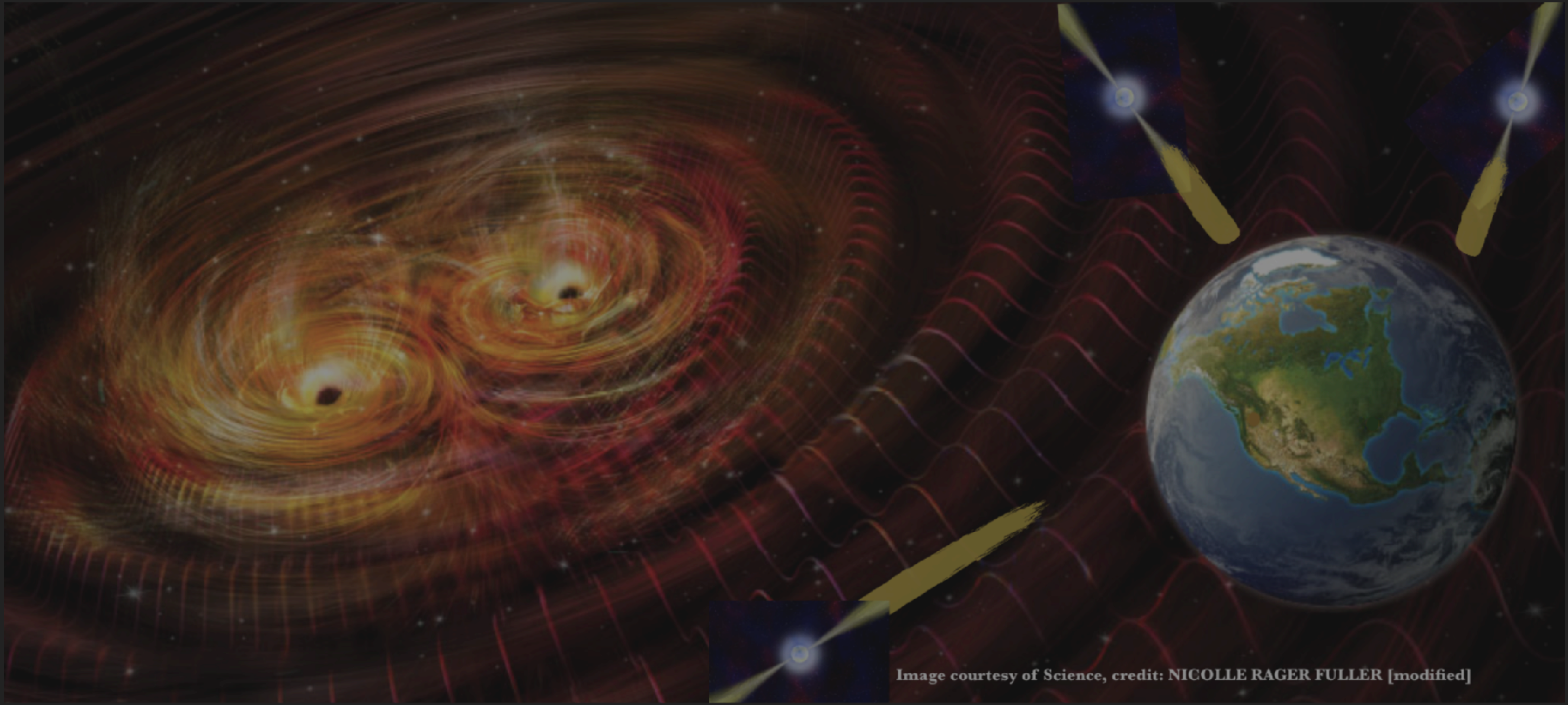
- Pulsar evolution: timing model

- Dispersion measure: ionised gas clouds

['23 NANOGrav-15]



ORIGIN OF THE SIGNAL: ASTROPHYSICAL INTERPRETATION



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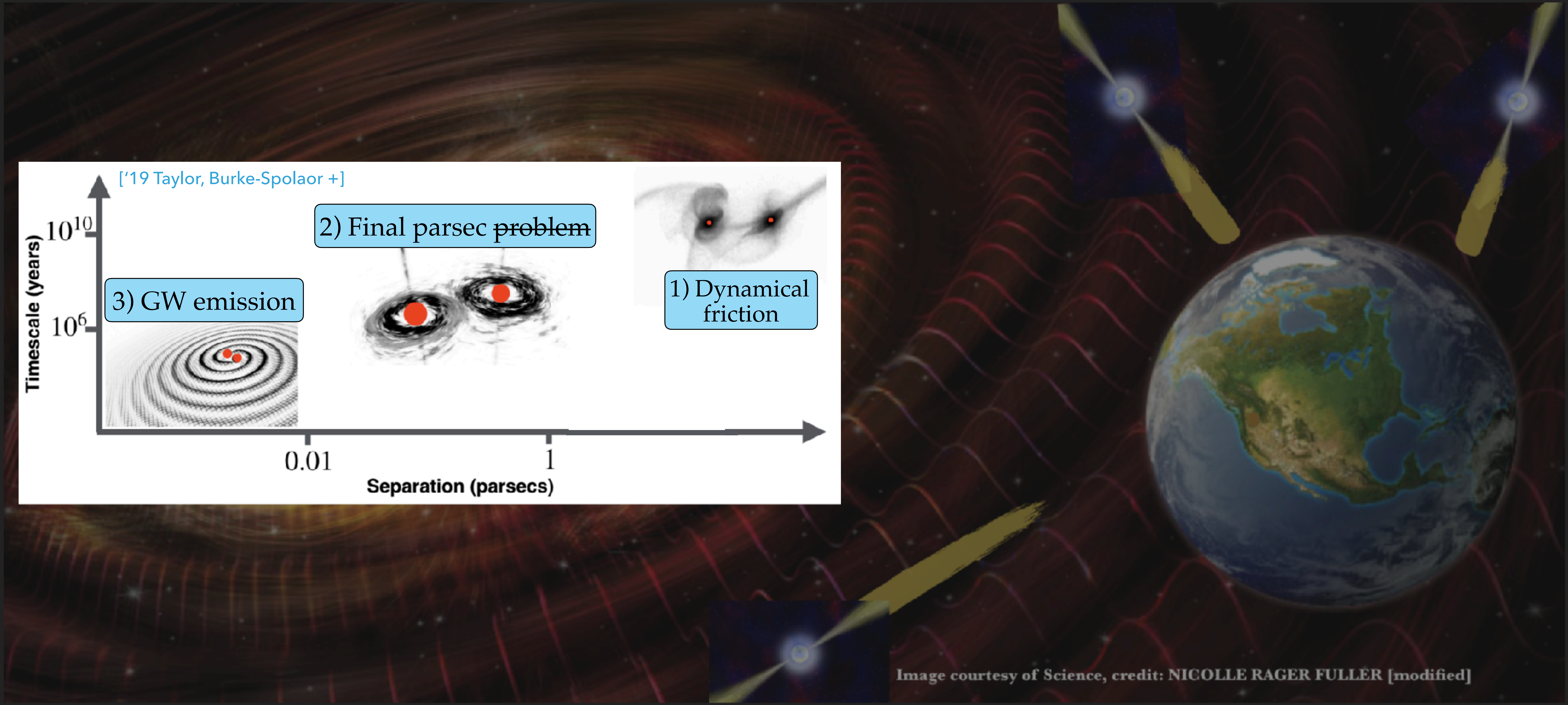

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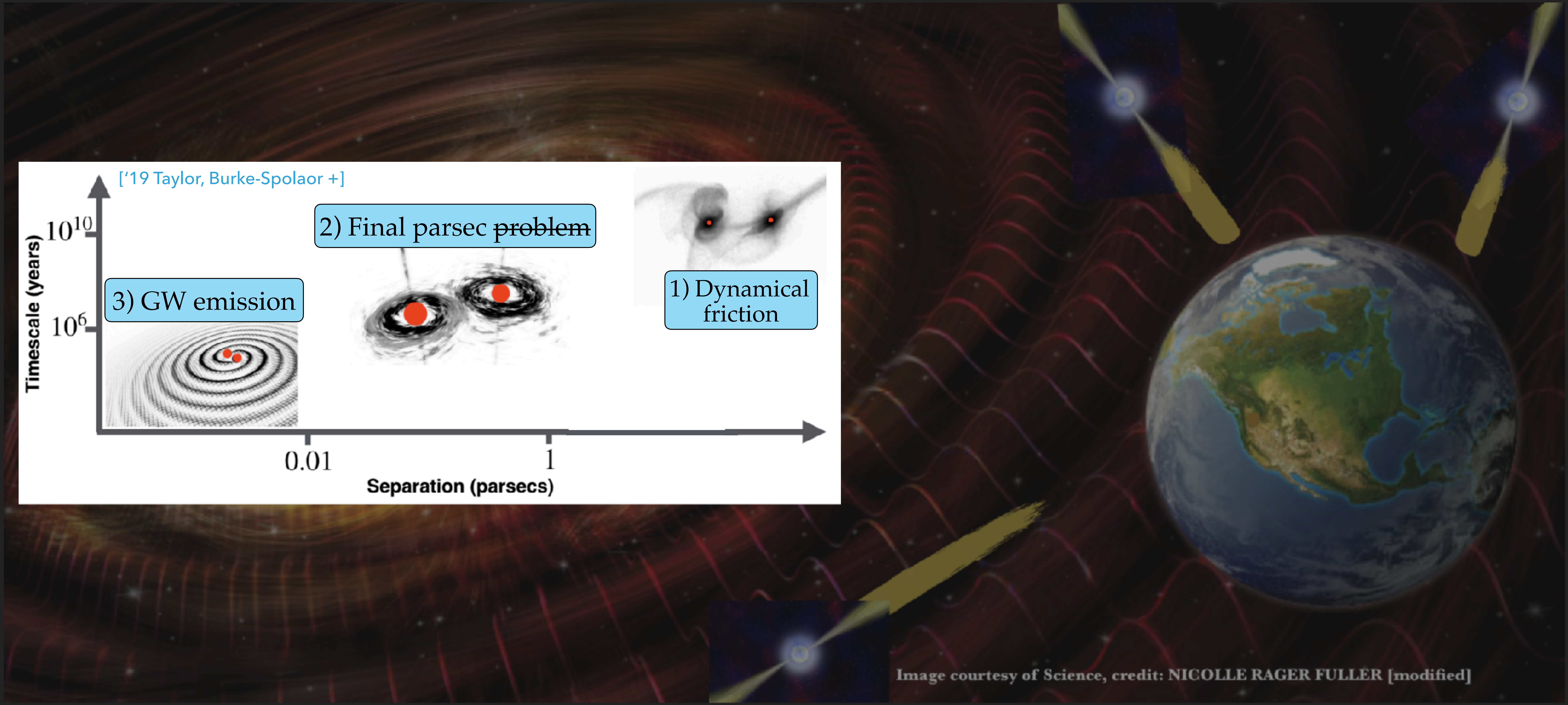

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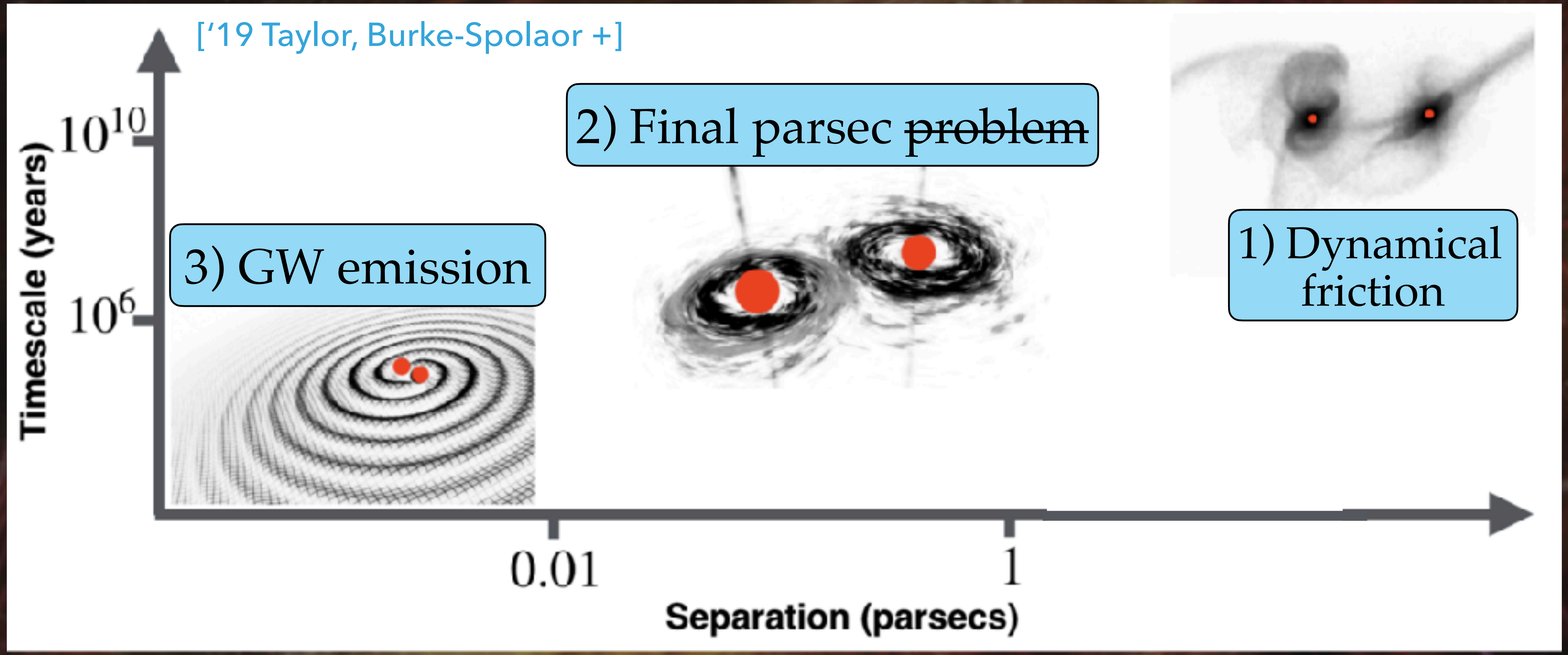


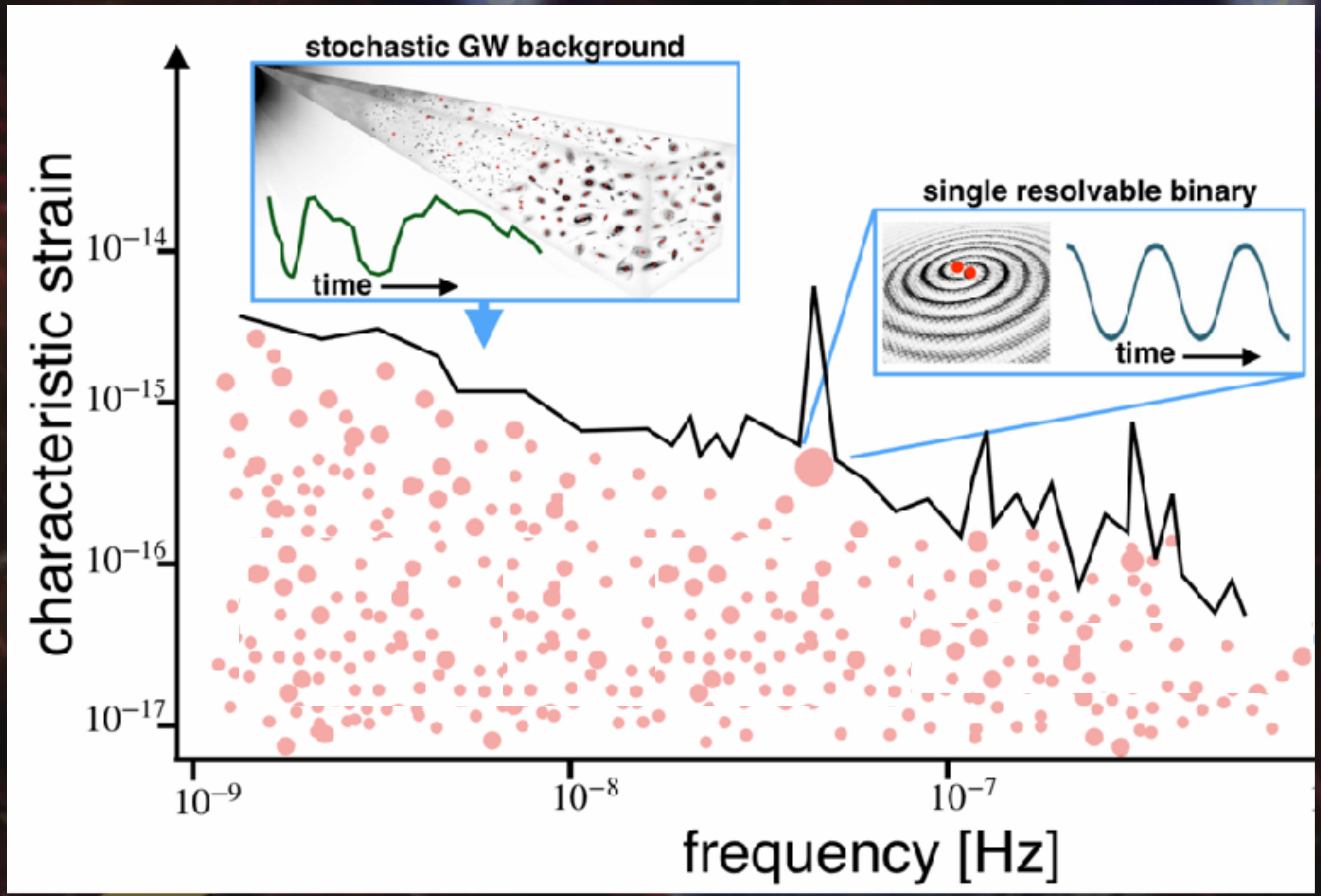
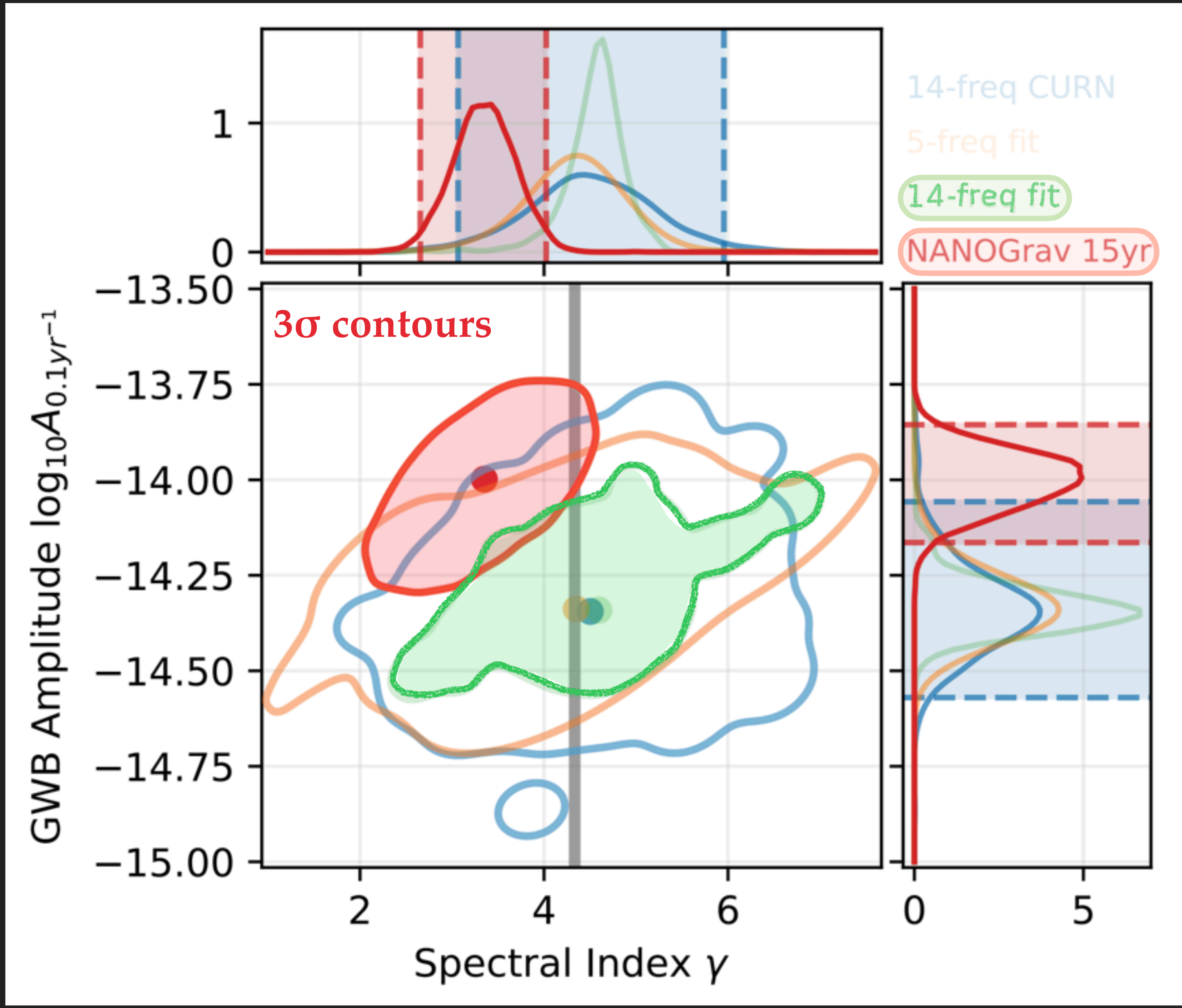


