Silk damping in induced gravitational waves: a novel probe for new physics

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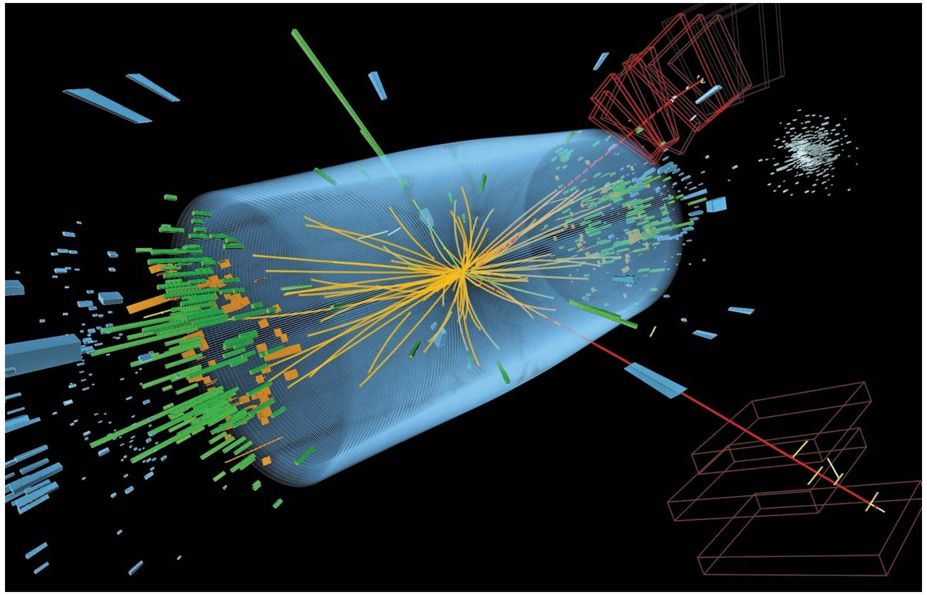
2025.4.21 @ HIAS-UCAS

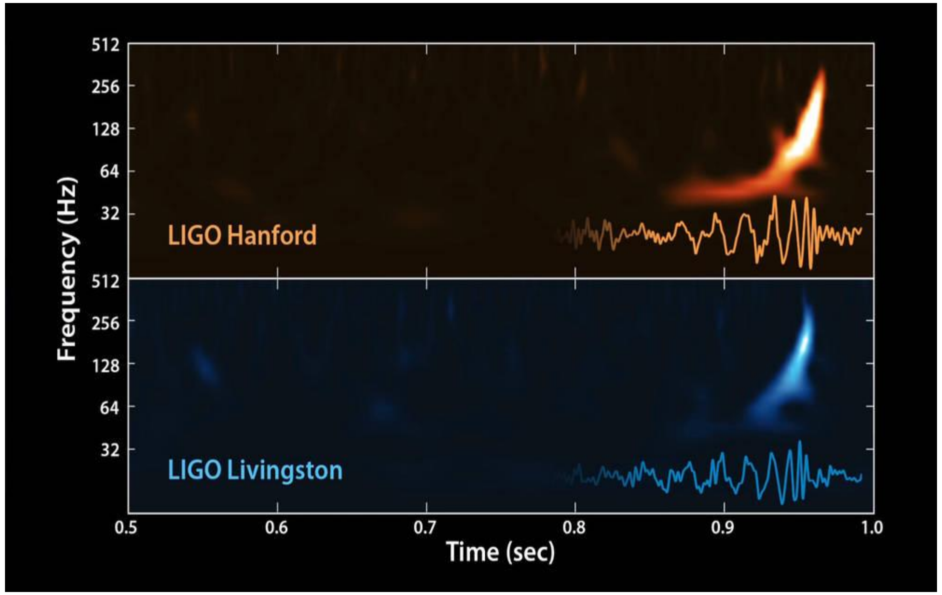
*Based on: **YHY** and Sai Wang: Sci.China Phys.Mech.Astron. 68 (2025) 210412, arXiv: 2405.02960*

Two breakthroughs in 21st century



Higgs bosons (2012)

additional symmetry breakings?