Image courtesy of Science, credit: NICOLLE RAGER FULLER [modified]

ORIGIN OF THE SIGNAL: ASTROPHYSICAL INTERPRETATION

['23 Becsy+ (NG15)]

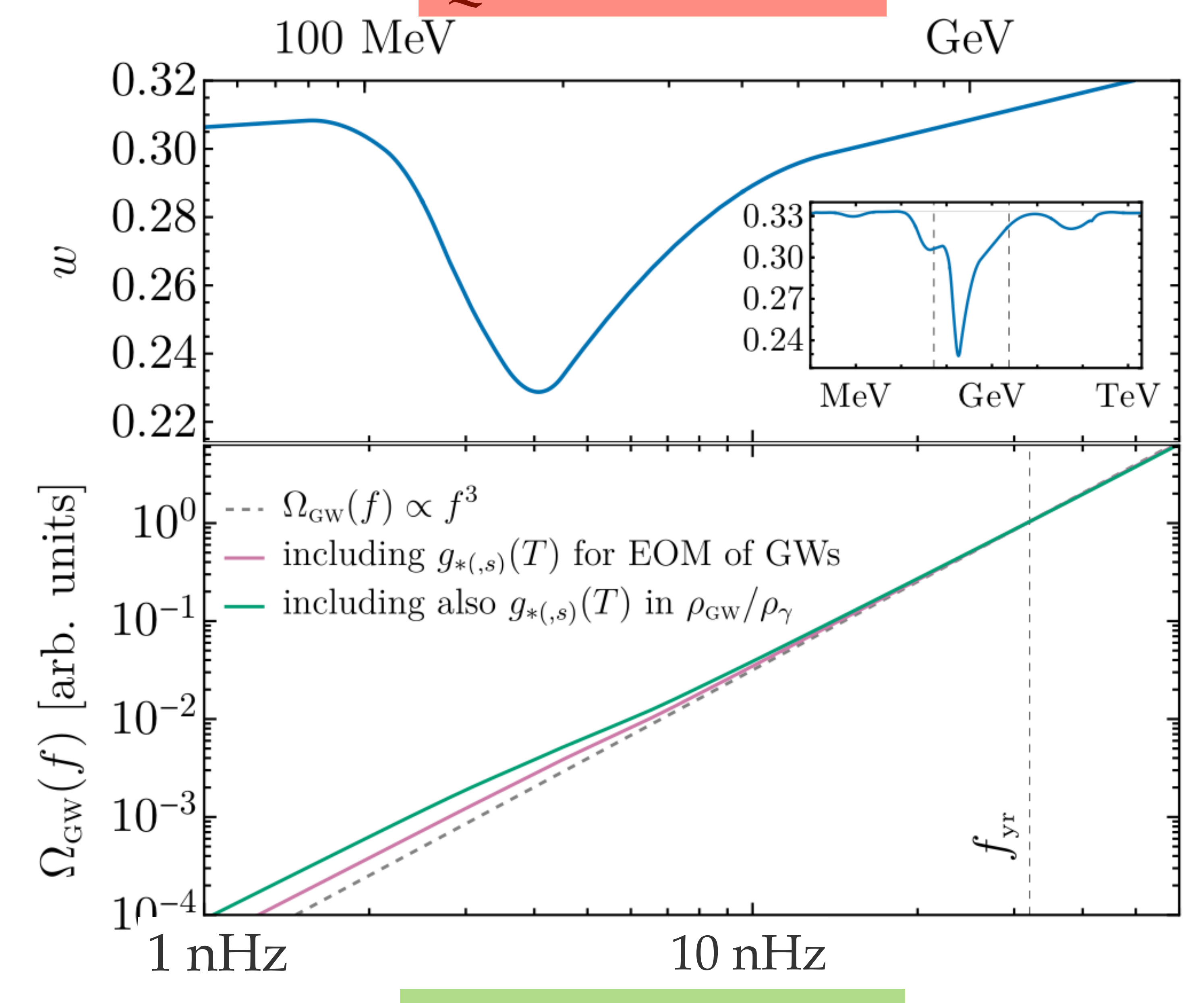


- Handle to discriminate different origins: identify **robust** spectral features

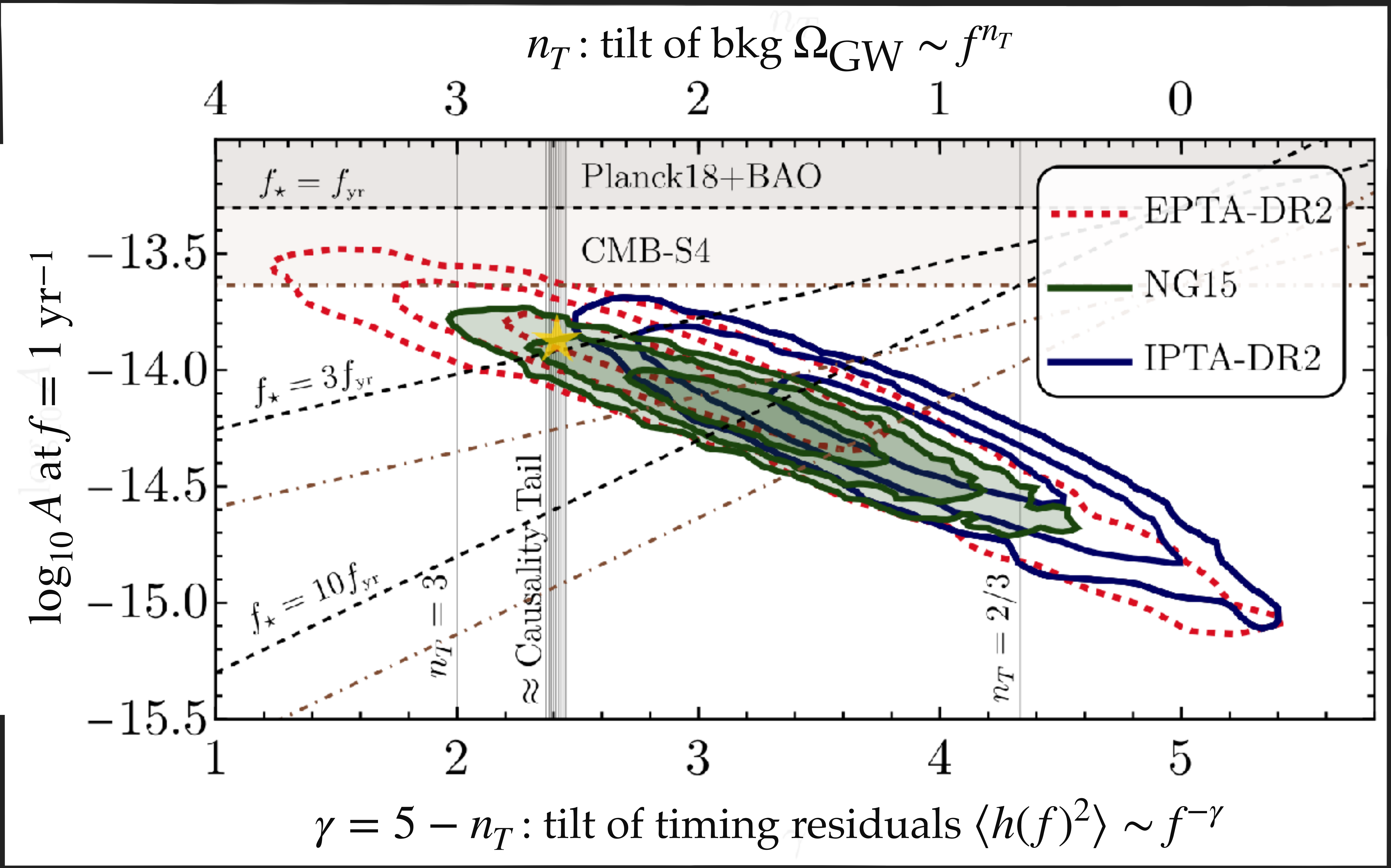
GW BACKGROUND DETECTED BY PTA

['23 Franciolini, **DR**, Rompineve]

QCD crossover



GW bkg at PTAs



GW BACKGROUND DETECTED BY PTA

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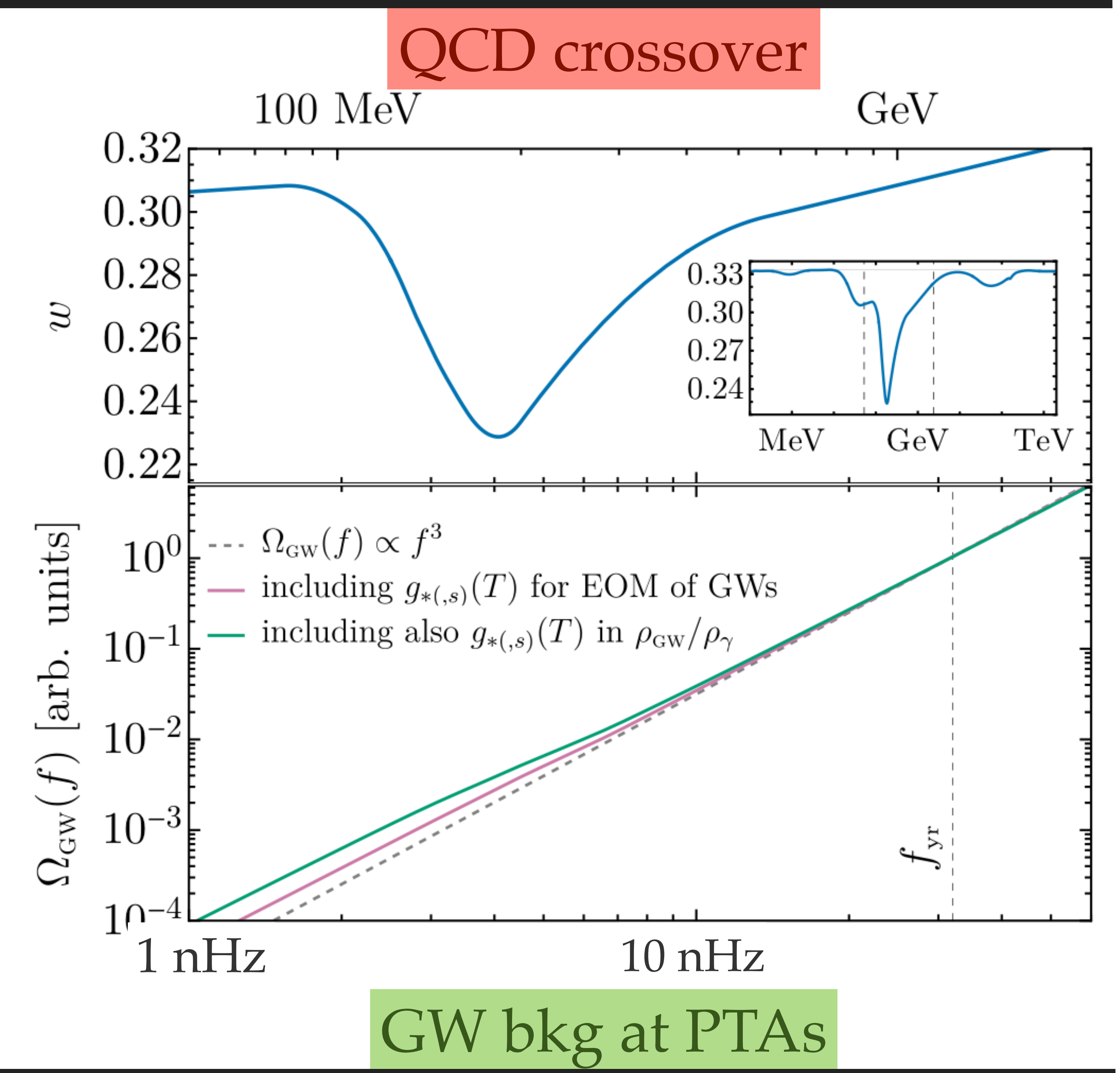
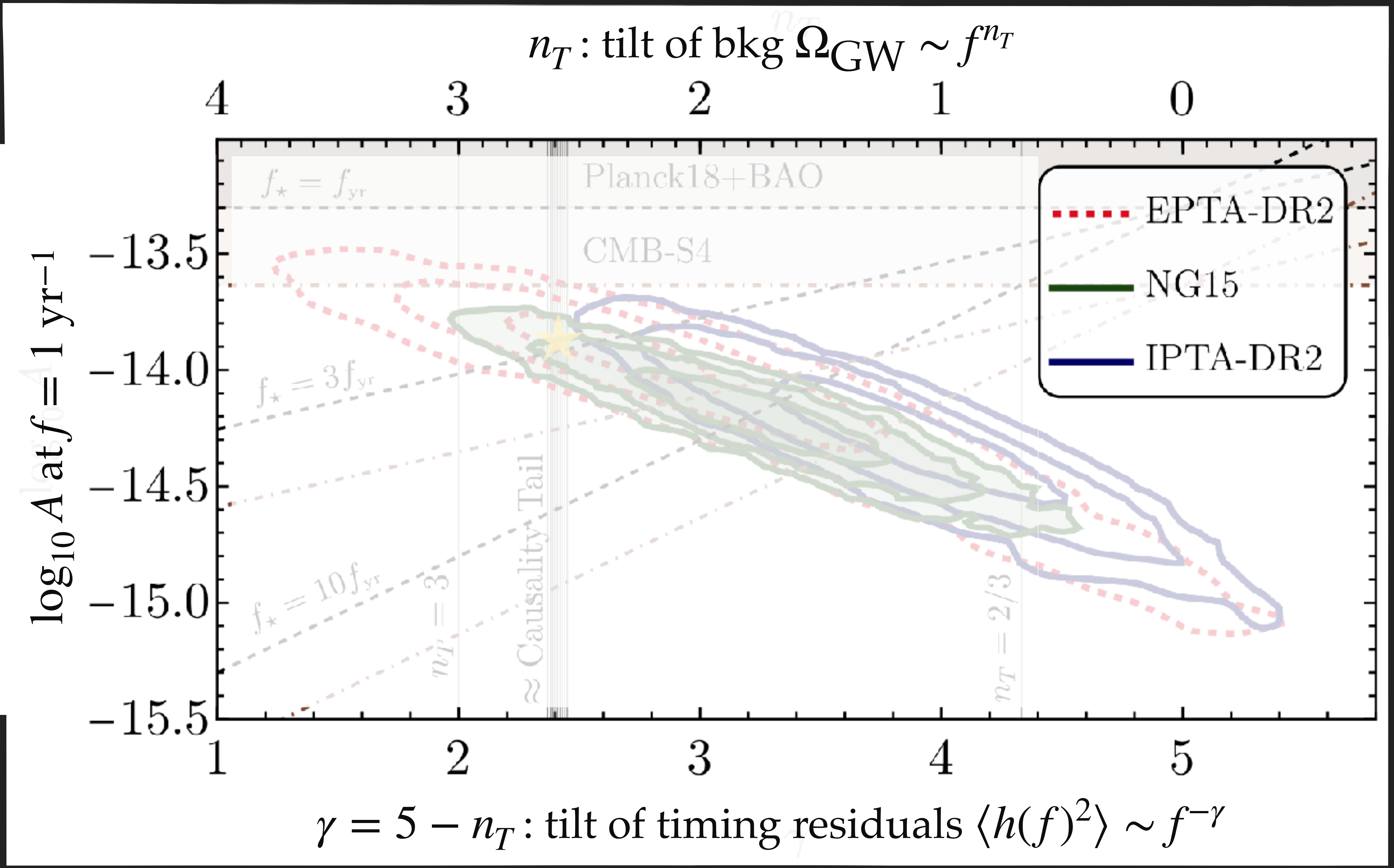
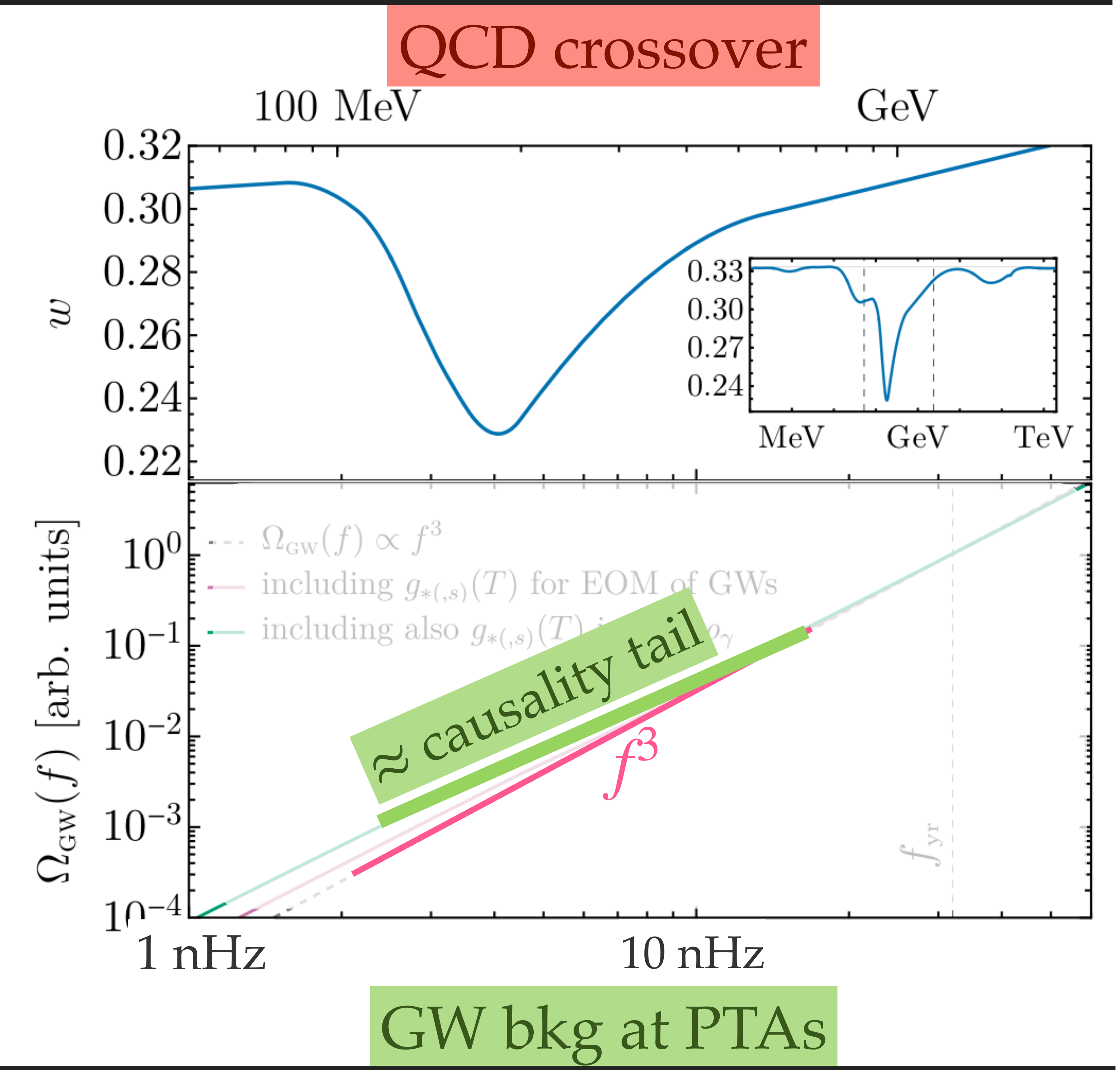
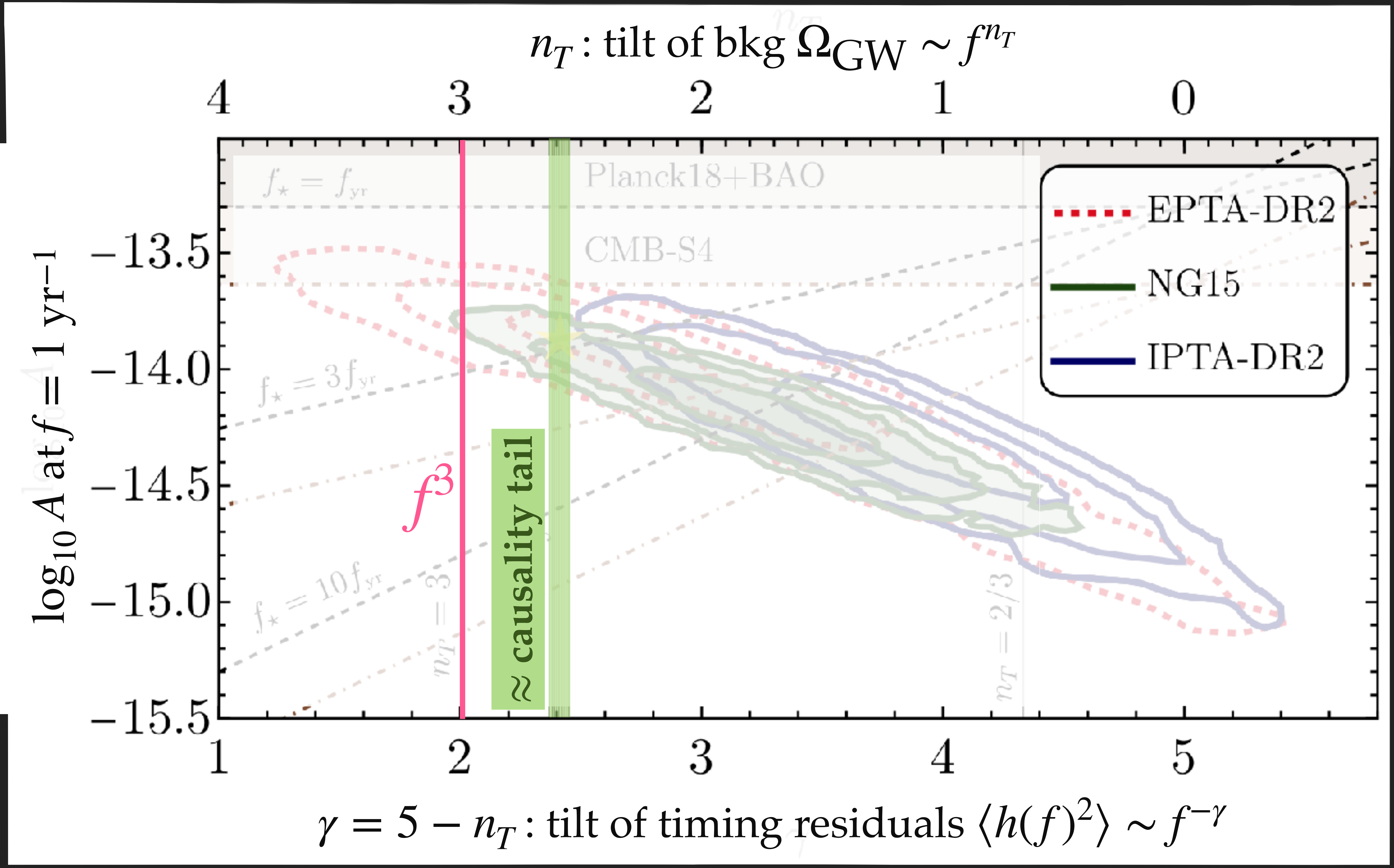
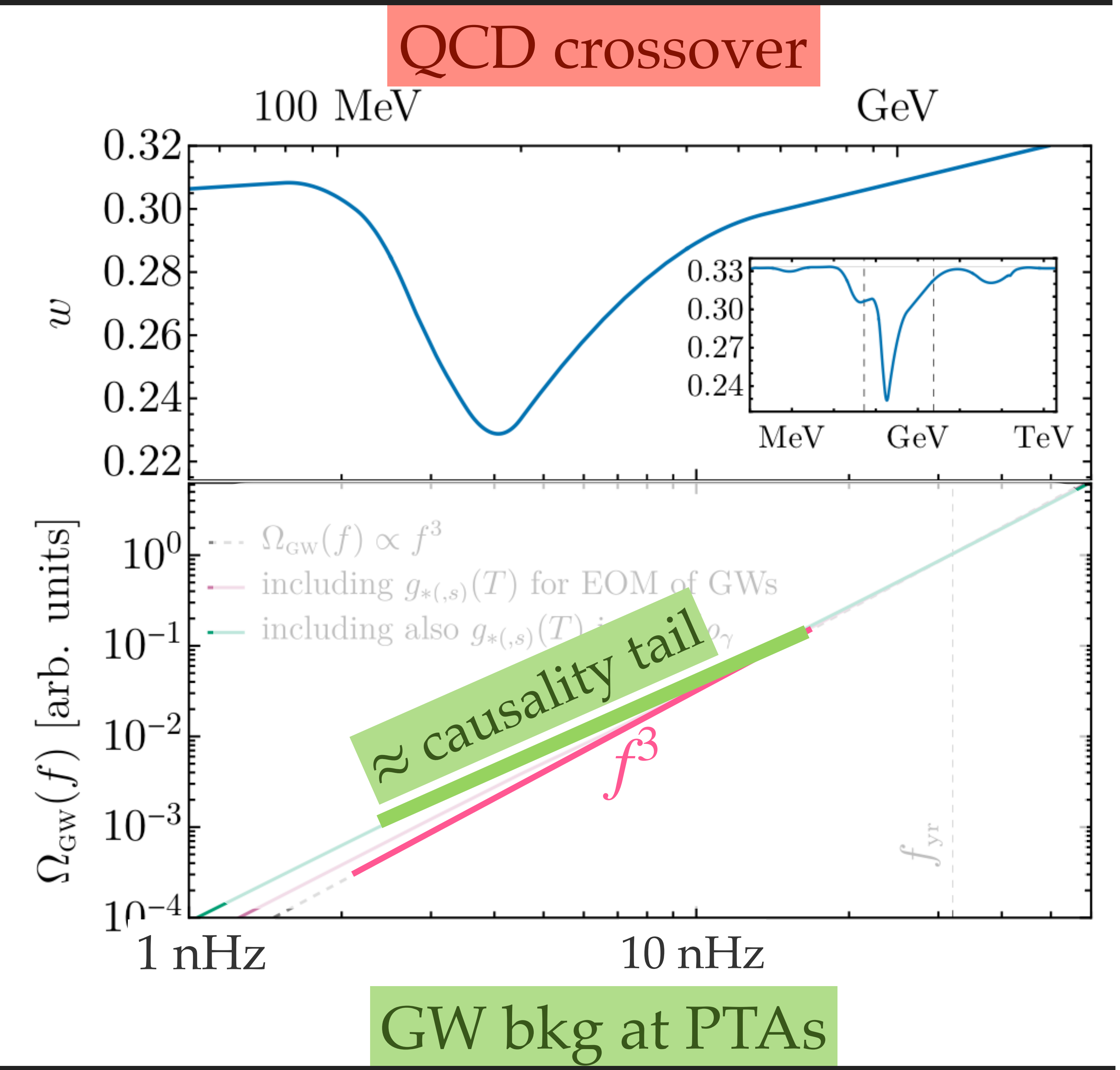


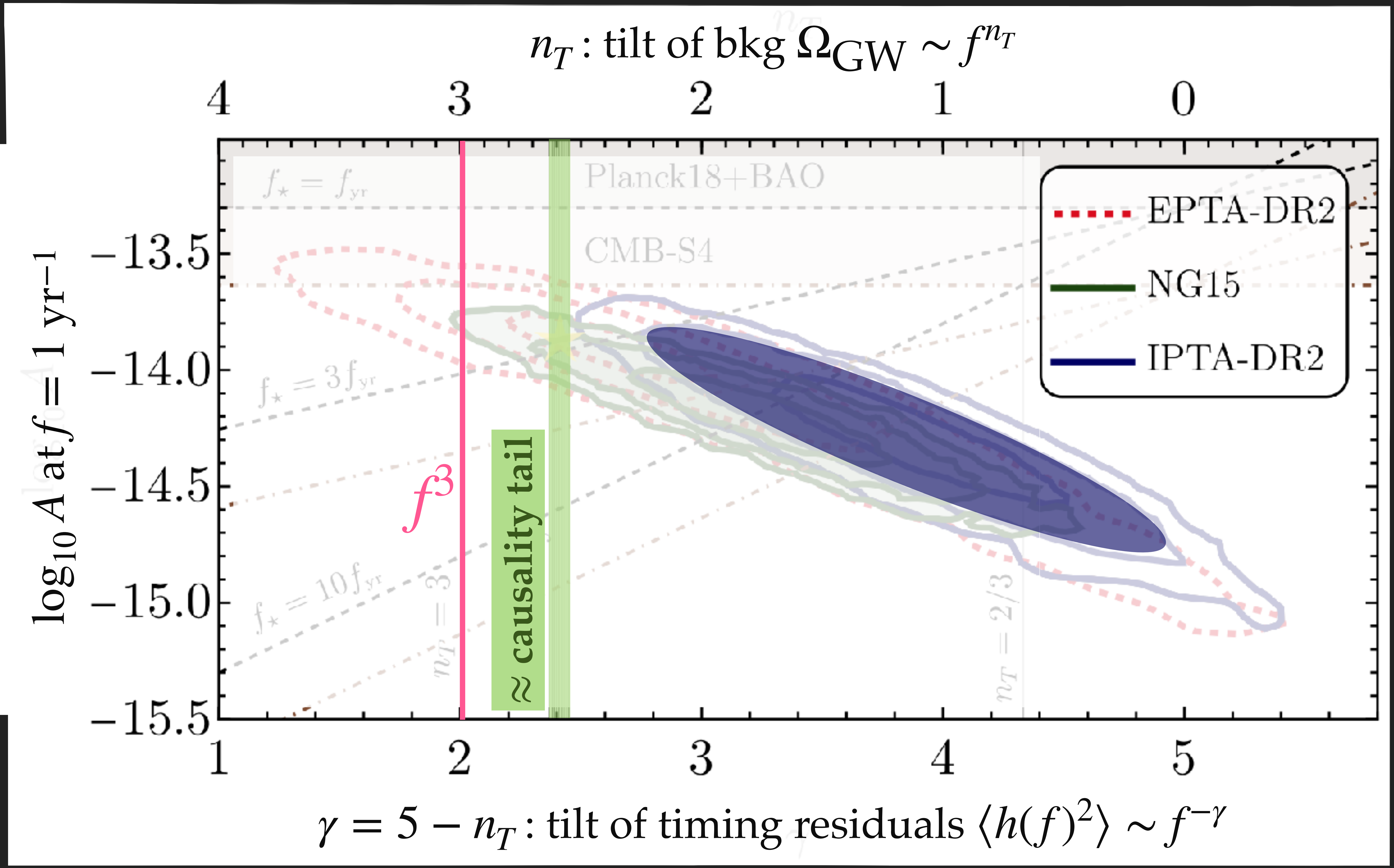


['23 Franciolini, **DR**, Rompineve]



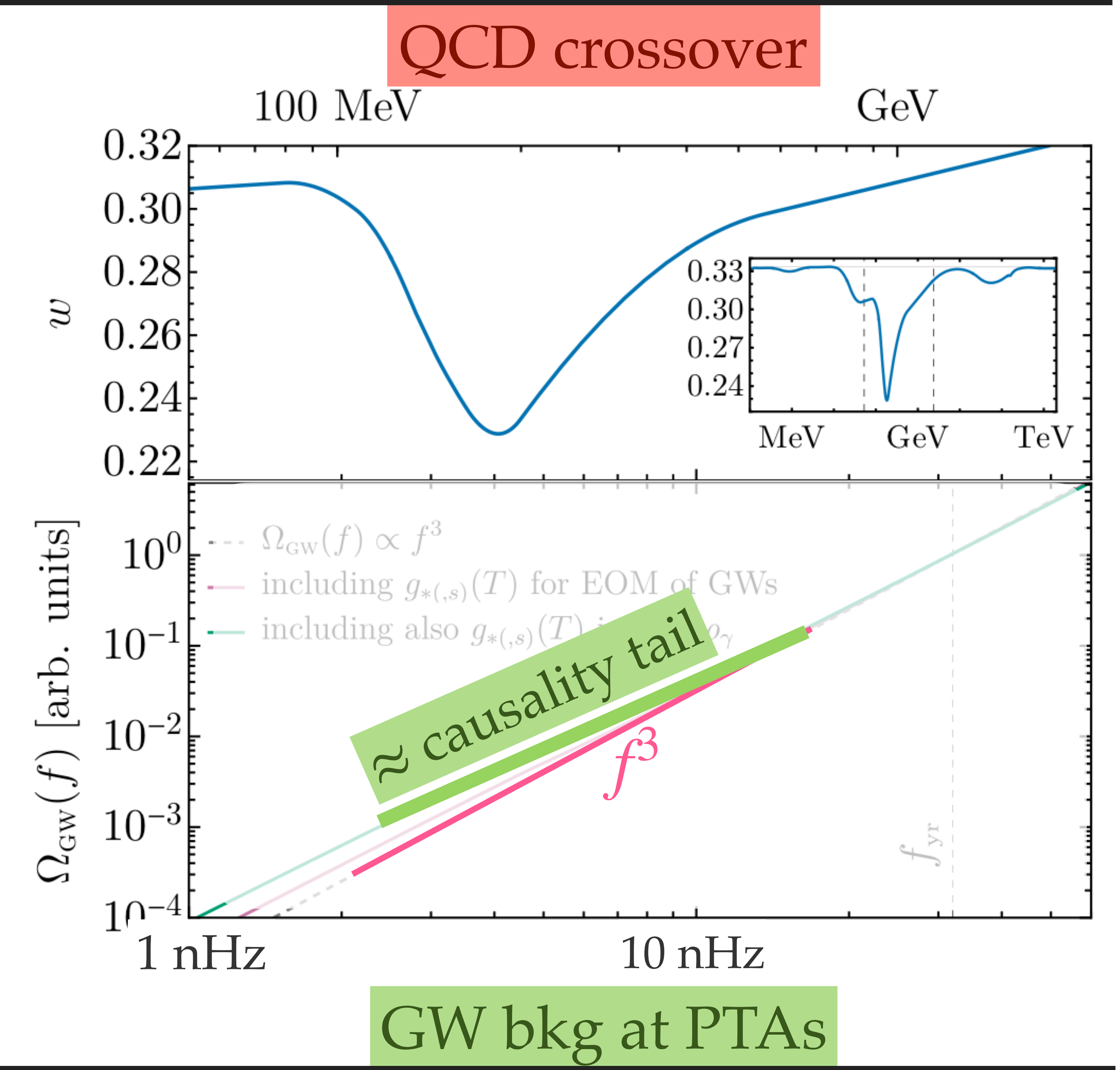


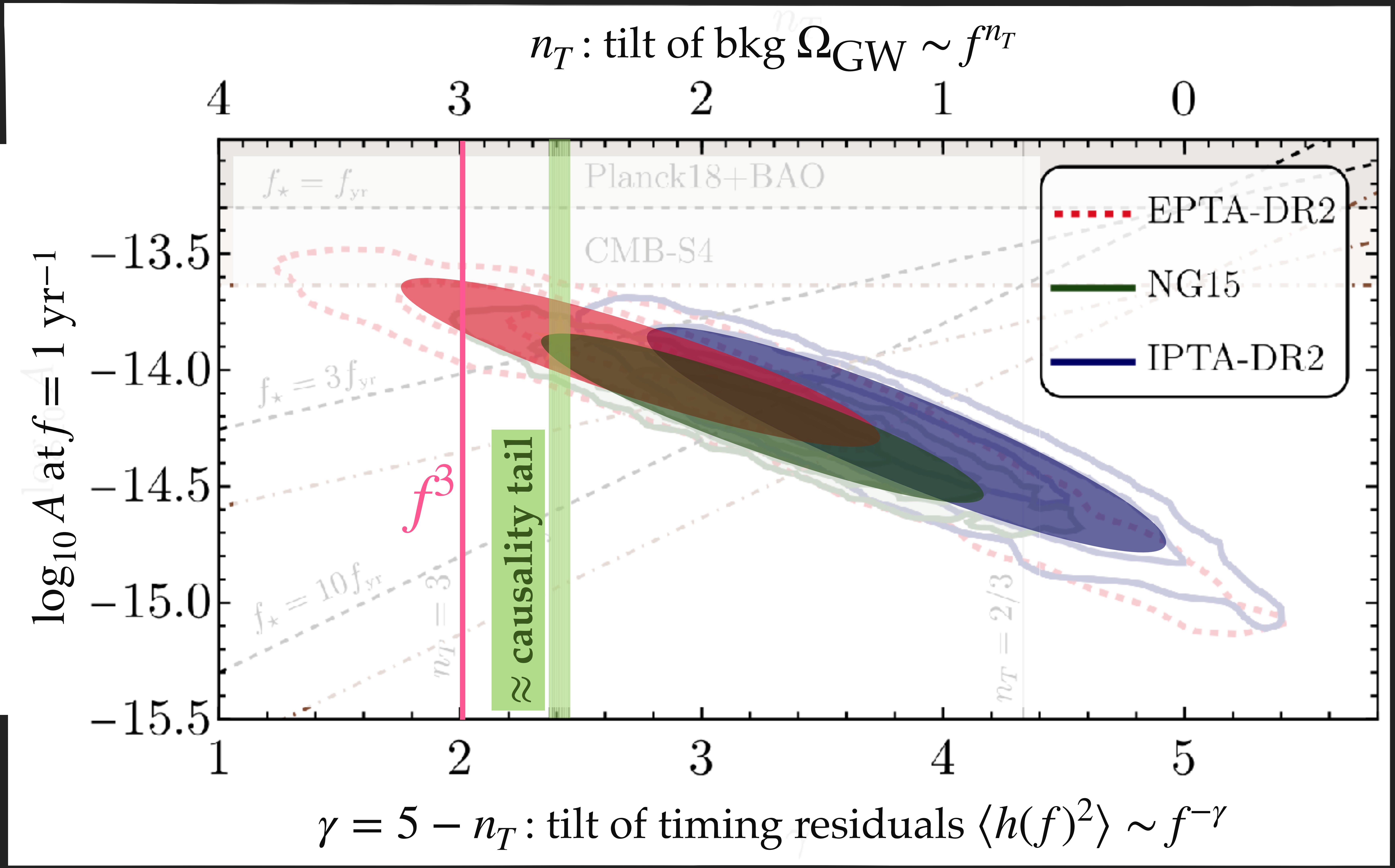

QCD crossover
100 MeV
GeV
w
MeV
GeV
TeV
$\Omega_{GW}(f)$ [arb. units]
$\Omega_{GW}(f) \propto f^3$
including $g_{*(,s)}(T)$ for EOM of GWs
$\approx$ causality tail
f^3
1 nHz
10 nHz
GW bkg at PTAs


n_T : tilt of bkg $\Omega_{GW} \sim f^{n_T}$
4
3
2
1
0
Planck18+BAO
CMB-S4
EPTA-DR2
NG15
IPTA-DR2
$\log_{10} A$ at $f = 1$ yr^{-1}
−13.5
−14.0
−14.5
−15.0
−15.5
f^3
$\approx$ causality tail
1
2
3
4
5
$\gamma = 5 - n_T$: tilt of timing residuals $\langle h(f)^2 \rangle \sim f^{-\gamma}$

GW BACKGROUND DETECTED BY PTA

['23 Franciolini, **DR**, Rompineve]