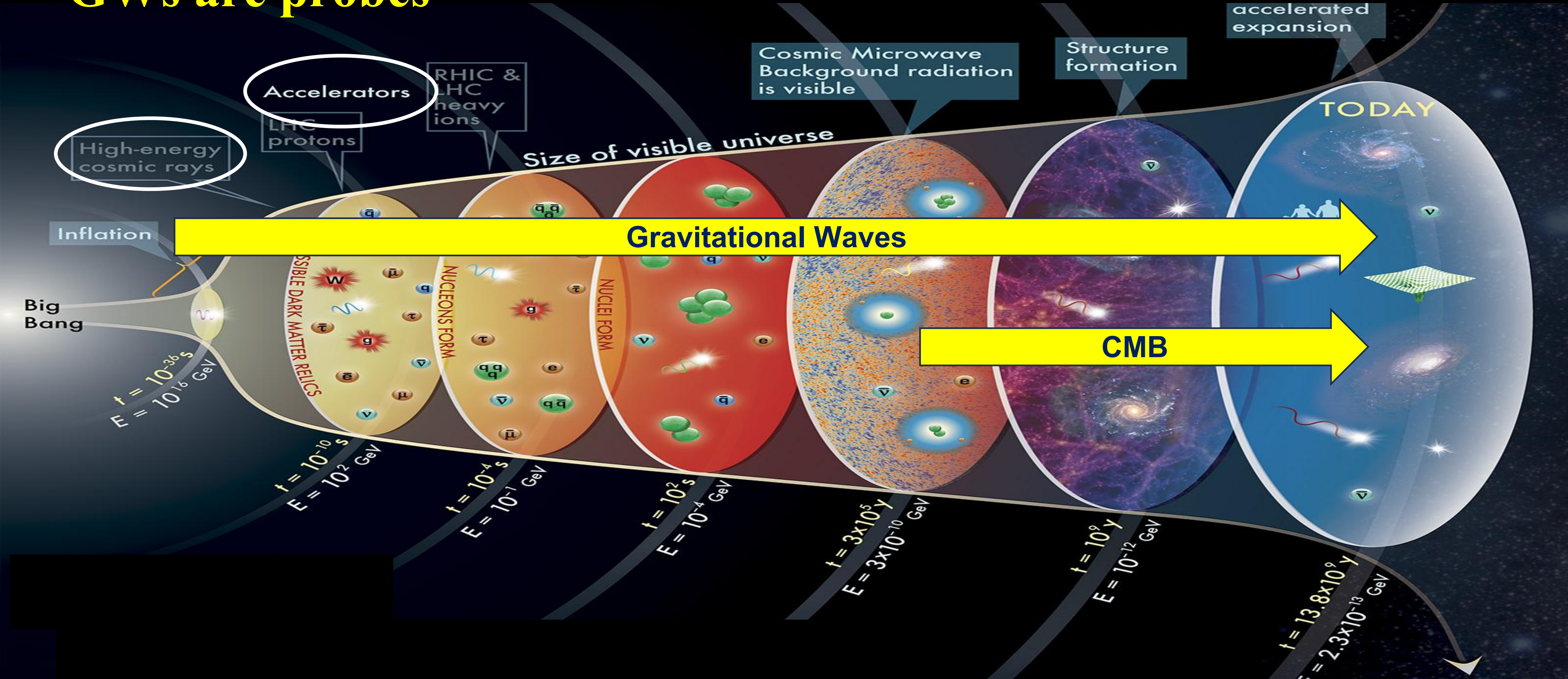


Gravitational waves (2016)

GW astronomy & GW cosmology

GWs provide new opportunities to detect fundamental particle physics!

GWs are probes



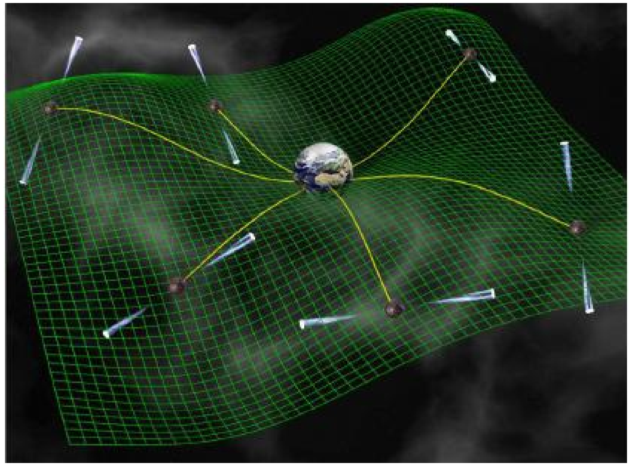
The early Universe is a high-energy laboratory

GWs in the early Universe

- Primordial GWs
- Preheating GWs
- GWs from first-order phase transition
- GWs from cosmological topological defects
- Induced GWs
- ......