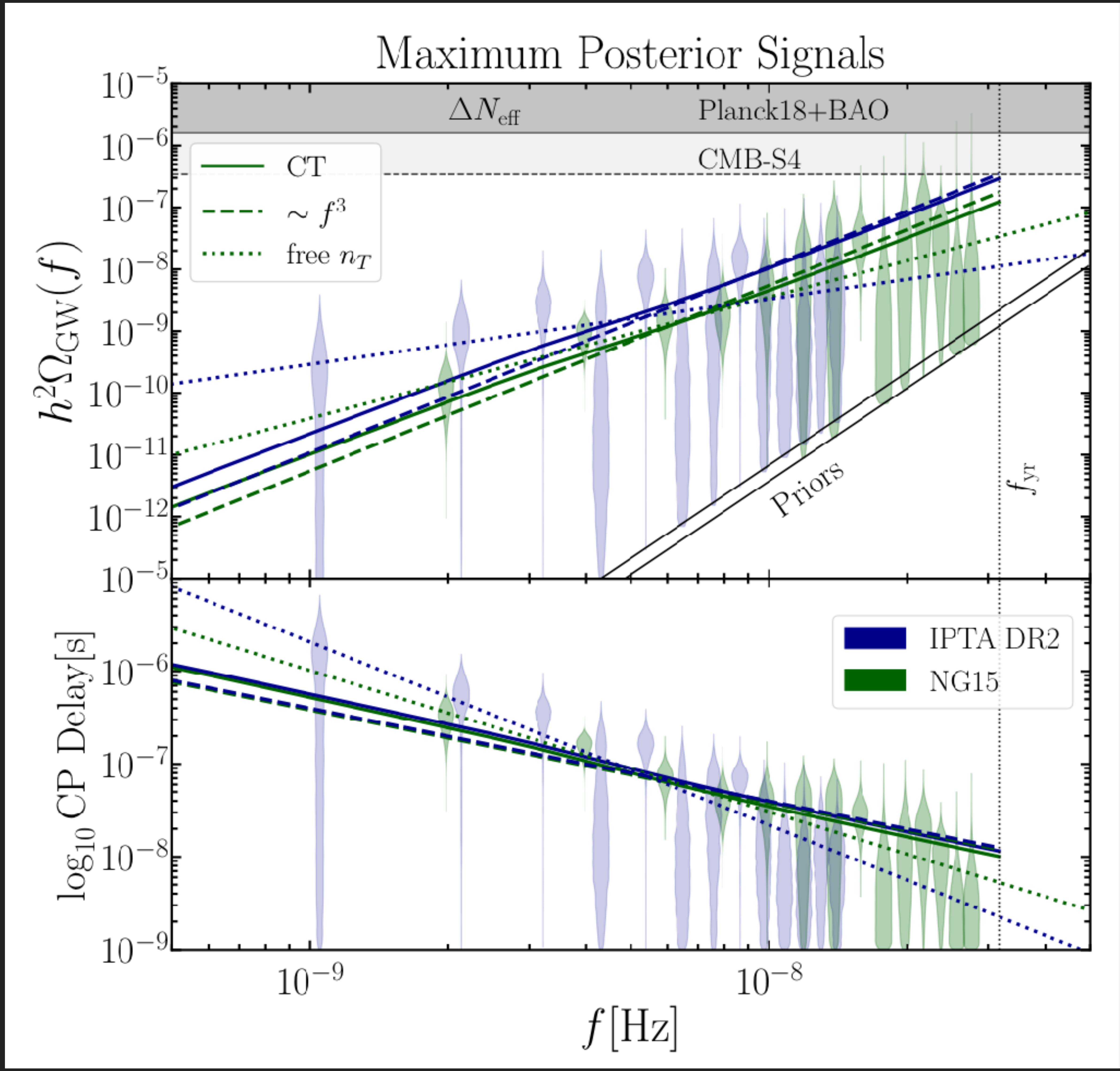


- Bayesian model comparison: causality tail vs. f^3

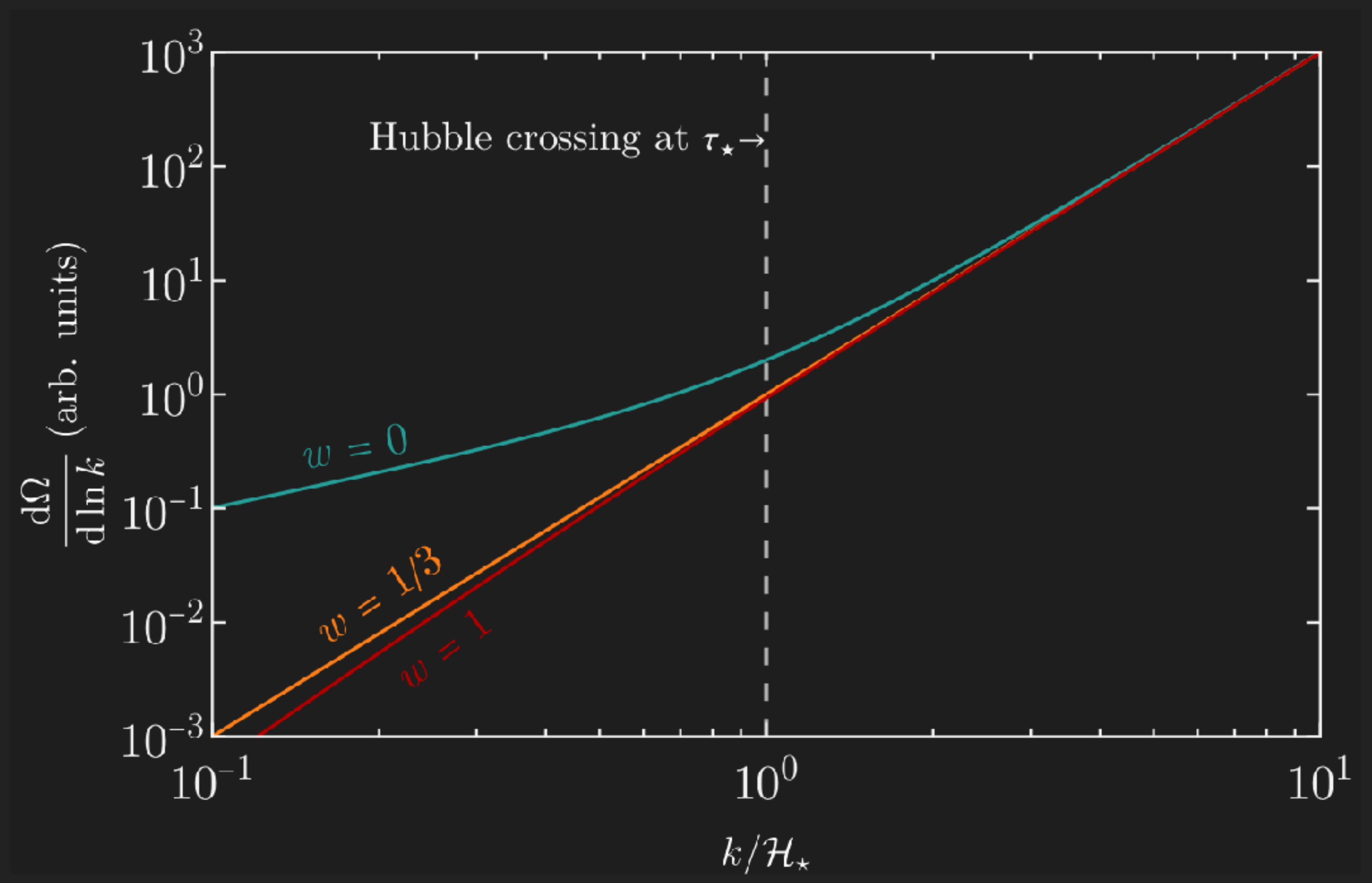
$$\log_{10}\mathscr{B} = \begin{cases} 1.6 & \text{(NANOGrav-15)} \\ 1.3 & \text{(IPTA-DR2)} \end{cases}$$

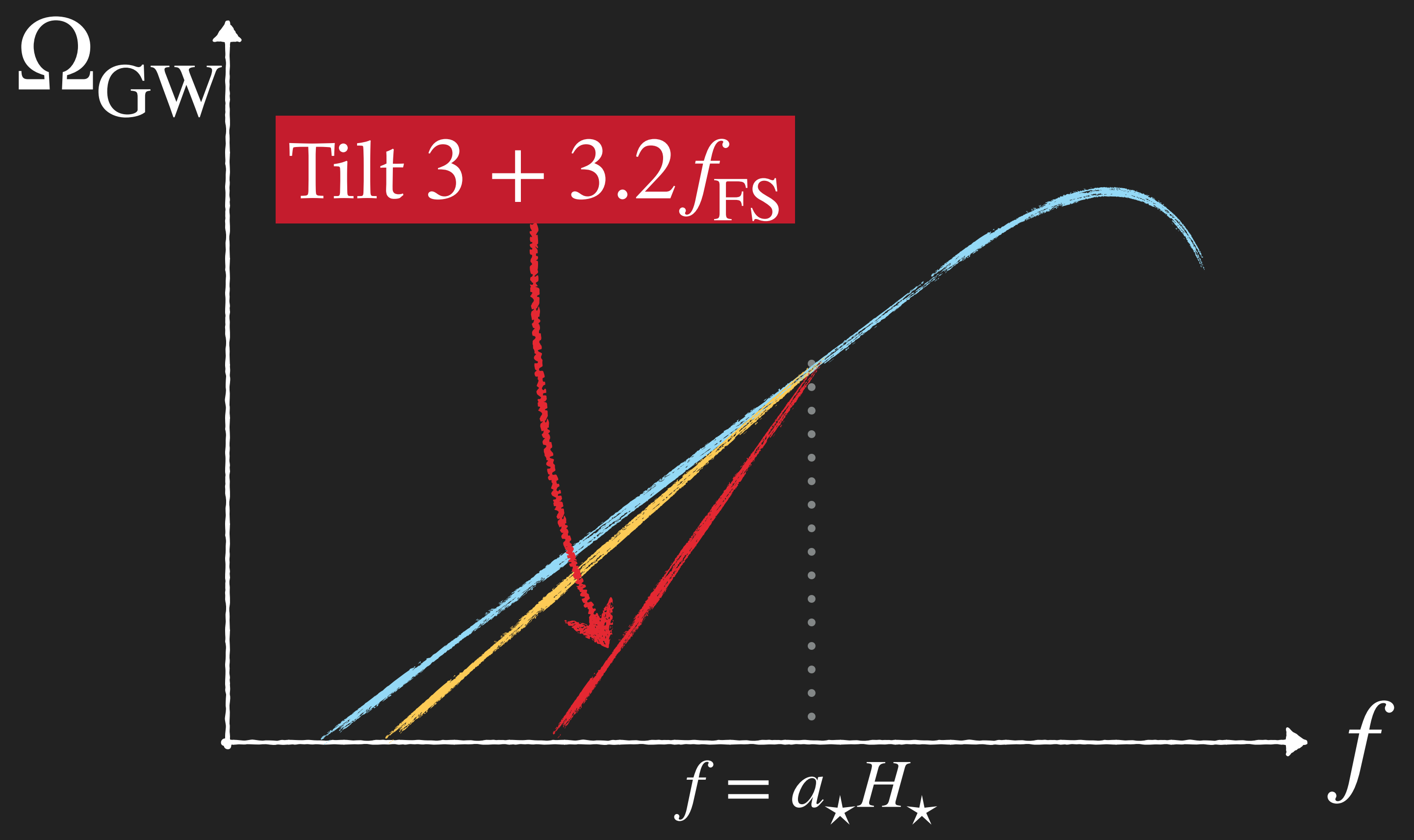
(*strong* evidence)

- Must account for causality tail in model comparison for PTAs



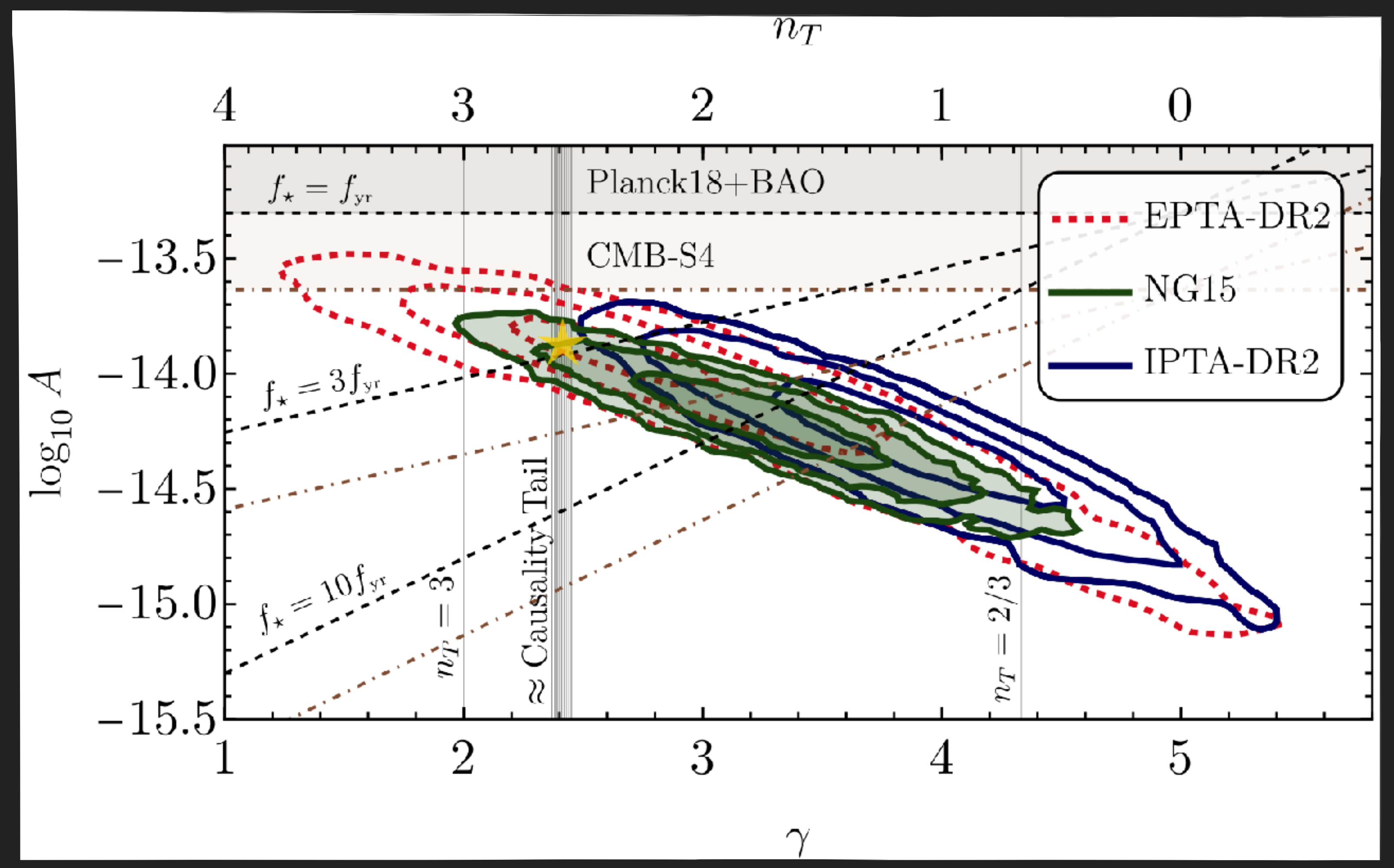
- Causality tail ⇔ probe w and $f_{\rm FS}$ independently of the primordial GW source





Hook, Marques-Tavares, **DR**
JHEP (2021)

- SM effects on the causality tail must be included at PTAs



Franciolini, **DR**, Rompineve
Phys. Rev. Lett. (2024)

Buchalter Cosmology Prize 2023

9 — 20 September 2024

POLLICA PHYSICS CENTRE

Fundamental Physics and Gravitational Wave Detectors

Gravitational waves (GWs) from compact binaries have been detected in the kHz regime, and Pulsar Timing Arrays are revealing a GW background in the nHz band. Experimental ideas spanning from nHz to MHz are being explored to cover the gravitational spectrum. This is an exciting time to explore what GWs can uncover about fundamental physics and cosmology by detecting astrophysical and primordial GW sources, as well as exploring effects that could be induced by various Dark Matter candidates.

This workshop will unite astrophysicists, cosmologists, and particle physicists to discuss open questions and define theoretical targets, guiding the field in experimental strategies across the gravitational spectrum to learn about our Universe. All of this is to be set against the backdrop of the medieval town of Pollica in southwestern Italy (Cilento region).

ORGANIZING COMMITTEE

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Djuna Croon (Durham University)

Paolo Pani (Sapienza University & INFN Roma)

Davide Racco (ETH & University of Zurich)

Géraldine Servant (DESY & Universität Hamburg)

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APPLICATIONS ARE OPEN!

Thank you for your attention!

BACKUP SLIDES

DERIVATION OF CAUSALITY TAIL

wavelength $k^{-1} \gg$ corr. length λ_{source}

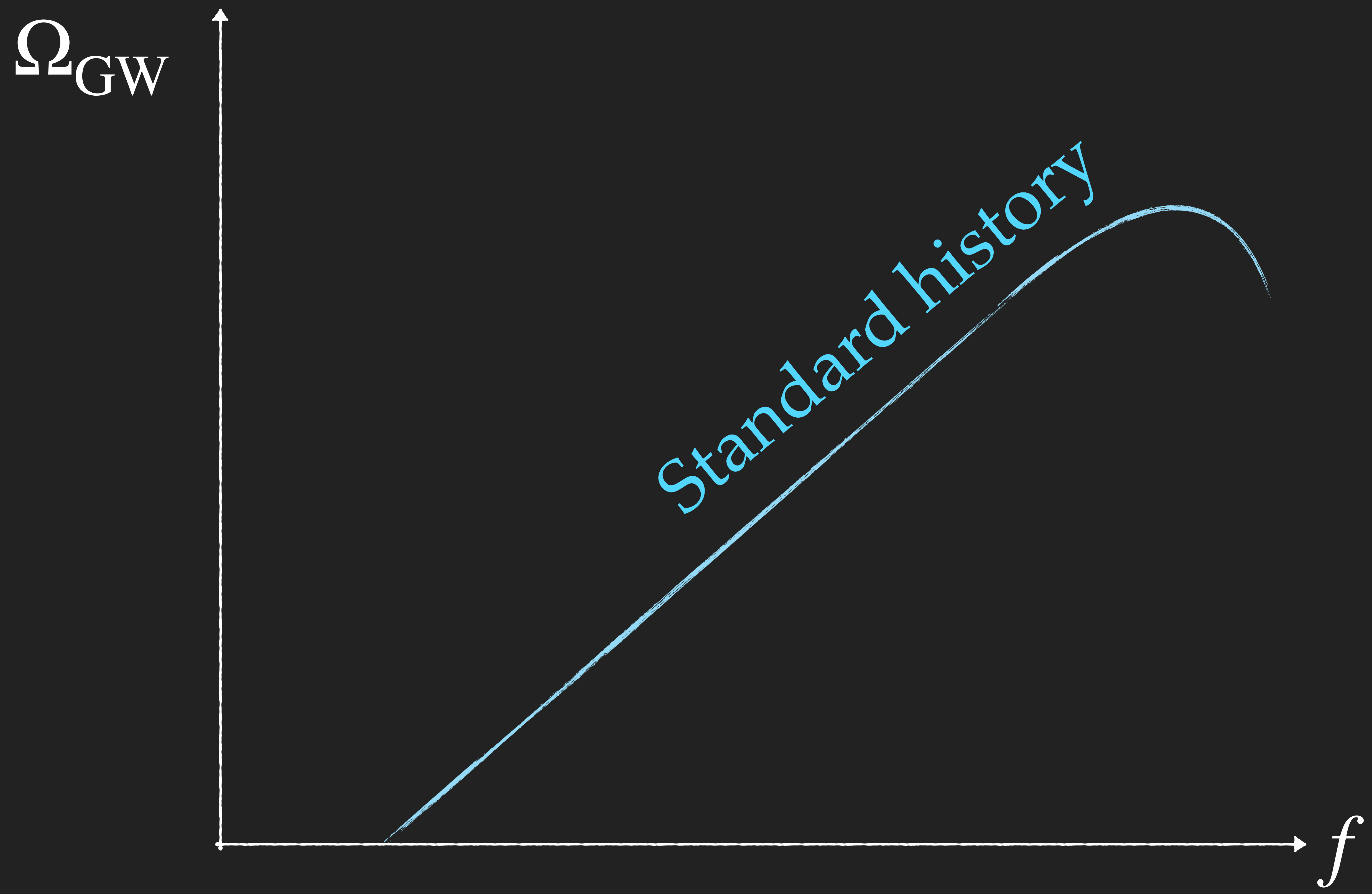
period $f^{-1} \gg$ duration of phase transition β^{-1}

$$\Box h = \boxed{J_\star}\,\boxed{\delta(\tau - \tau_\star)} \quad \Longrightarrow \quad \begin{cases} h = 0 \\ h' = J_\star \end{cases}$$

$$|h(\tau)| \sim \underbrace{\frac{a_\star}{a}}_{\text{redshift}} \cdot \underbrace{\frac{1}{k}}_{\text{for RD}} \cdot J_\star$$

$$\frac{\mathrm{d}\,\Omega_{\text{GW}}}{\mathrm{d}\ln k} \sim \underbrace{k^3}_{\text{phase space}} \cdot \underbrace{k^2}_{\rho_{\text{GW}} \sim h'^2} \cdot \underbrace{\frac{1}{k^2}}_{\text{for RD}} \cdot \underbrace{P_{\Pi}(k)}_{k \text{ ind. from causality}} \sim k^3 .$$

- Intermediate MD phase → amplify low-f spectrum



 ['20 Hook, Marques-Tavares, **DR**]