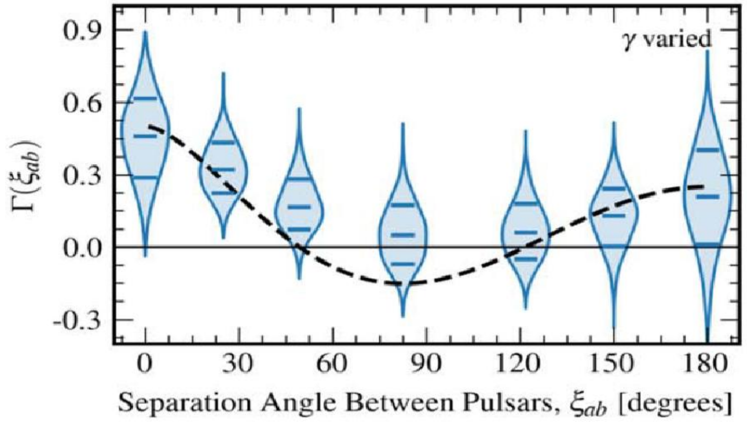
Evidence for GWB

PTA experiments

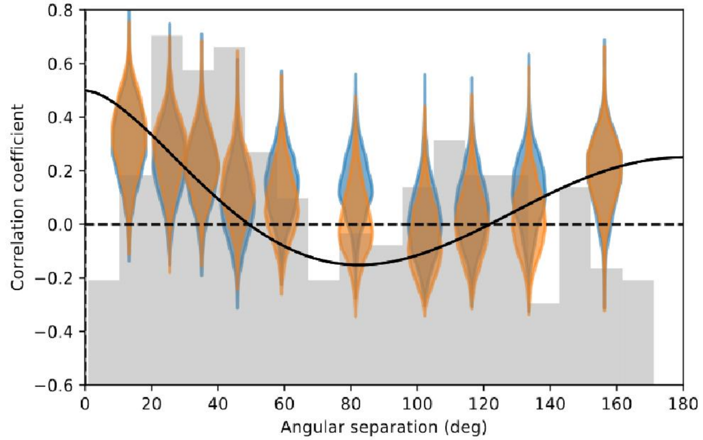


ApJL 951 (2023) L8: NANOGrav
A&A 678 (2023) A50: EPTA, InPTA
ApJL 951 (2023) L6: PPTA
RAA 23 (2023) 075024: CPTA

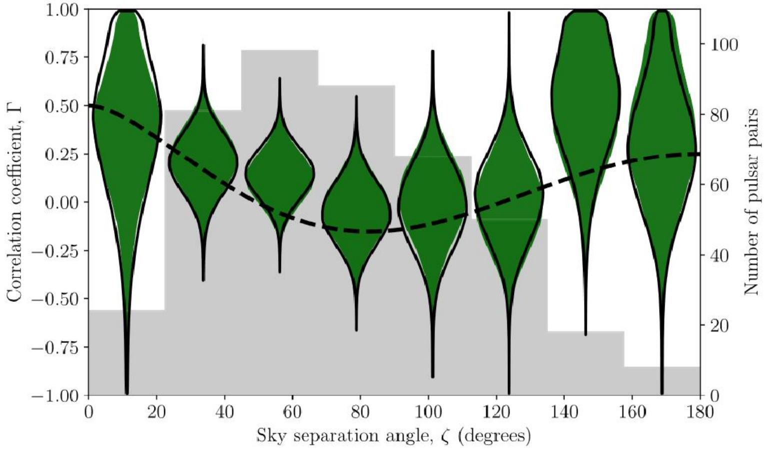
NANOGrav



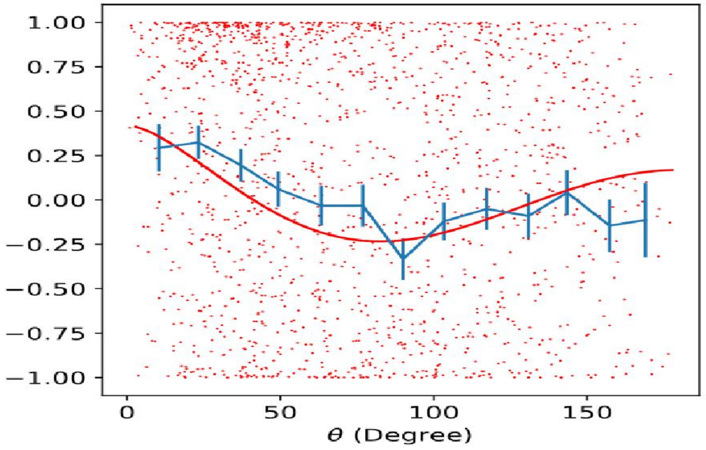
EPTA



PPTA



CPTA



Induced GWs

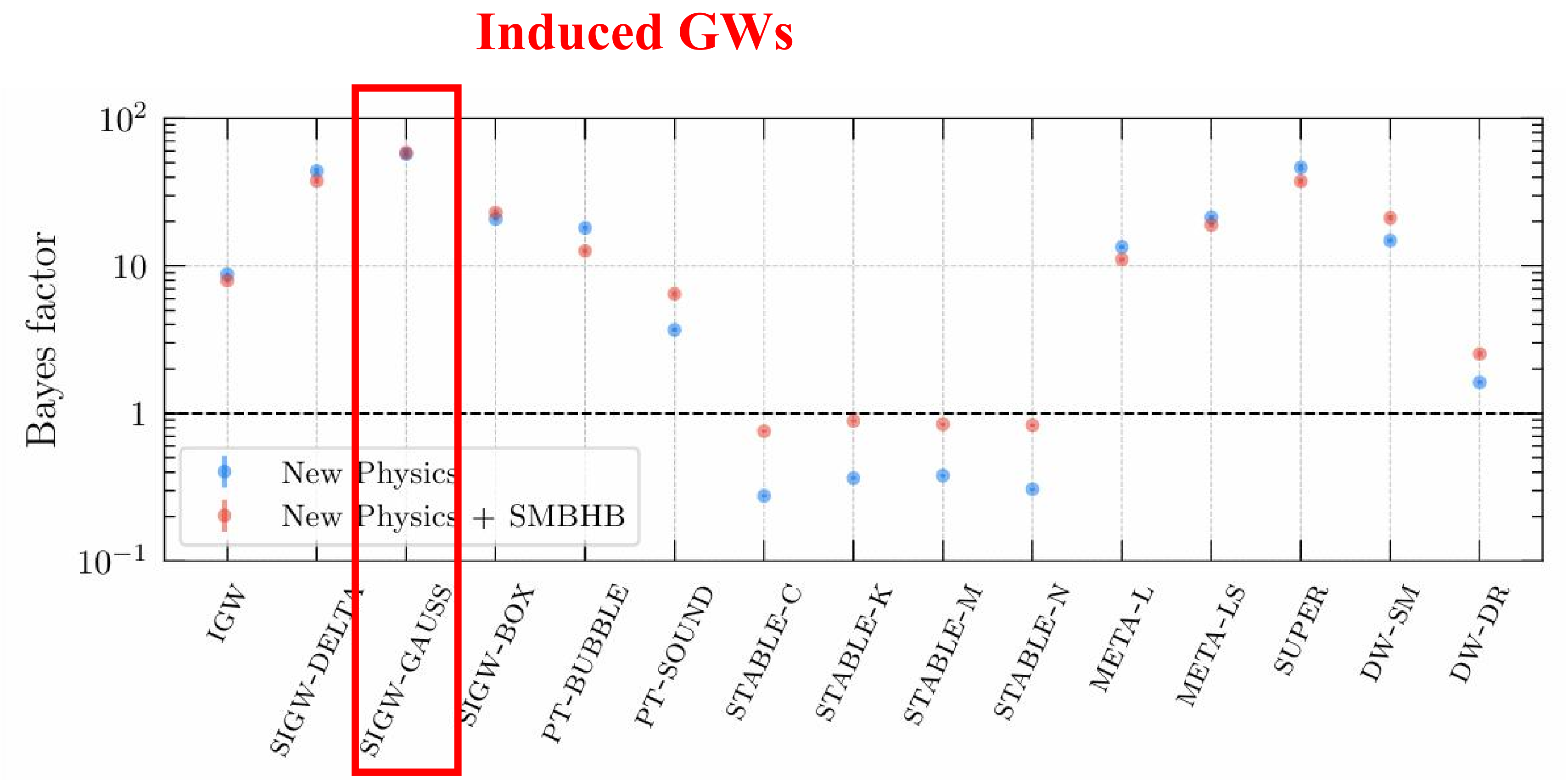


Figure 2. Bayes factors for the model comparisons between the new-physics interpretations of the signal considered in this work and the interpretation in terms of SMBHBs alone. Blue points are for the new physics alone, and red points are for the new physics in combination with the SMBHB signal. We also plot the error bars of all Bayes factors, which we obtain following the bootstrapping method outlined in Section 3.2. In most cases, however, these error bars are small and not visible.

ApJL 951 (2023) 1, L11: NANOGrav

Induced GWs

- **Spacetime metric:** $$\mathrm{d}s^2 = a^2\left\{-(1+2\phi^{(1)})\,\mathrm{d}\tau^2 + \left[(1-2\phi^{(1)})\delta_{ij} + \frac{1}{2}h_{ij}^{(2)}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}$$

- **Induced GWs:** $$h''_{\lambda,\mathbf{k}} + 2\mathcal{H}h'_{\lambda,\mathbf{k}} - \nabla^2 h_{\lambda,\mathbf{k}} = 4\mathcal{S}_{\lambda,\mathbf{k}}$$

$$h^{(2)} \sim \phi^{(1)}\phi^{(1)}$$

$$\mathcal{S}_{\lambda,\mathbf{k}} = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^{3/2}}\,\epsilon^{\lambda}_{\mathbf{q},ij}q^iq^j\left\{2\phi_{\mathbf{k}-\mathbf{q}}\phi_{\mathbf{q}} + \frac{4}{3(1+w)\mathcal{H}^2}\left[\phi'_{\mathbf{k}-\mathbf{q}} + \mathcal{H}\phi_{\mathbf{k}-\mathbf{q}}\right]\left[\phi'_{\mathbf{q}} + \mathcal{H}\phi_{\mathbf{q}}\right]\right\}$$