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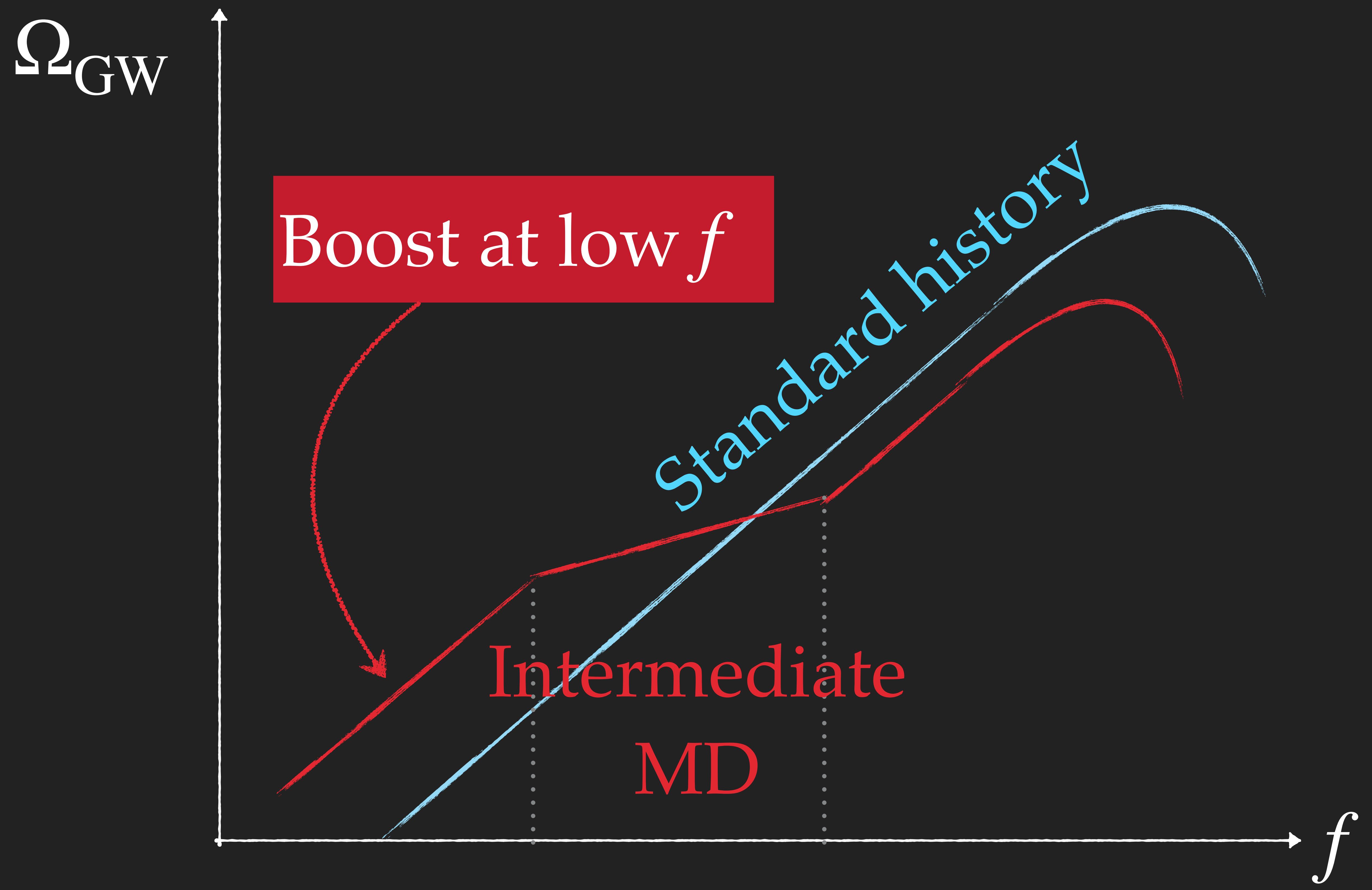
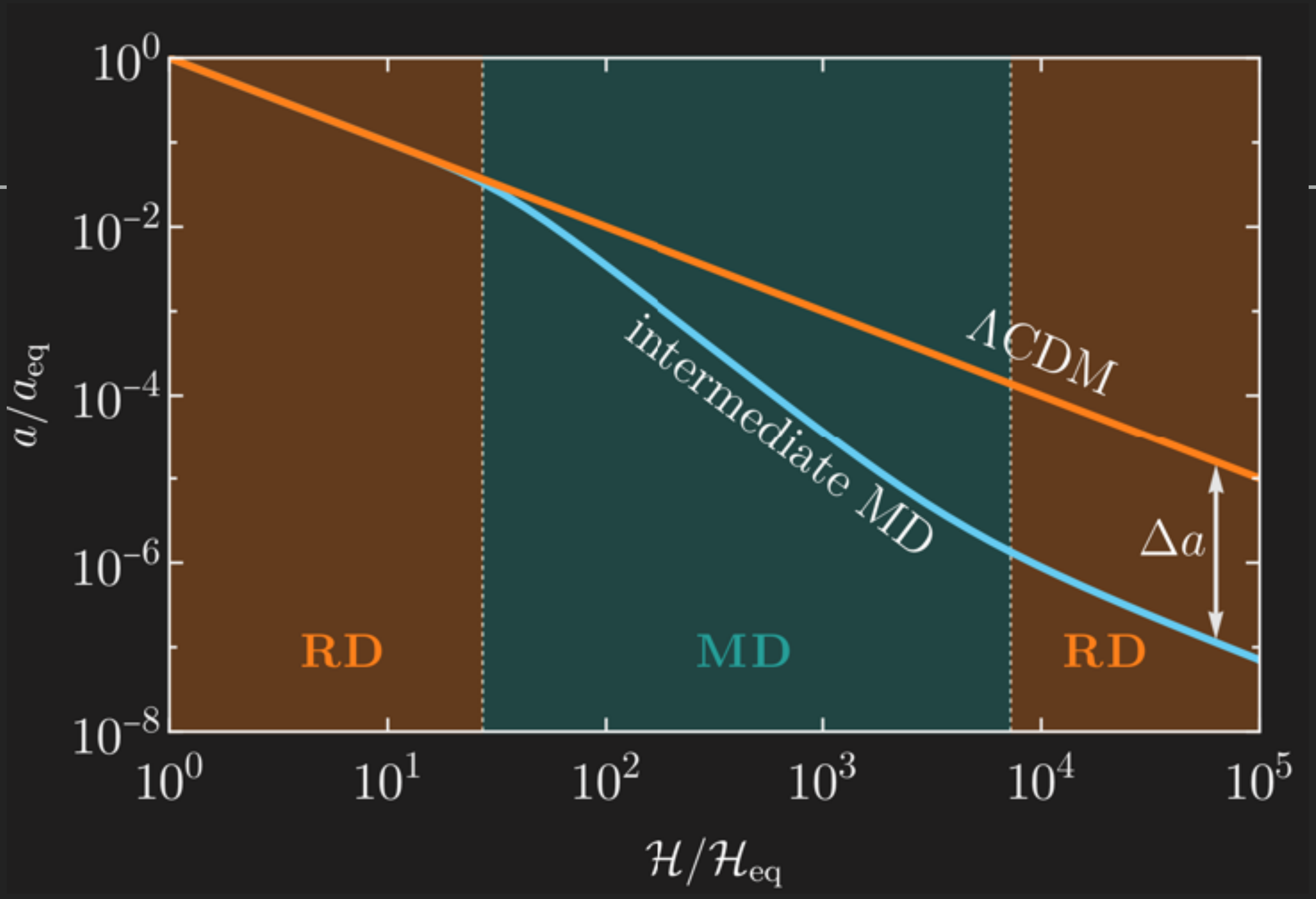
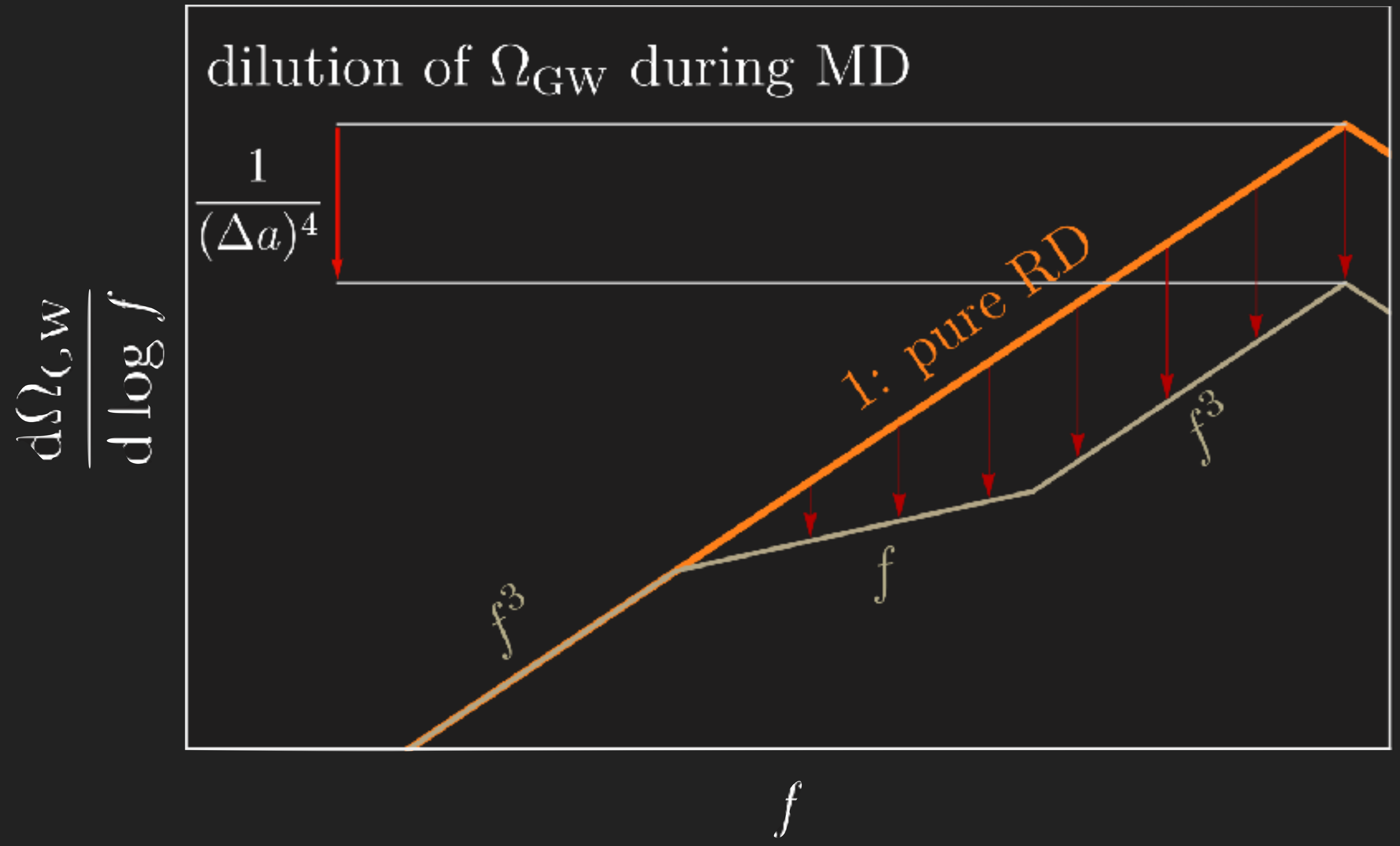
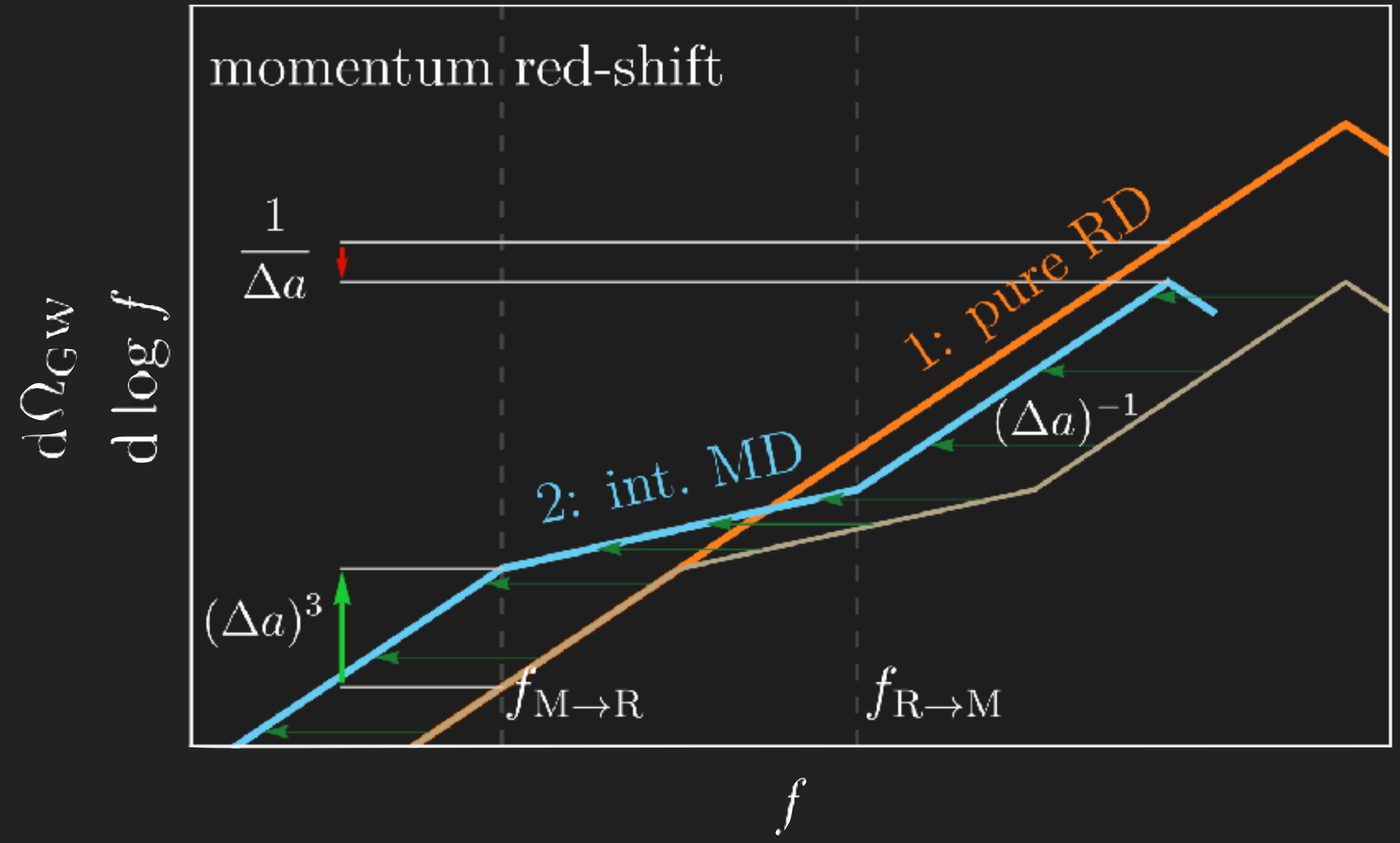


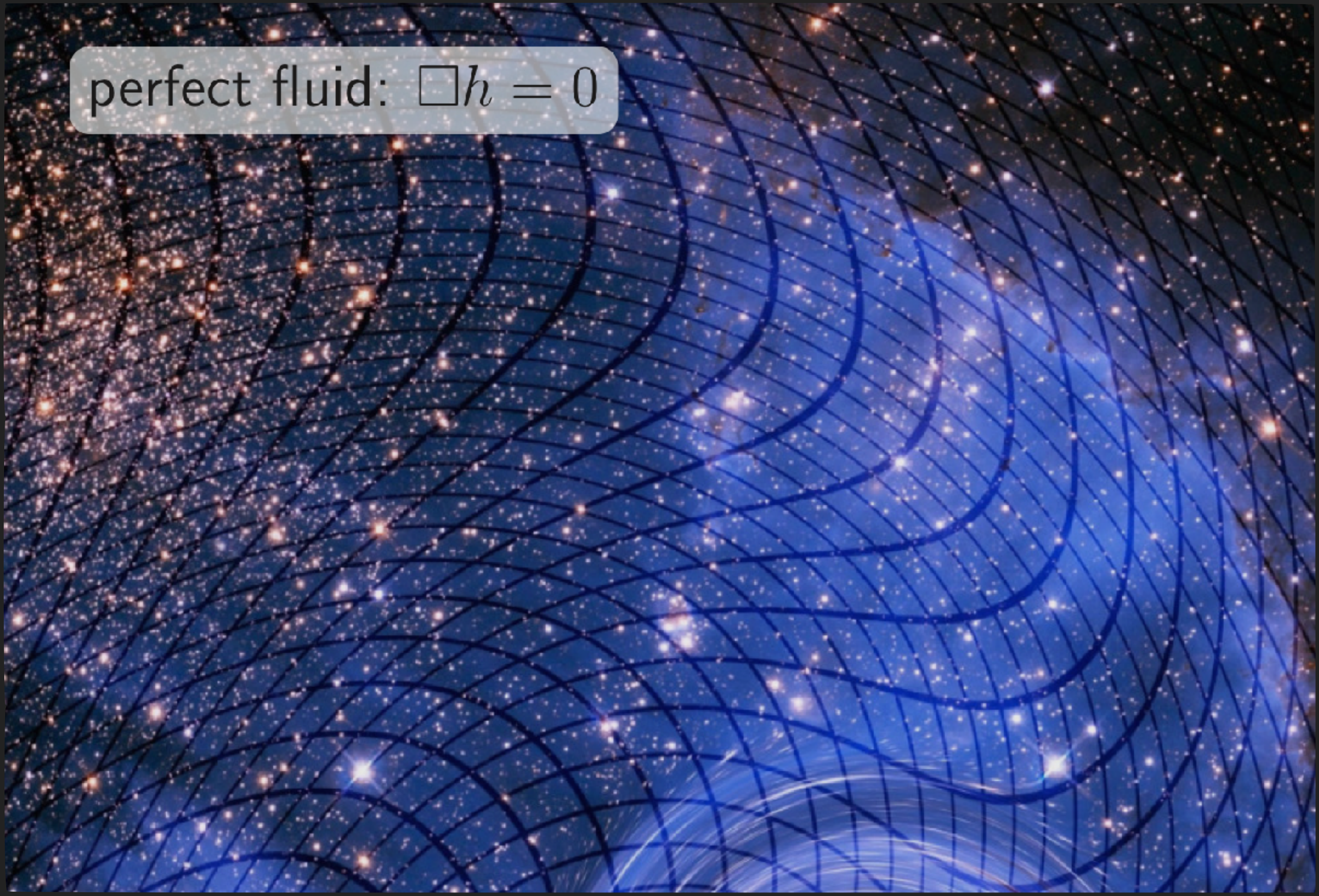
INTERMEDIATE MD



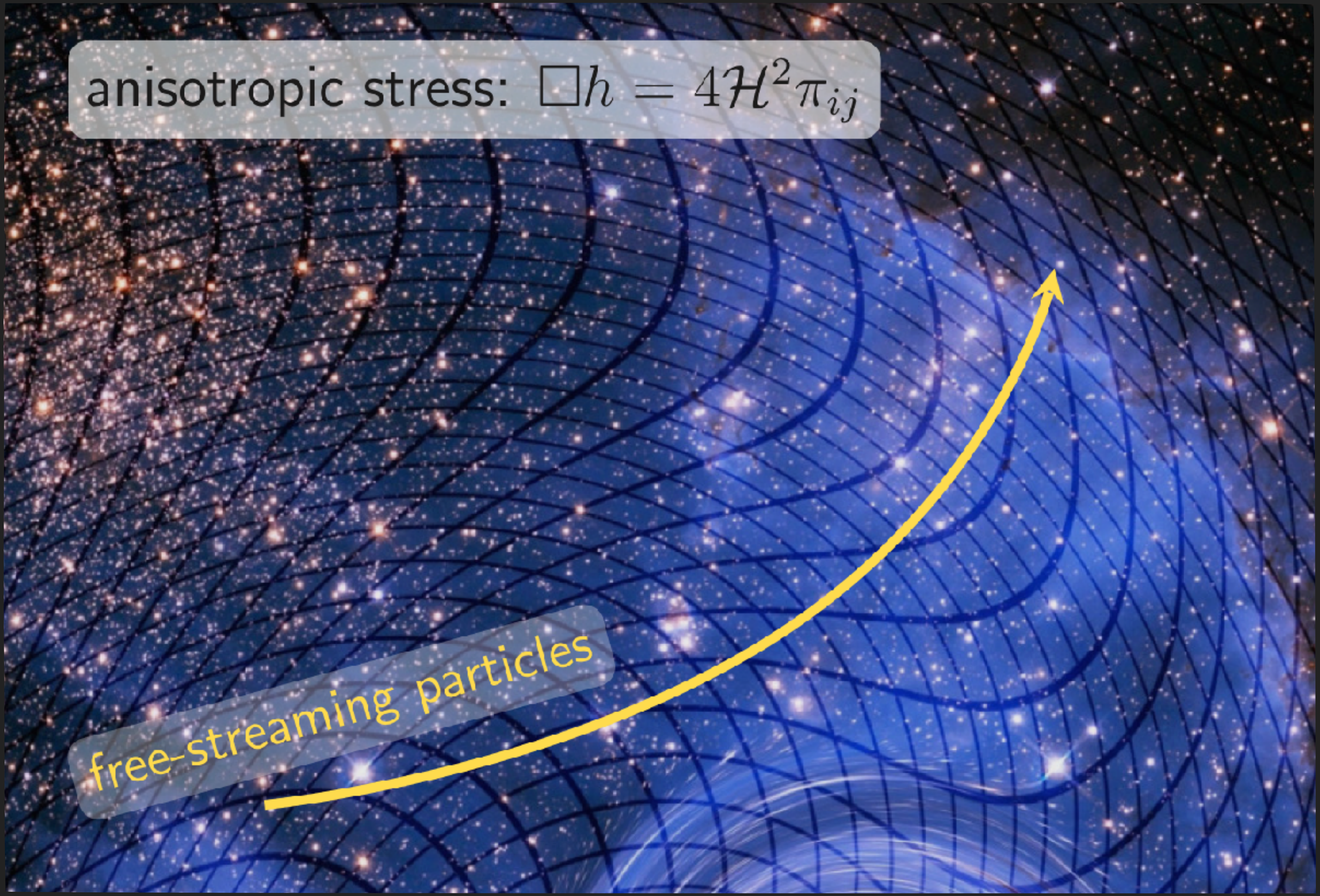




EFFECTS ON GW PROPAGATION



['86 Bond]
['04 Weinberg]
['06 Watanabe, Komatsu]