- **Energy–density fraction spectrum:**

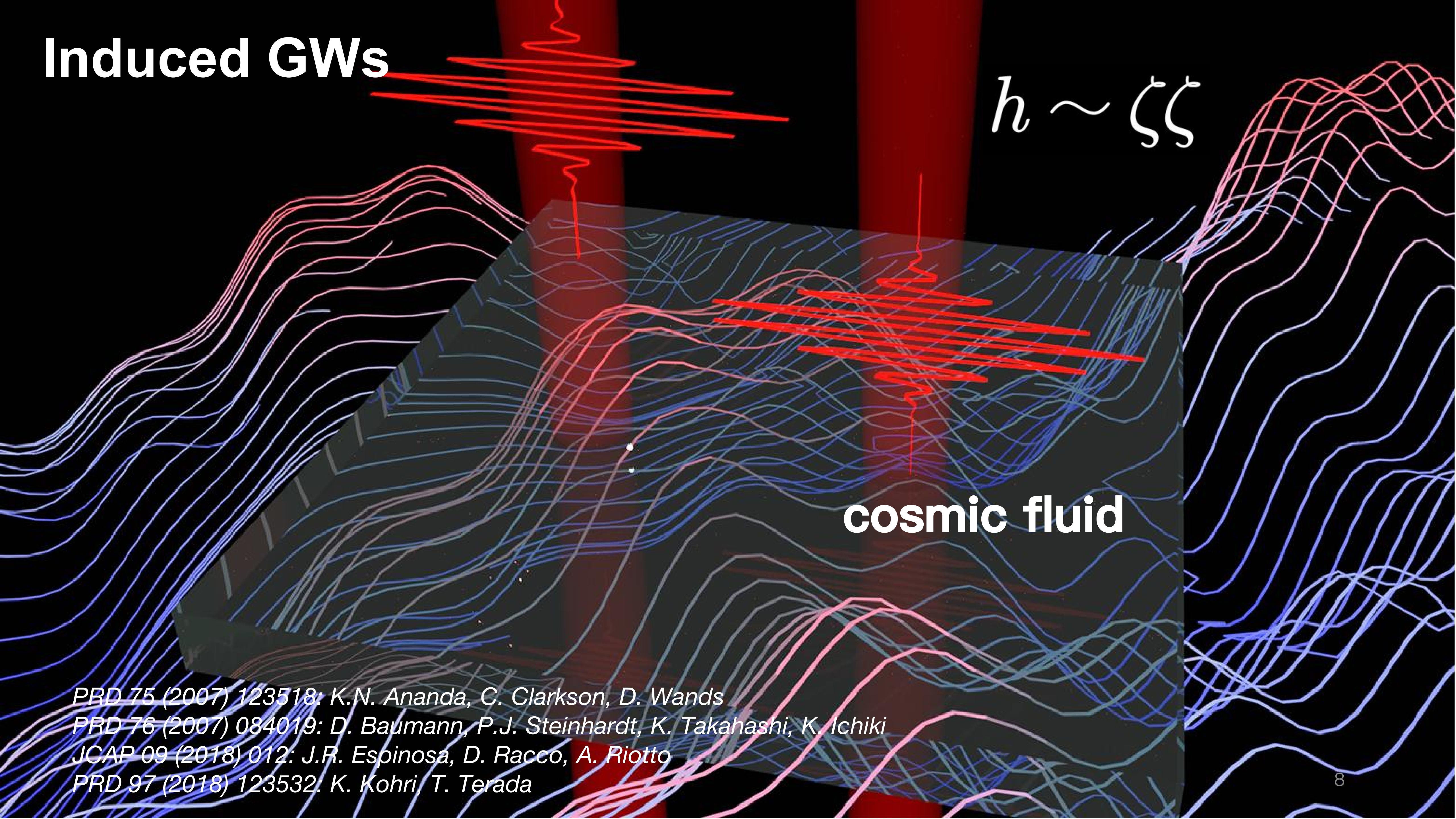
$$\phi^{(1)}_{\mathbf{k}}(\tau) = \Phi(k,\tau)\,\zeta_{\mathbf{k}}$$

$$\Omega_{\mathrm{gw}}(k) = \frac{k^2}{6a^2H^2}\int_0^{\infty}\mathrm{d}u\int_{|1-u|}^{|1+u|}\mathrm{d}v\left[\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right]^2 \times \overline{I^2(u,v,k,\tau)}\,\mathcal{P}_\zeta(uk)\mathcal{P}_\zeta(vk)$$

classical evolution after inflation

primordial curvature perturbations

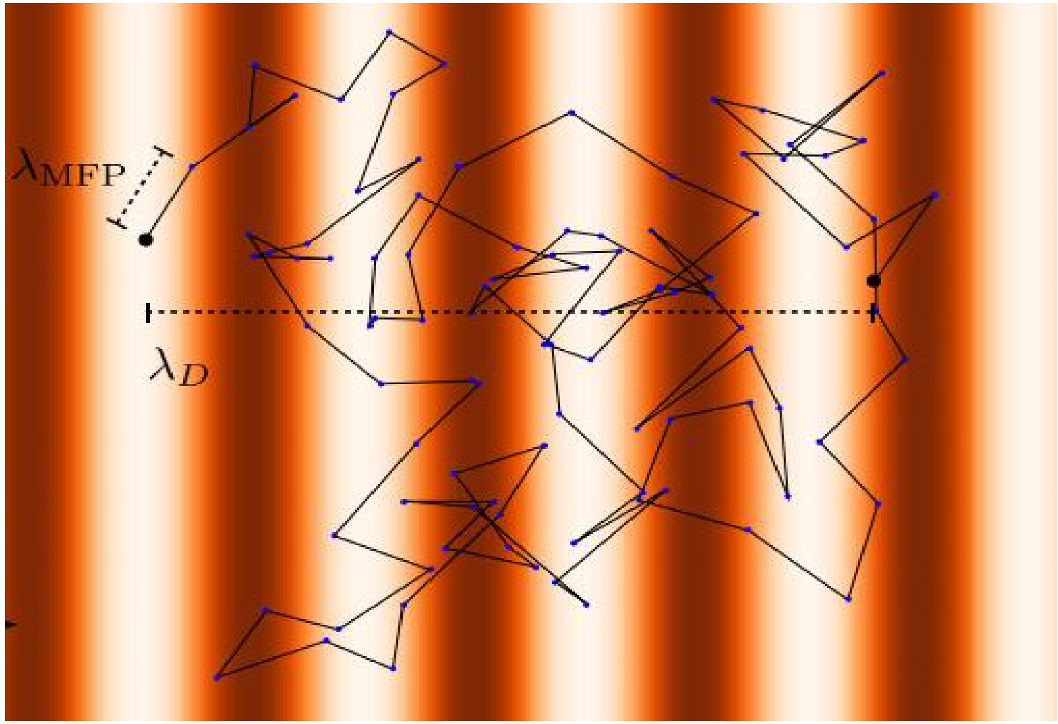
Induced GWs



PRD 75 (2007) 123518: K.N. Ananda, C. Clarkson, D. Wands
PRD 76 (2007) 084019: D. Baumann, P.J. Steinhardt, K. Takahashi, K. Ichiki
JCAP 09 (2018) 012: J.R. Espinosa, D. Racco, A. Riotto
PRD 97 (2018) 123532: K. Kohri, T. Terada

Silk damping

Cosmic fluid

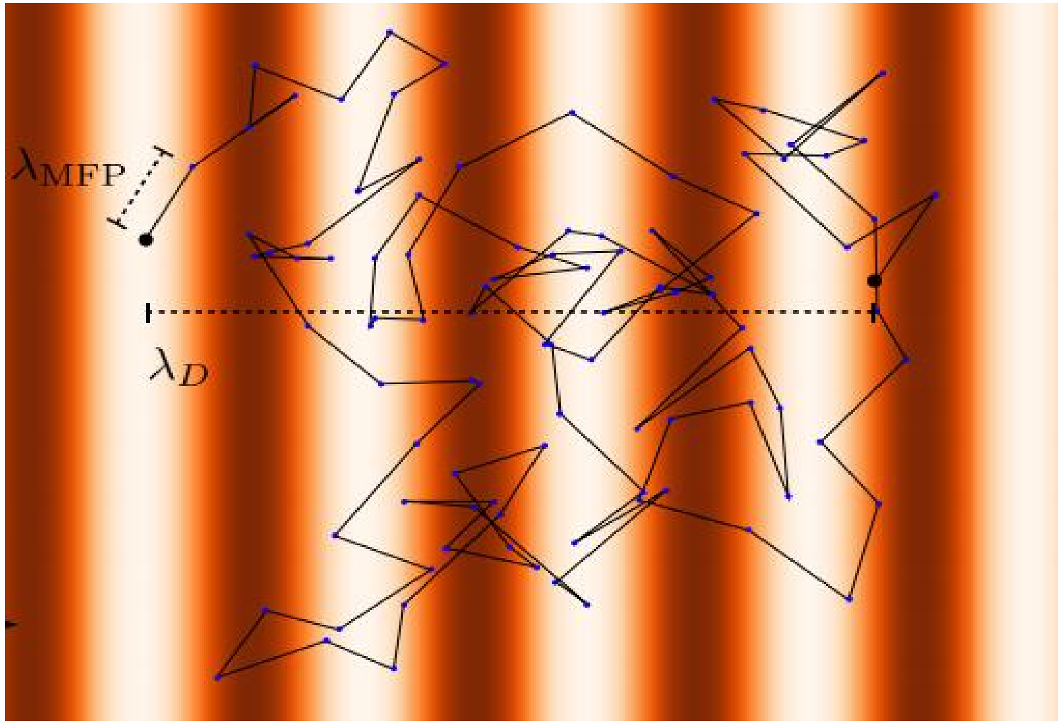


perturbation scale k^{-1} << diffusion scale k_D^{-1}

Diffusion erases perturbations !

Silk damping in the CMB

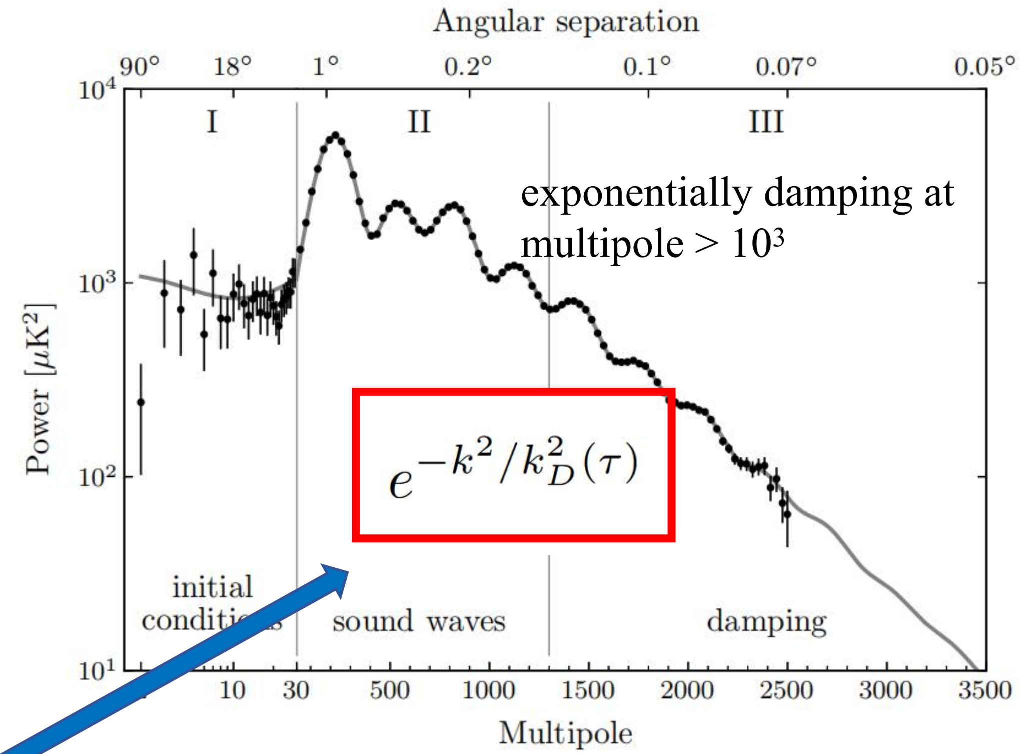
Photon–baryon plasma



perturbation scale k^{-1} << diffusion scale k_D^{-1}

Diffusion erases perturbations !