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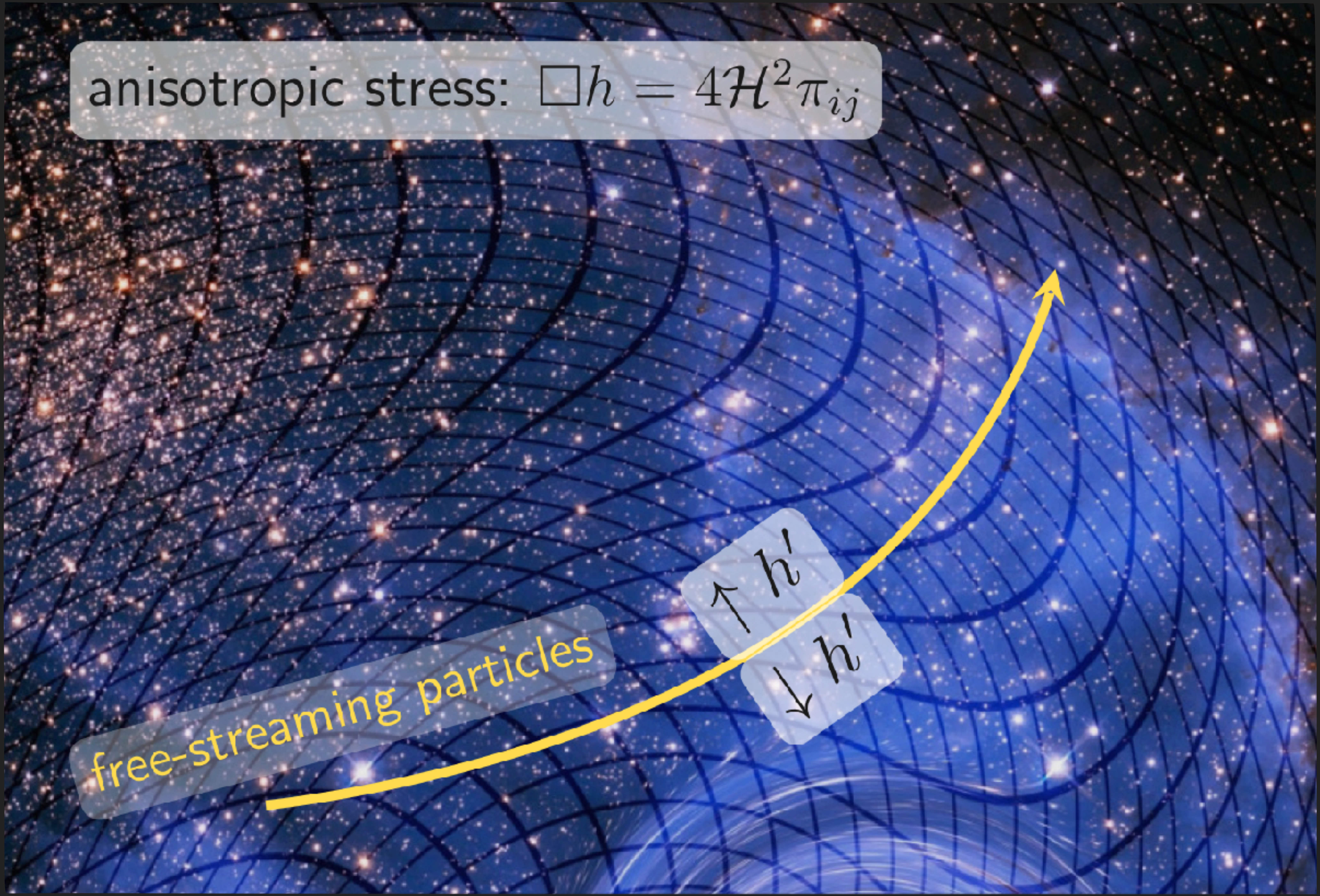

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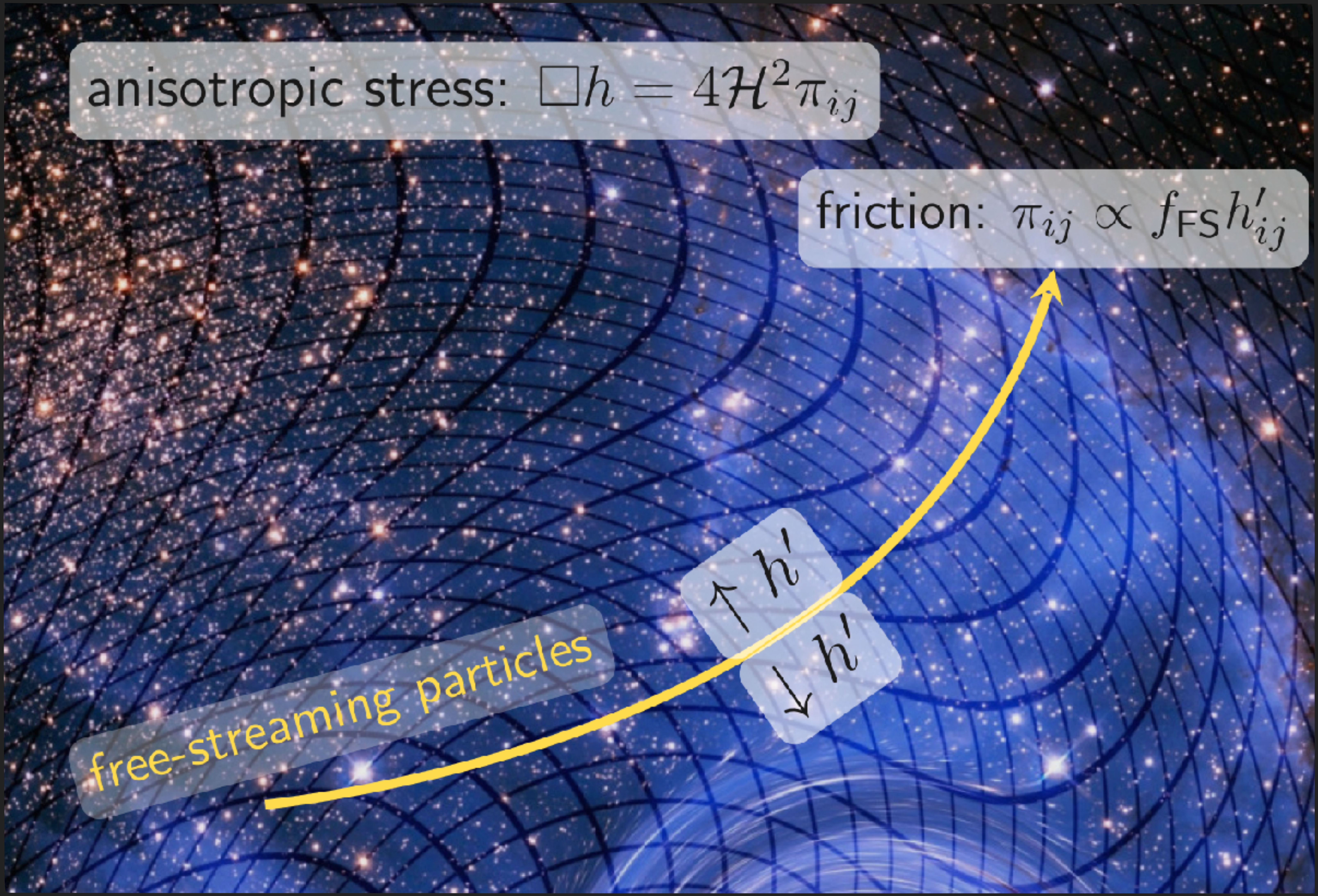

['86 Bond]
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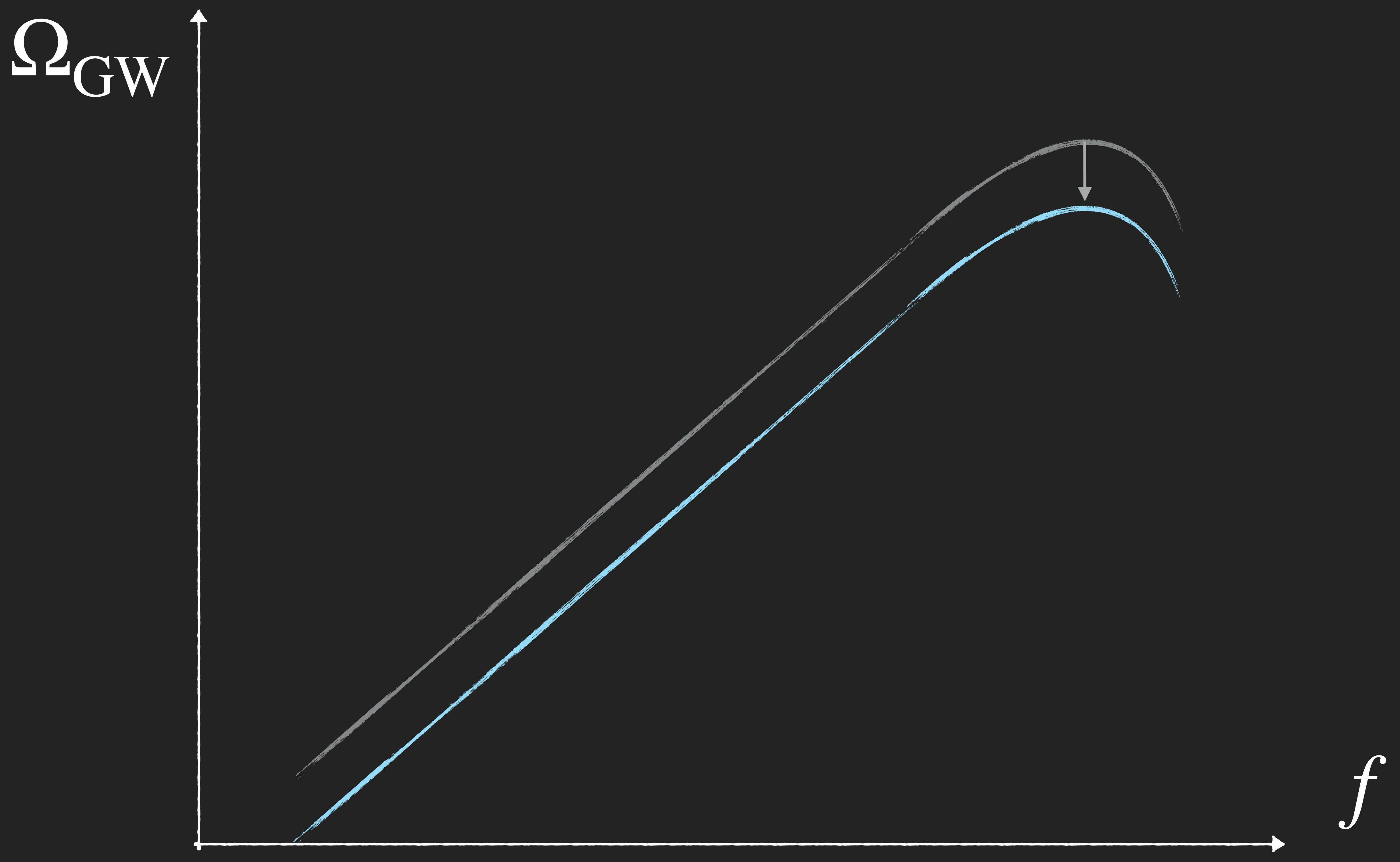
['06 Watanabe, Komatsu]

- Weinberg damping: $h' \neq 0$ at horizon crossing
- Frequency-independent ['04 Weinberg]



- Weinberg damping: $h' \neq 0$ at horizon crossing
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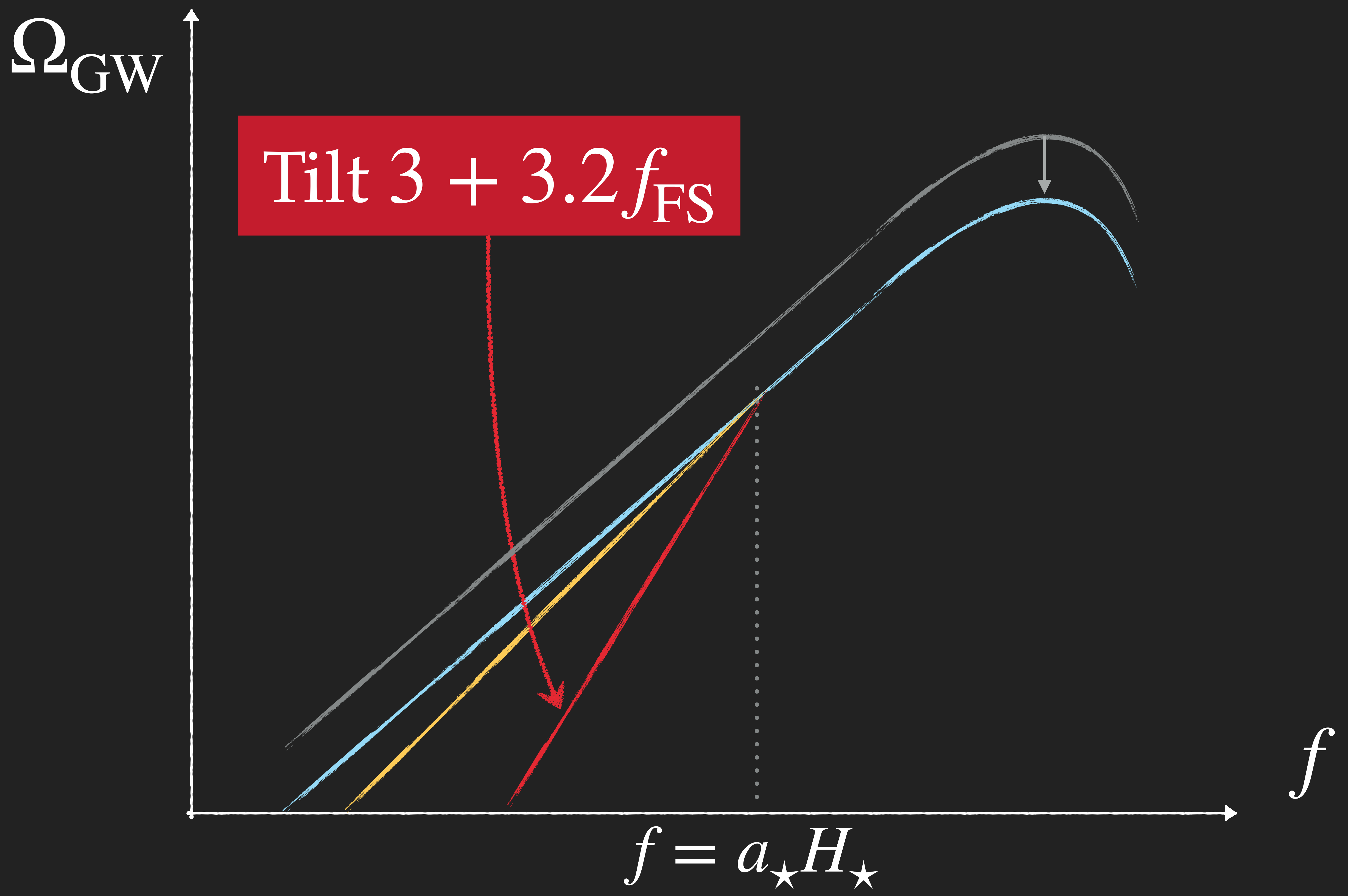
- Causality-limited sources: **also** affected at GW *production*
- Frequency-dependent

['20 Hook, Marques-Tavares, **DR**]

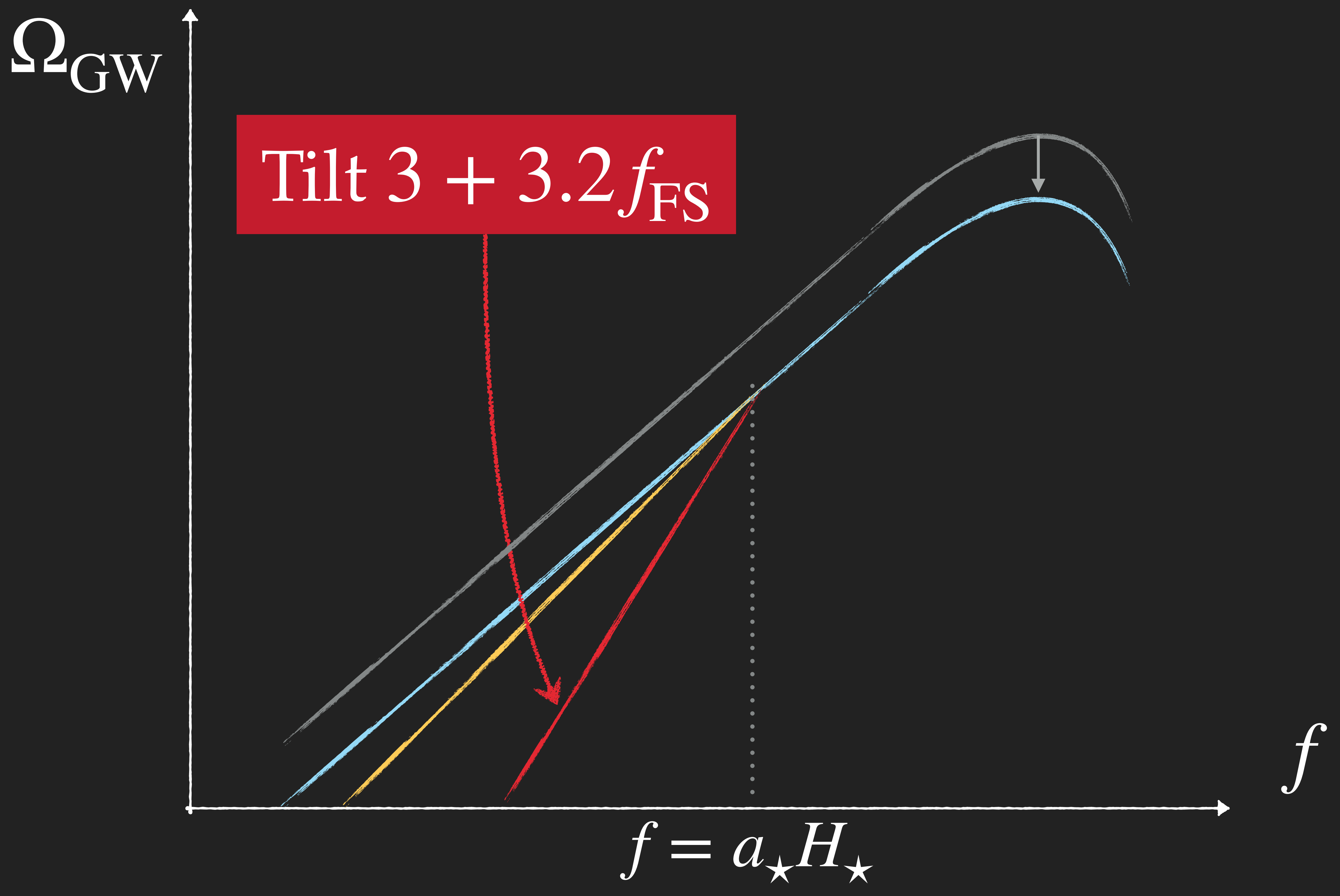


CAUSALITY TAIL AS A PROBE OF FREE-STREAMING PARTICLES

- Weinberg damping: $h' \neq 0$ at horizon crossing
- Frequency-independent ['04 Weinberg]
- Causality-limited sources: **also** affected at GW *production*
- Frequency-dependent

['20 Hook, Marques-Tavares, **DR**]

- Causality tail ⇔ probe new free-streaming particles before BBN



DAMPING FROM FREE-STREAMING PARTICLES

- **Standard Model**: free-streaming *neutrinos* ($T \lesssim 2$ MeV).
  Primordial GWs: $h' = 0$ until horizon-entry $\Rightarrow$ frequency-ind. suppression.

$$h'' + 2\mathcal{H}h' + k^2 h = -24 f_\nu \mathcal{H}^2 \int_{\tau_0}^{\tau} \mathrm{d}\tau' \frac{j_2[k(\tau - \tau')]}{k^2(\tau - \tau')^2} h'(\tau')$$

- **Phase transitions**: with extra FS species, also suppression at *generation*: $h'(\tau_\star) \neq 0$. ['20 Hook, Marques-Tavares, **DR**]

sub-$\mathcal{H}$ no effect

super-$\mathcal{H}$ $$h'' + \underbrace{2\mathcal{H}h'}_{\text{friction}} + \underbrace{\left(k^2 + \boxed{\frac{8 f_{\mathsf{FS}}}{5}\mathcal{H}^2}\right)}_{\text{mass term}} h = 0$$

Schematic derivation of Weinberg damping

[Weinberg '04; Watanabe, Komatsu '06]

- $$h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = 4\mathcal{H}^2 \pi_{ij}$$

$$T_{ij} = p\, g_{ij} + a^2 \pi_{ij}\,, \qquad T_{ij}^{(\nu)} = \frac{1}{\sqrt{-g}} \int \frac{d^3 q}{q^0} q_i q_j F^{(\nu)}(q)$$

- Boltzmann eq.:

$$0 = \frac{dF}{dt} = \frac{\partial F}{\partial \tau} + \frac{dx^i}{dt}\frac{\partial F}{\partial x^i} + \frac{dp^0}{dt}\frac{\partial F}{\partial p^0}$$

- Geodesic eq.:

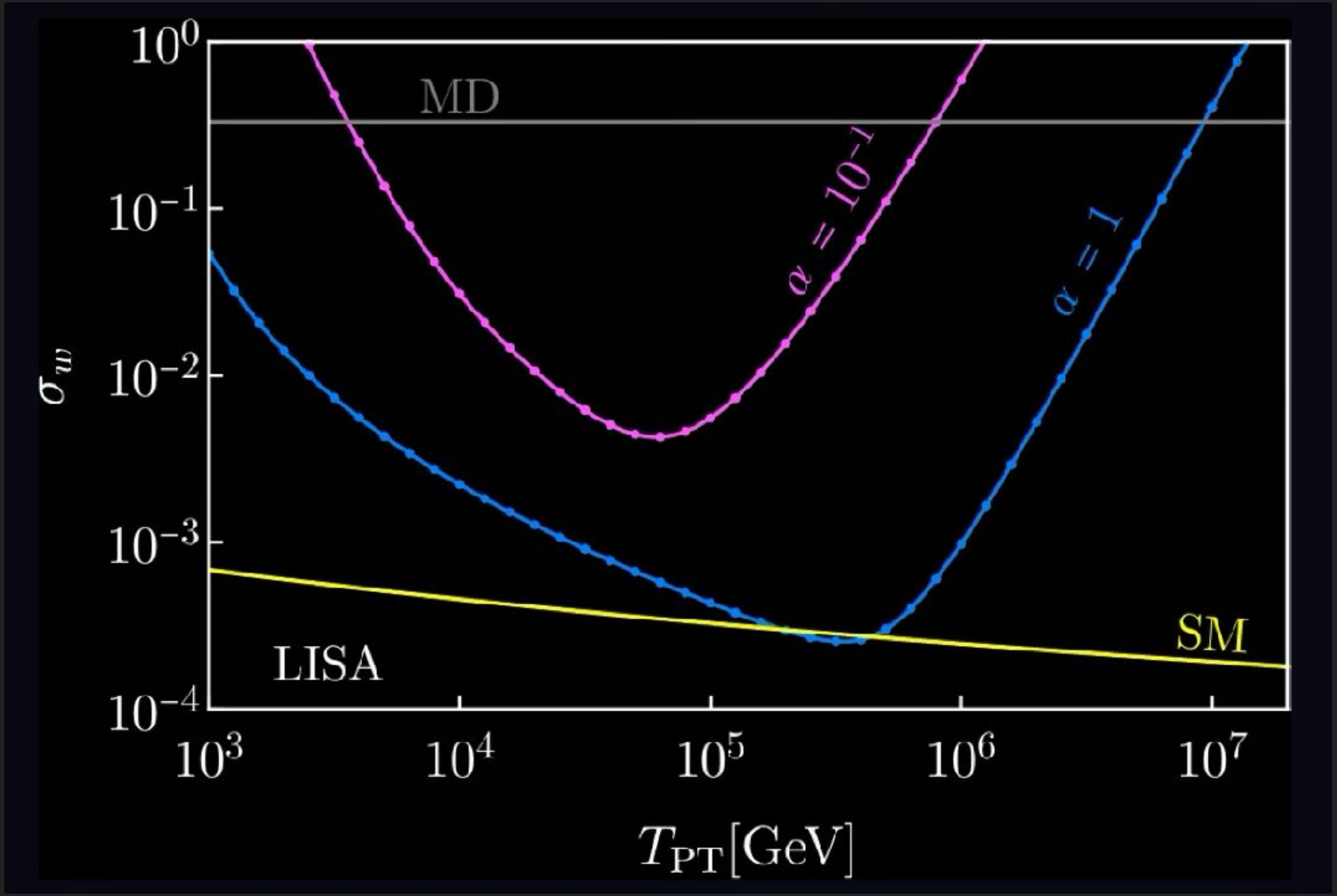
$$\frac{dp^\mu}{d\lambda} = -\Gamma^\mu_{\alpha\beta} p^\alpha p^\beta \implies \frac{1}{p^0}\frac{dp^0}{dt} = -H - \frac{1}{2}\boxed{\frac{\partial h_{ij}}{\partial t}}\frac{p^i p^j}{(p^0)^2}$$

- ν's lose (or gain) energy depending on the sign of h'.

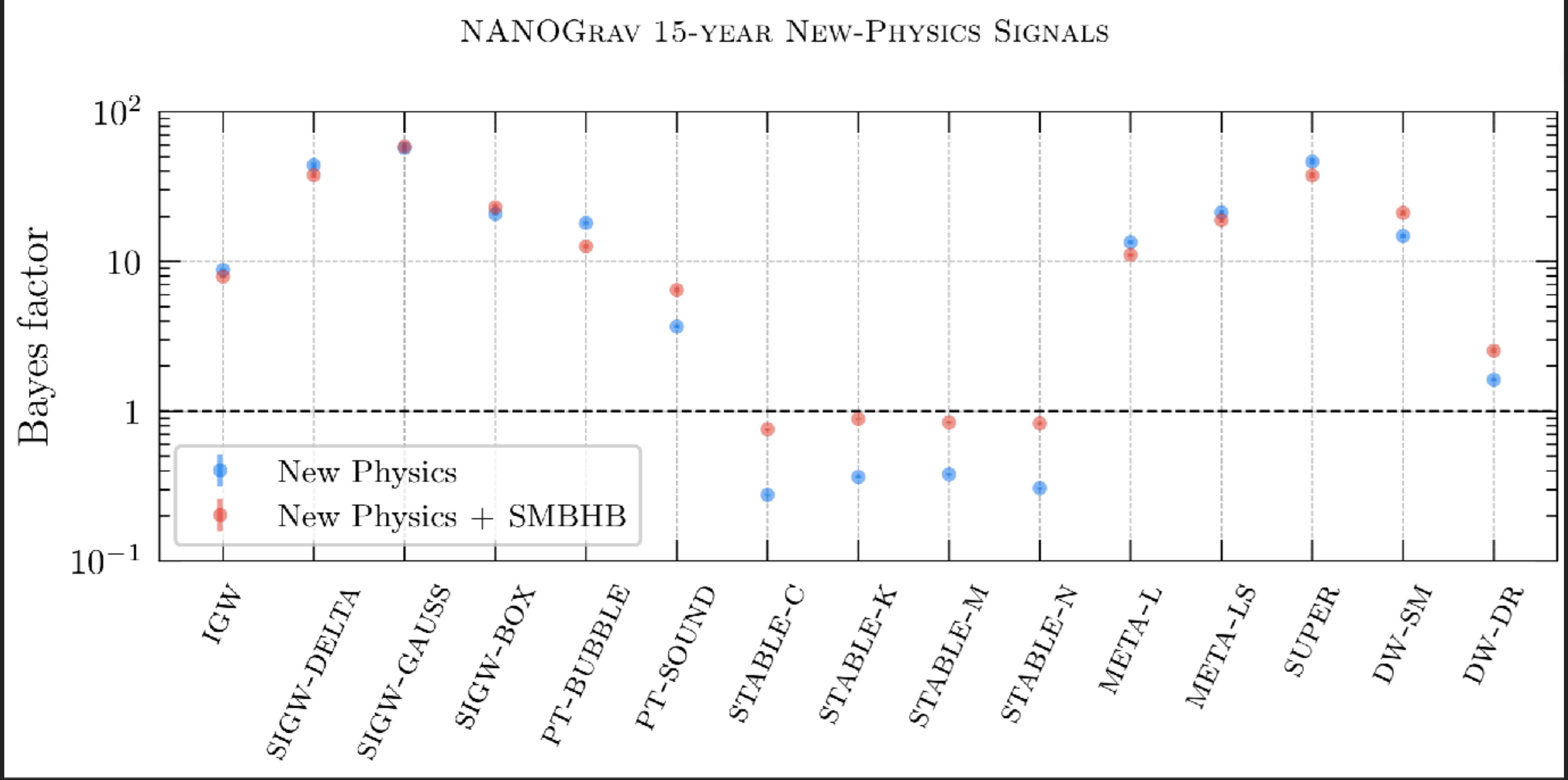
$$h'' + 2\mathcal{H}h' + k^2 h = -24 f_\nu \mathcal{H}^2 \int_{\tau_0}^{\tau} d\tau' \frac{j_2[k(\tau-\tau')]}{k^2(\tau-\tau')^2} h'(\tau')$$

HOW WELL CAN WE DETECT FEATURES IN THE CAUSALITY TAIL?

['22 Brzeminski, Hook, Marques-Tavares]



ORIGIN OF THE SIGNAL: PRIMORDIAL INTERPRETATION



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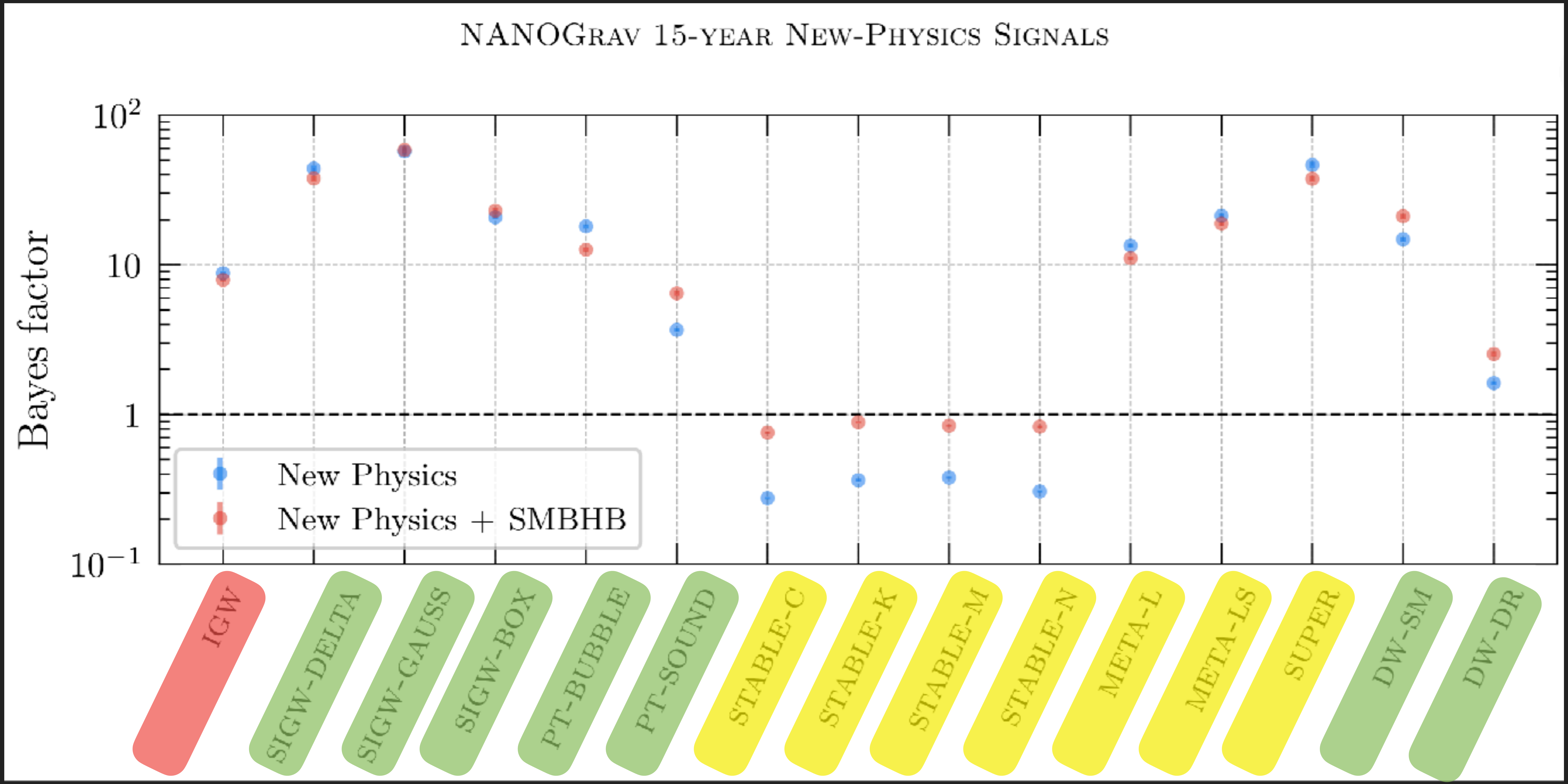
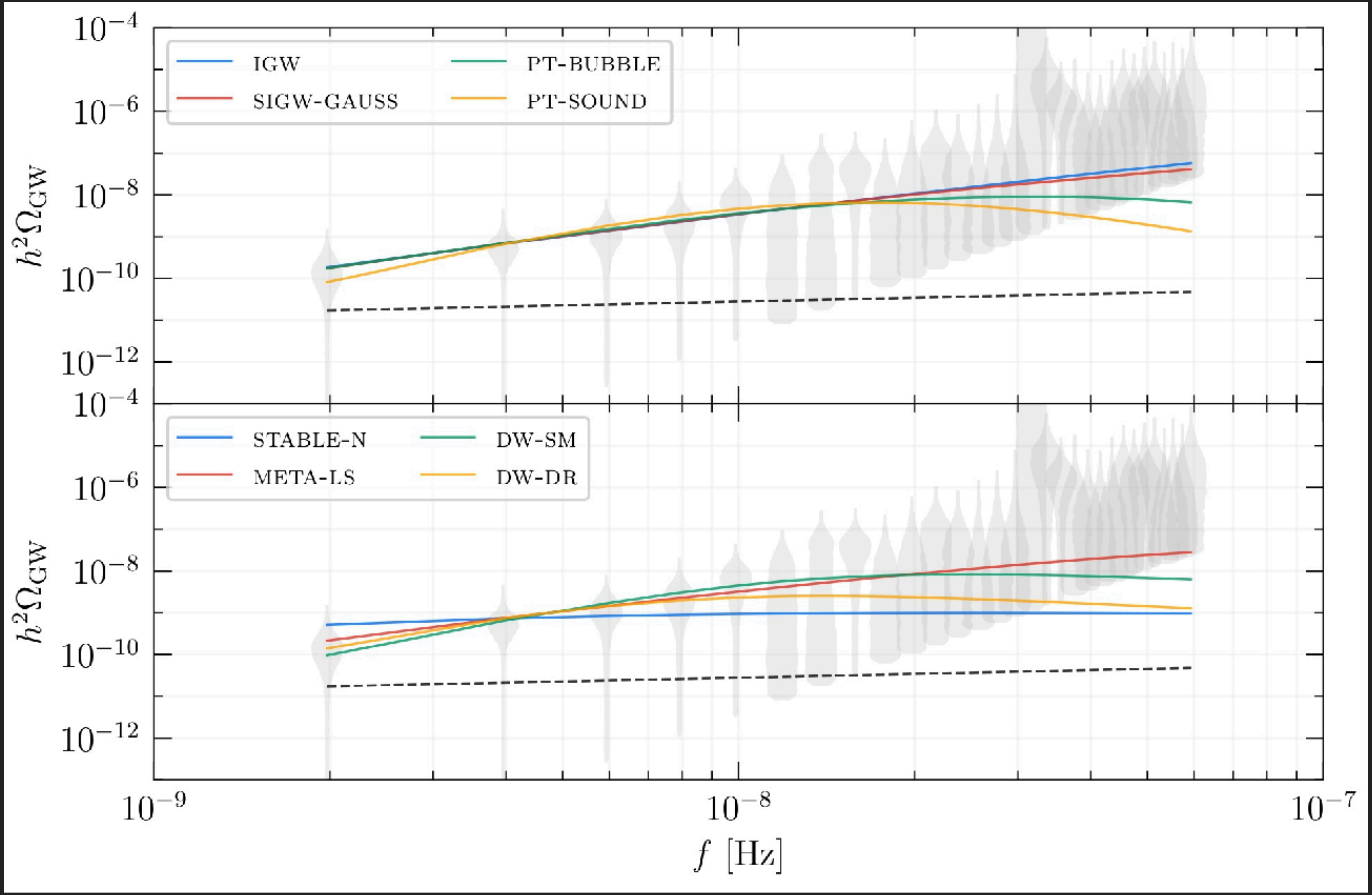


inflationary GWB: no CT

must go to CT at low f

can go to CT at low f

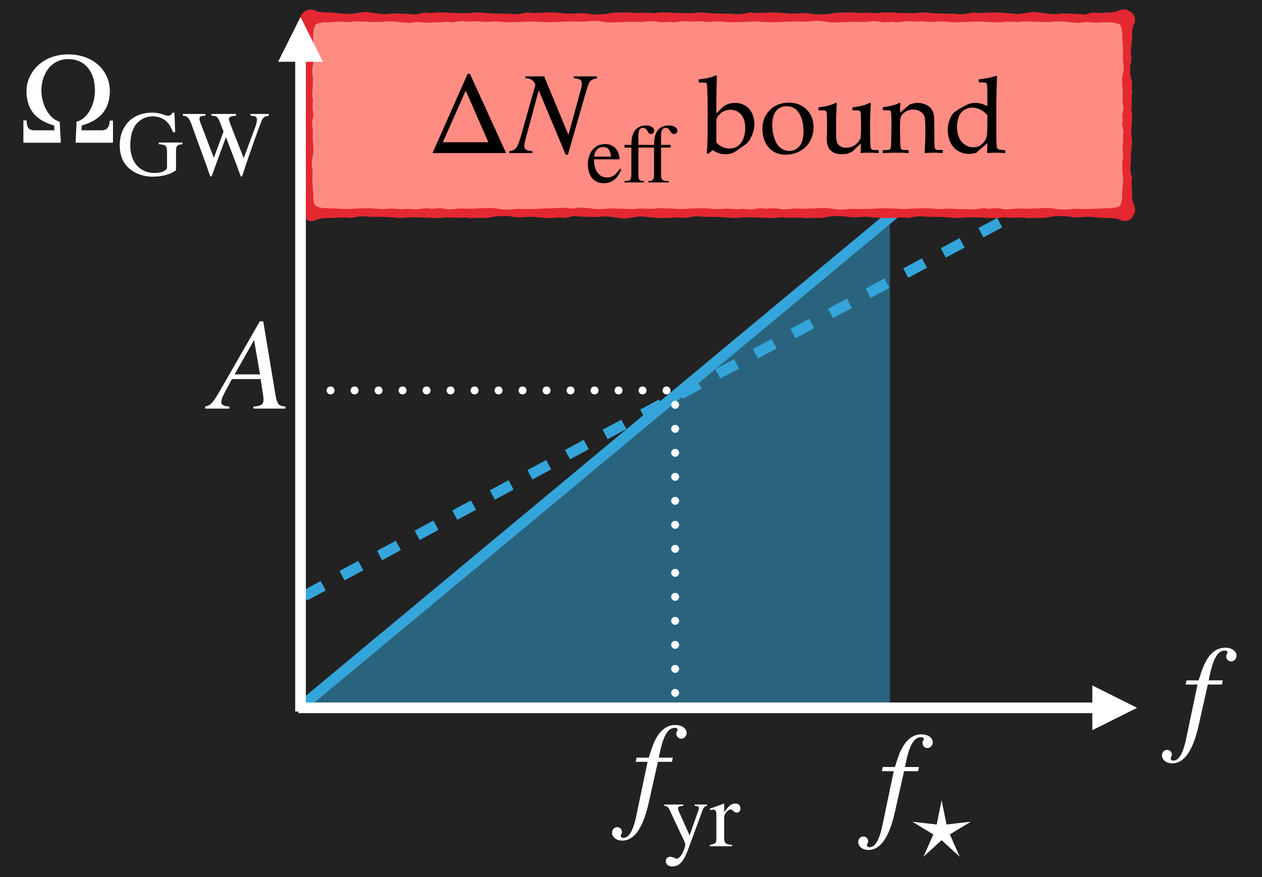
NG15: SEARCH FOR NEW PHYSICS — BEST FITS



BOUND FROM ΔN_{eff} FOR PRIMORDIAL SIGNAL

- Primordial GWs are relativistic energy not coupled to SM bath
- $\Rightarrow \Delta N_{\text{eff}}$ constrained by CMB

$$\Omega_{\text{CGW}} h^2 = 1.6 \cdot 10^{-6} \cdot \frac{\Delta N_{\text{eff}}^{\text{CGW}}}{0.28}$$