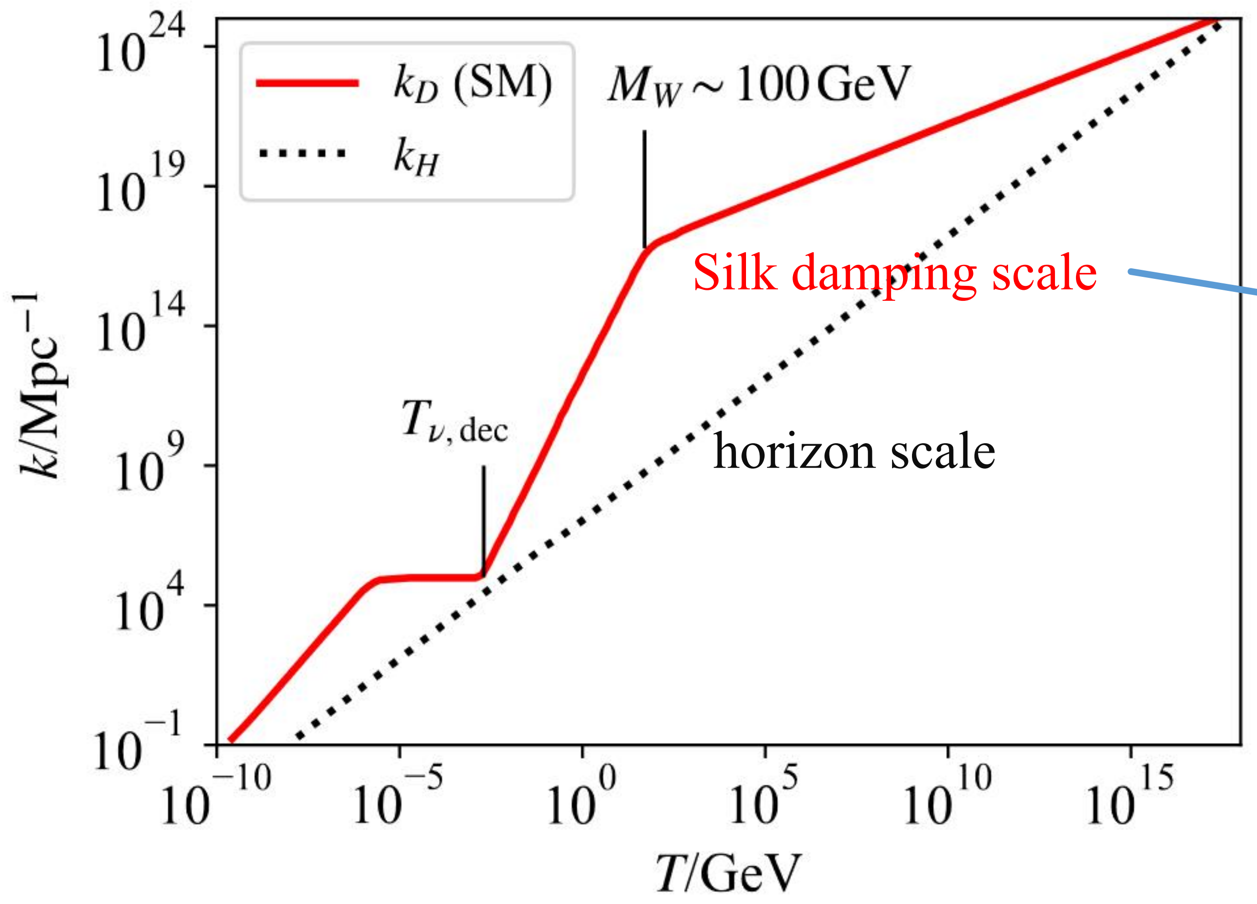
CMB anisotropy power spectrum



"Silk damping"

Nature 215 (1967) 5106: J. Silk

Silk damping scale



- **Microscopic origin:**

  particle interaction in cosmic fluid

$$k_D^{-2}(\tau) \simeq \int_0^{\tau} \mathrm{d}\tau' \, \frac{2\,\eta(\tau')}{3\,a\,(\rho+p)}$$

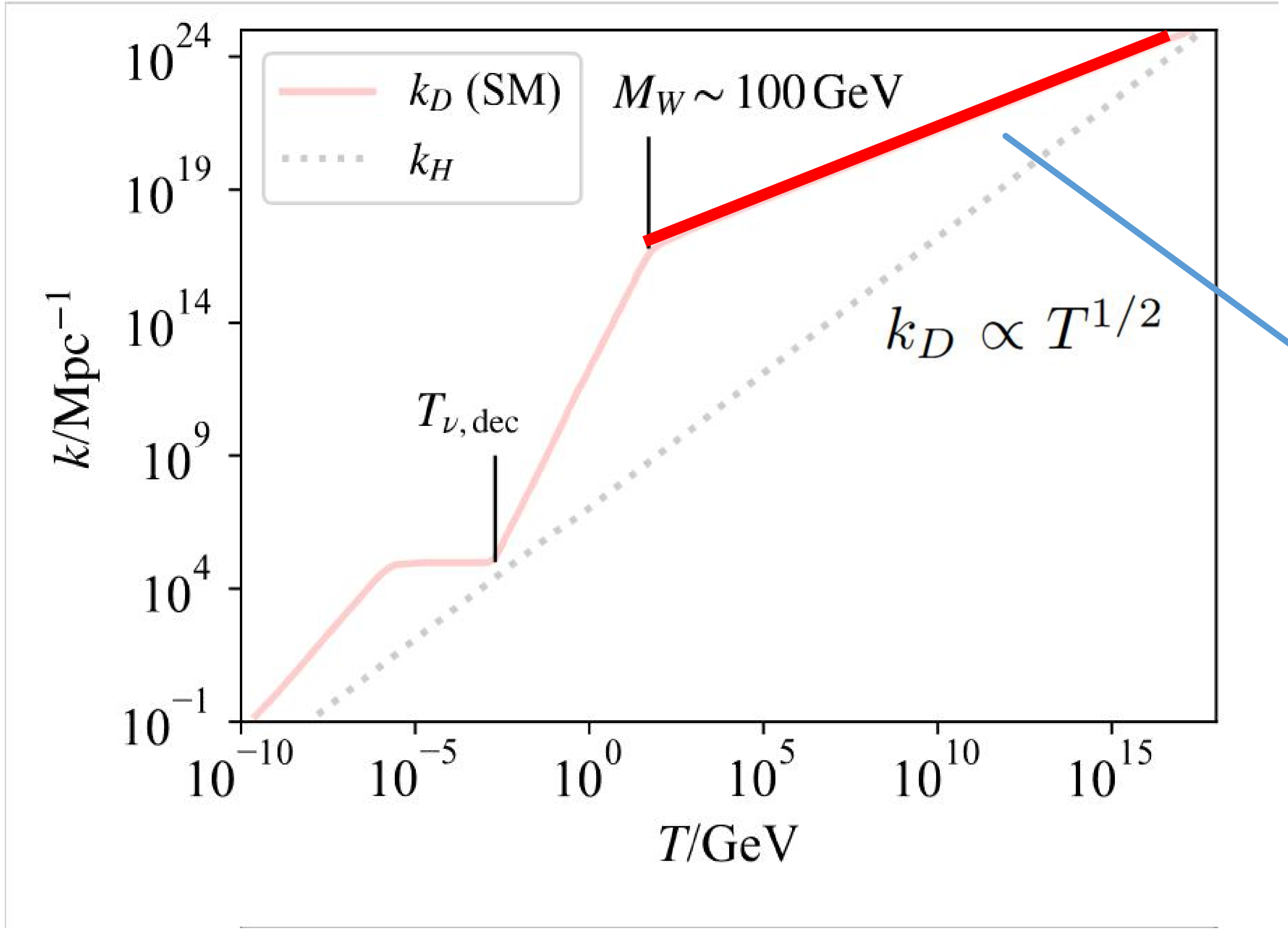
$$\eta(\tau) \simeq \sum_{j=\nu, X, \ldots} \frac{4}{15} \rho_j t_j \, \Theta(\tau_{j,\mathrm{dec}} - \tau)$$

$$t_j = 1/(n_j \langle \sigma_j v \rangle)$$

thermally-averaged cross section

PRL 113 (2014) 061301: D. Jeong, J. Pradler, J. Chluba, and M. Kamionkowski
SCPMA 68 (2025) 210412: ***YHY*** *and S. Wang*

Silk damping scale

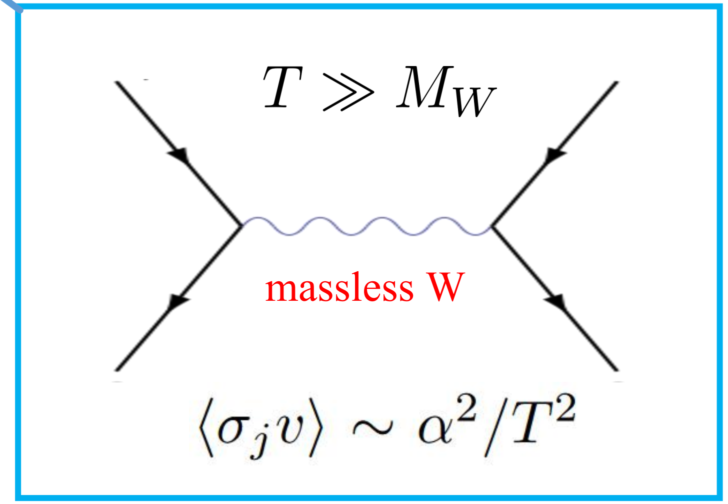


- **Microscopic origin:**

  particle interaction in cosmic fluid

- **Within the SM:**

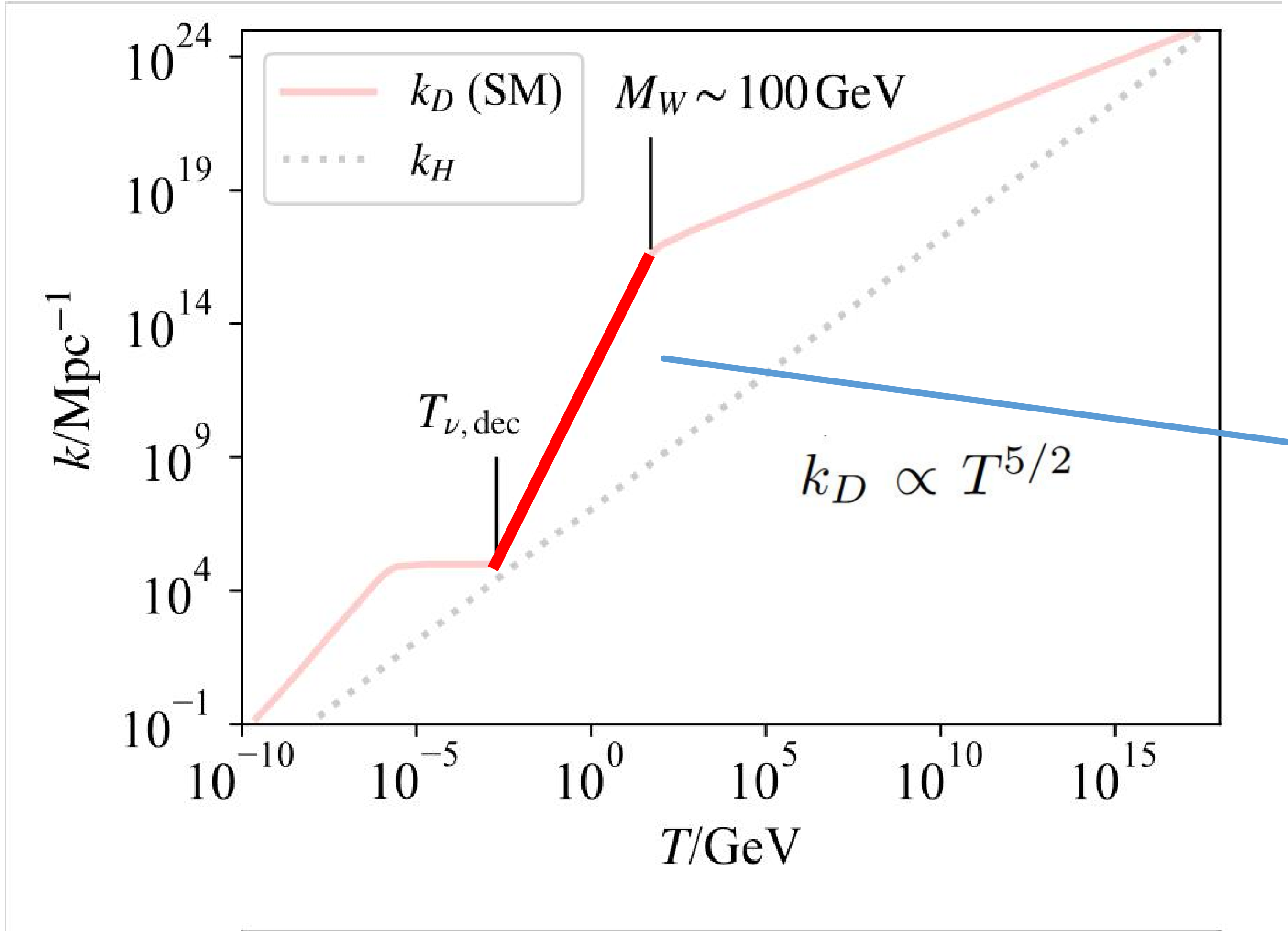
  dominated by neutrinos



$g = \sqrt{4\pi\alpha}$

PRL 113 (2014) 061301: D. Jeong, J. Pradler, J. Chluba, and M. Kamionkowski
SCPMA 68 (2025) 210412: ***YHY*** *and S. Wang*