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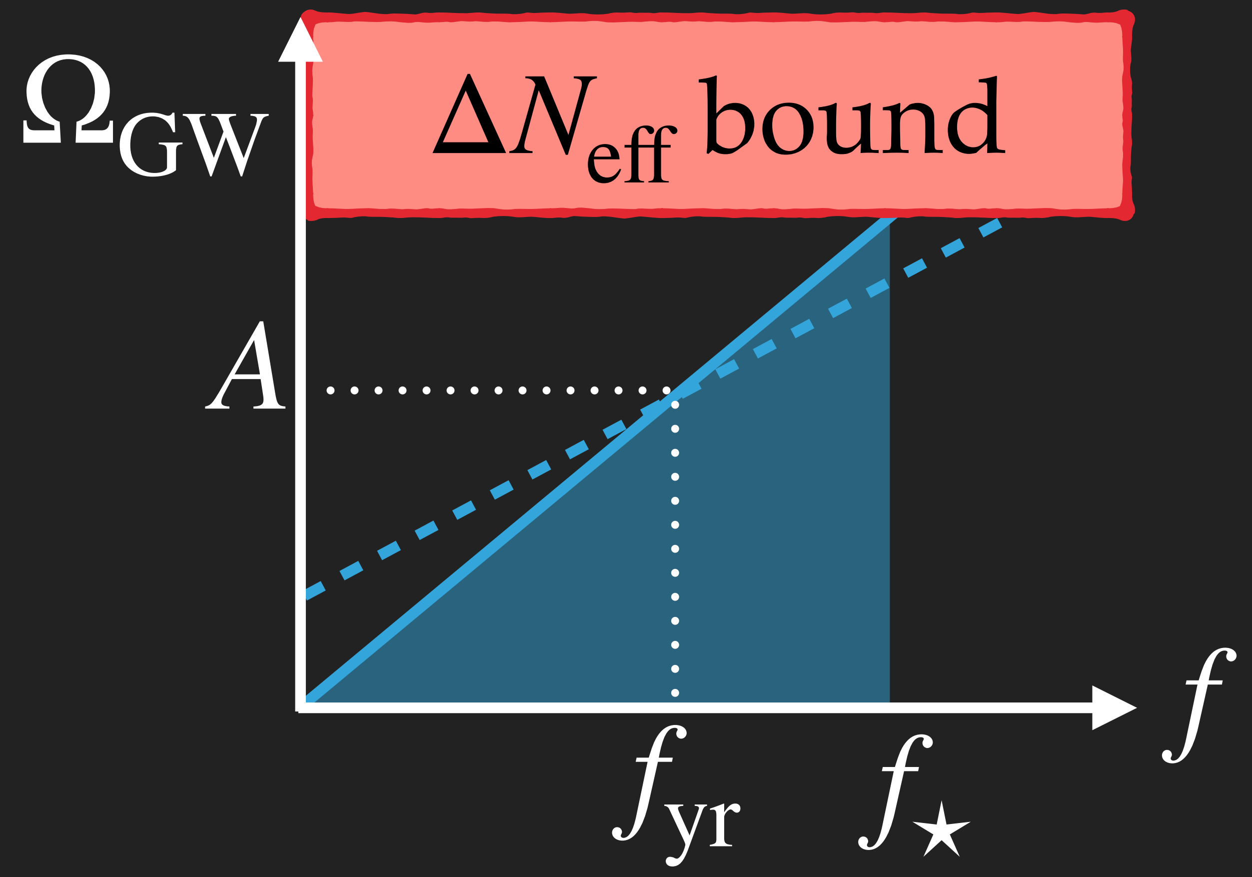

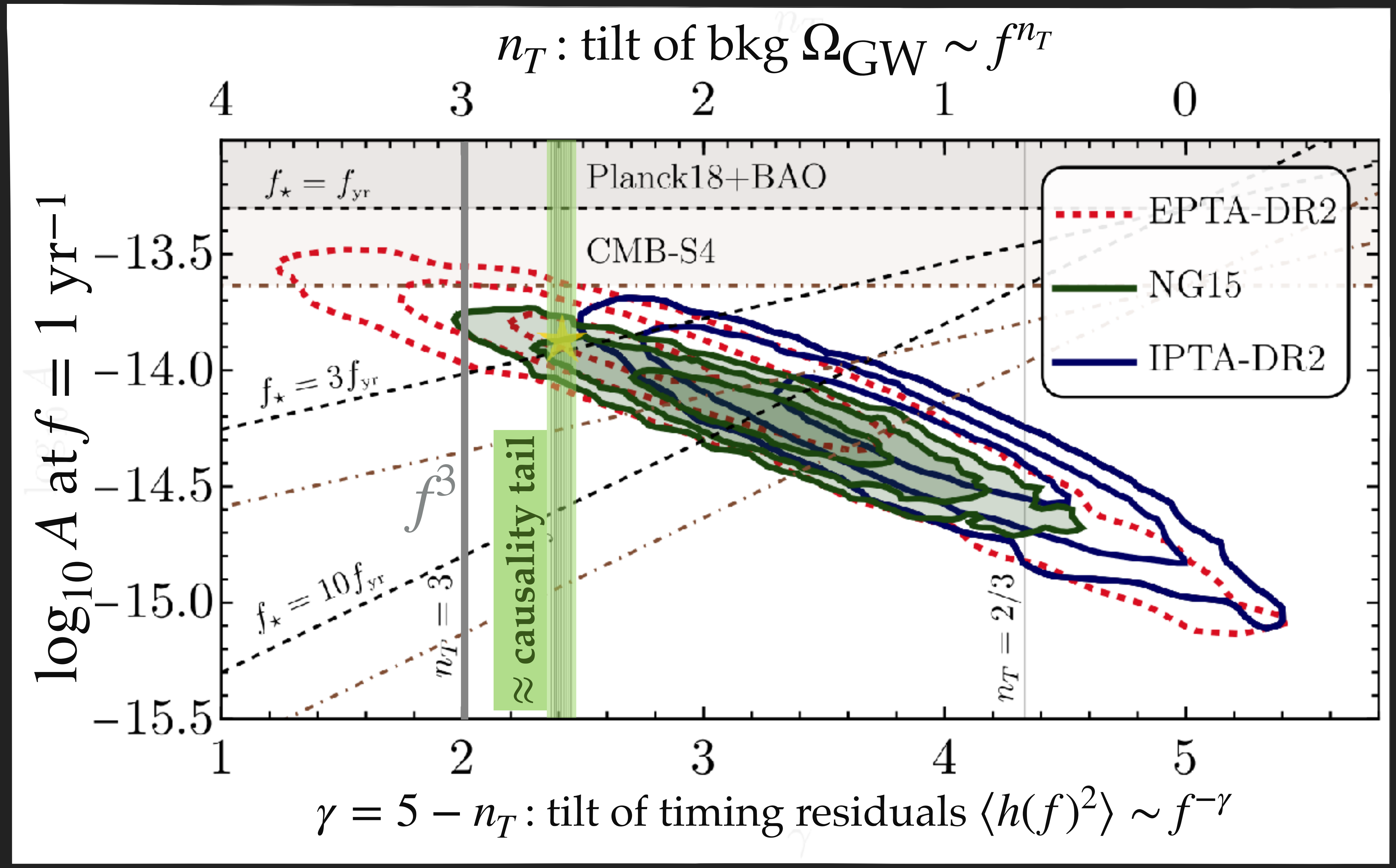

['23 Franciolini, **DR**, Rompineve]

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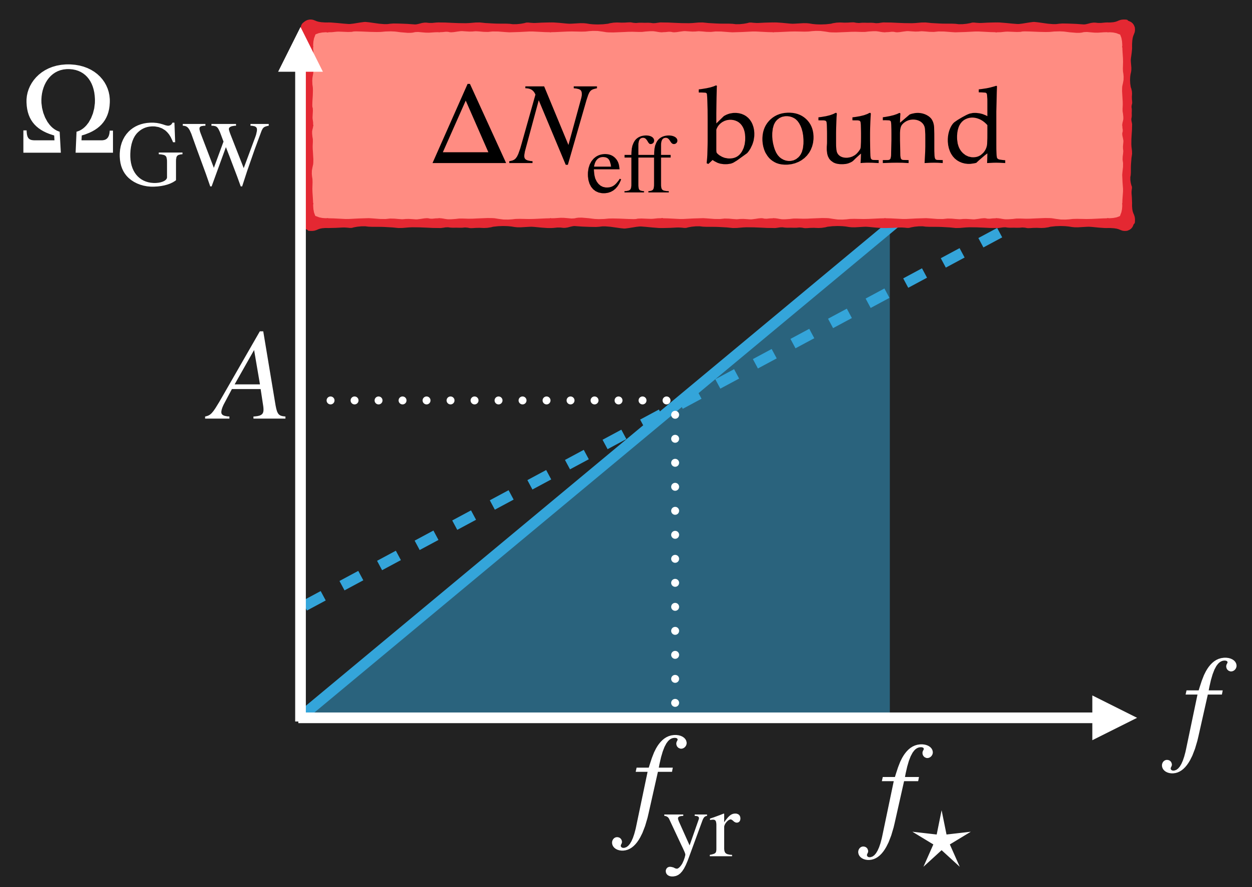

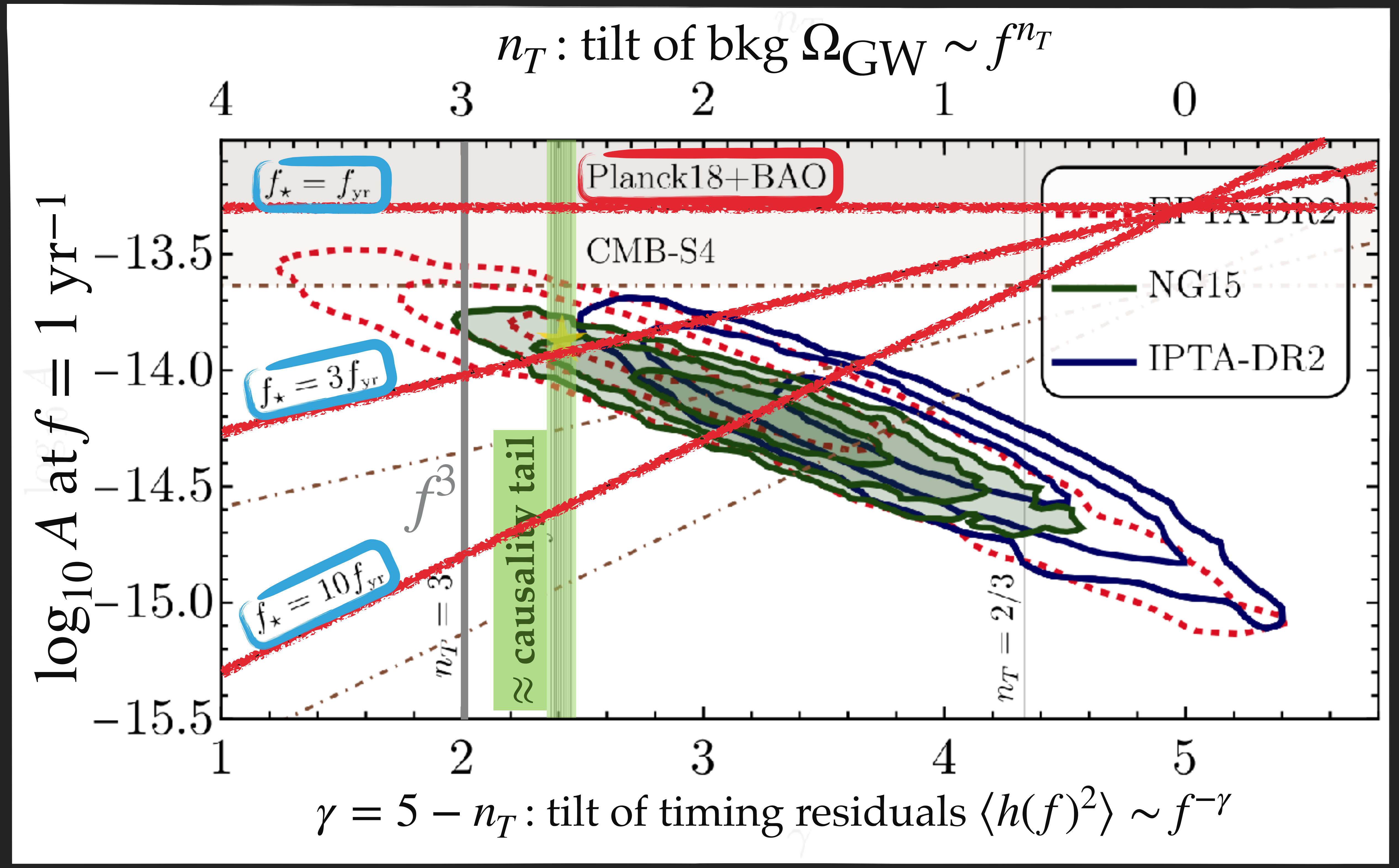

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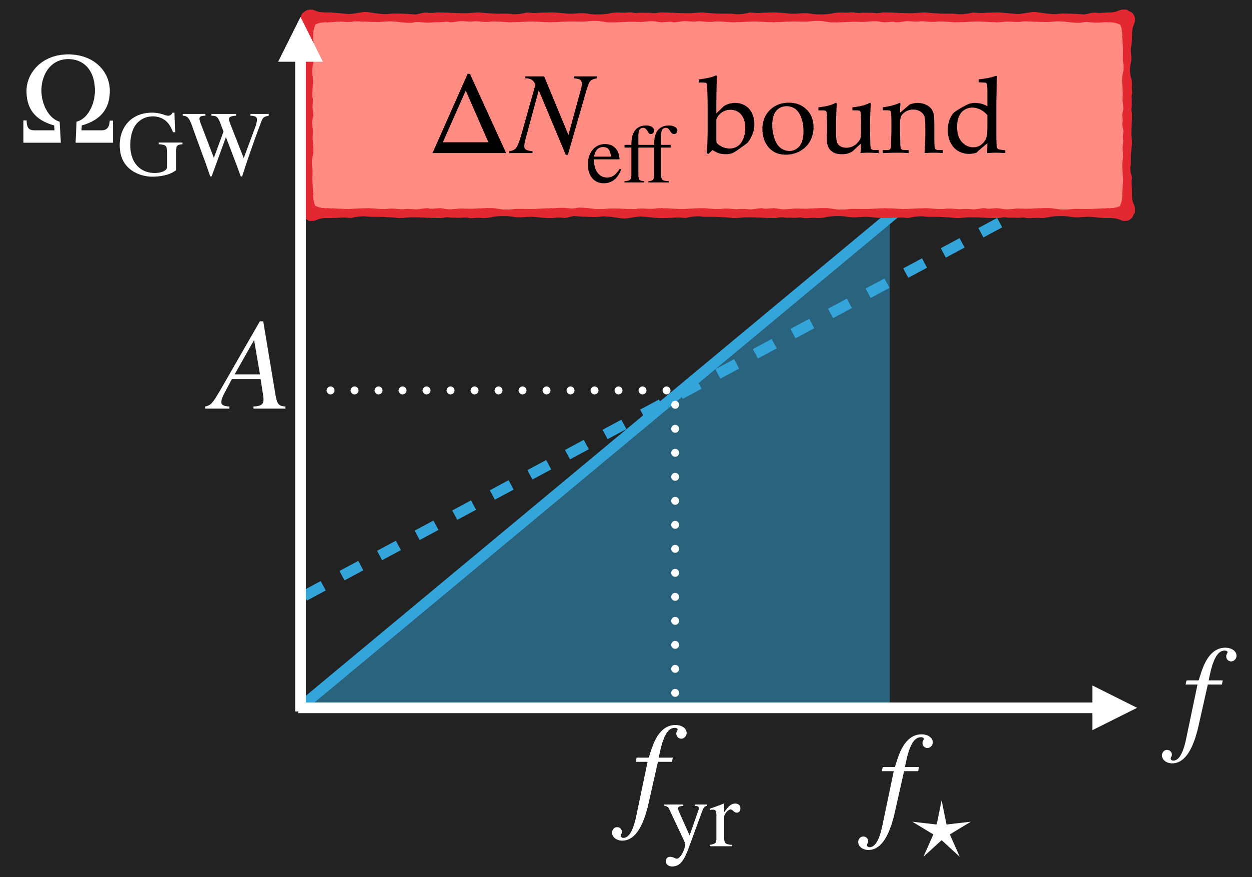

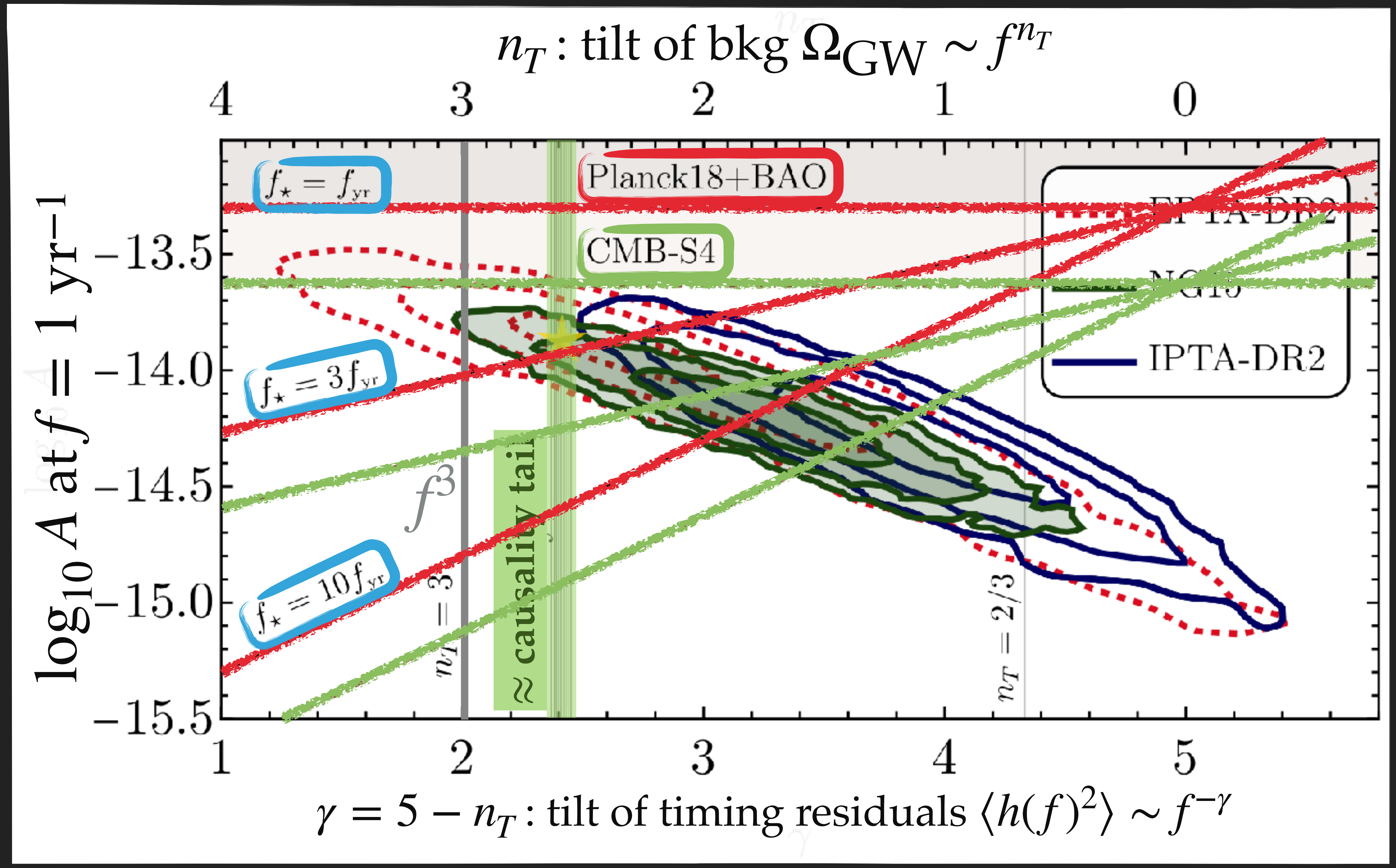

['23 Franciolini, **DR**, Rompineve]

- Primordial GWB can't grow until too large $f_\star$
- Signature in CMB if GWB is primordial!

TESTING PRIMORDIAL BLACK HOLES AS DARK MATTER

['18 Espinosa, **DR**, Riotto]

['18 Bartolo, De Luca, Franciolini, Peloso, **DR**, Riotto]