Silk damping scale



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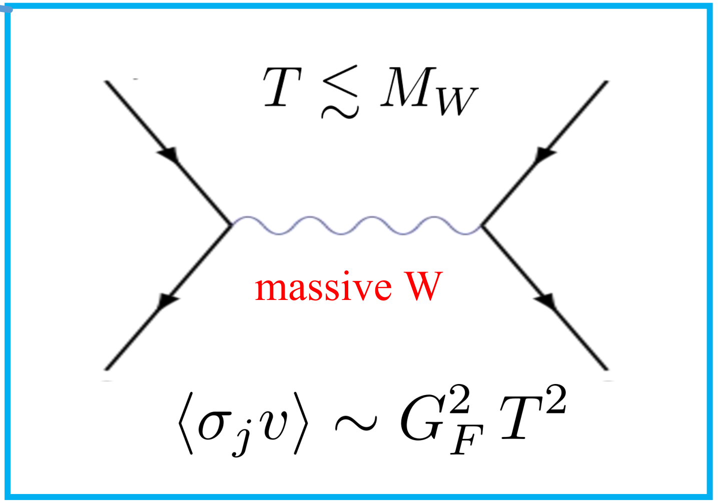
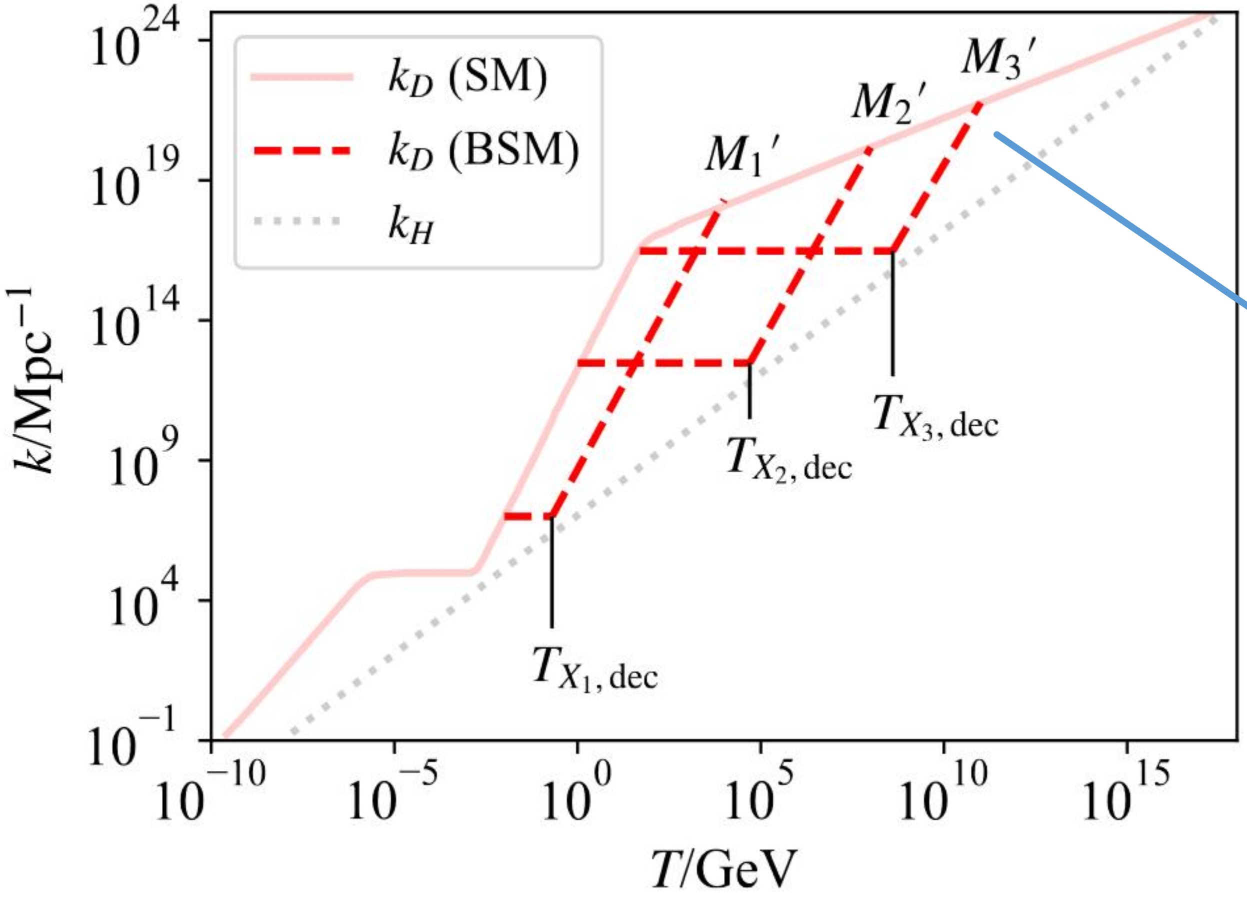


$G = \alpha / M^2$

PRL 113 (2014) 061301: D. Jeong, J. Pradler, J. Chluba, and M. Kamionkowski
SCPMA 68 (2025) 210412: ***YHY*** *and S. Wang*

Silk damping scale

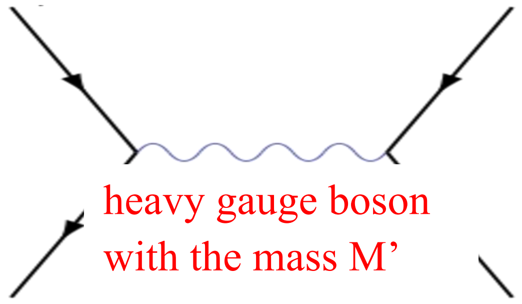


- **Microscopic origin:**

  particle interaction in cosmic fluid

- **Beyond the SM:**

  dominated by weakest-interacting particles

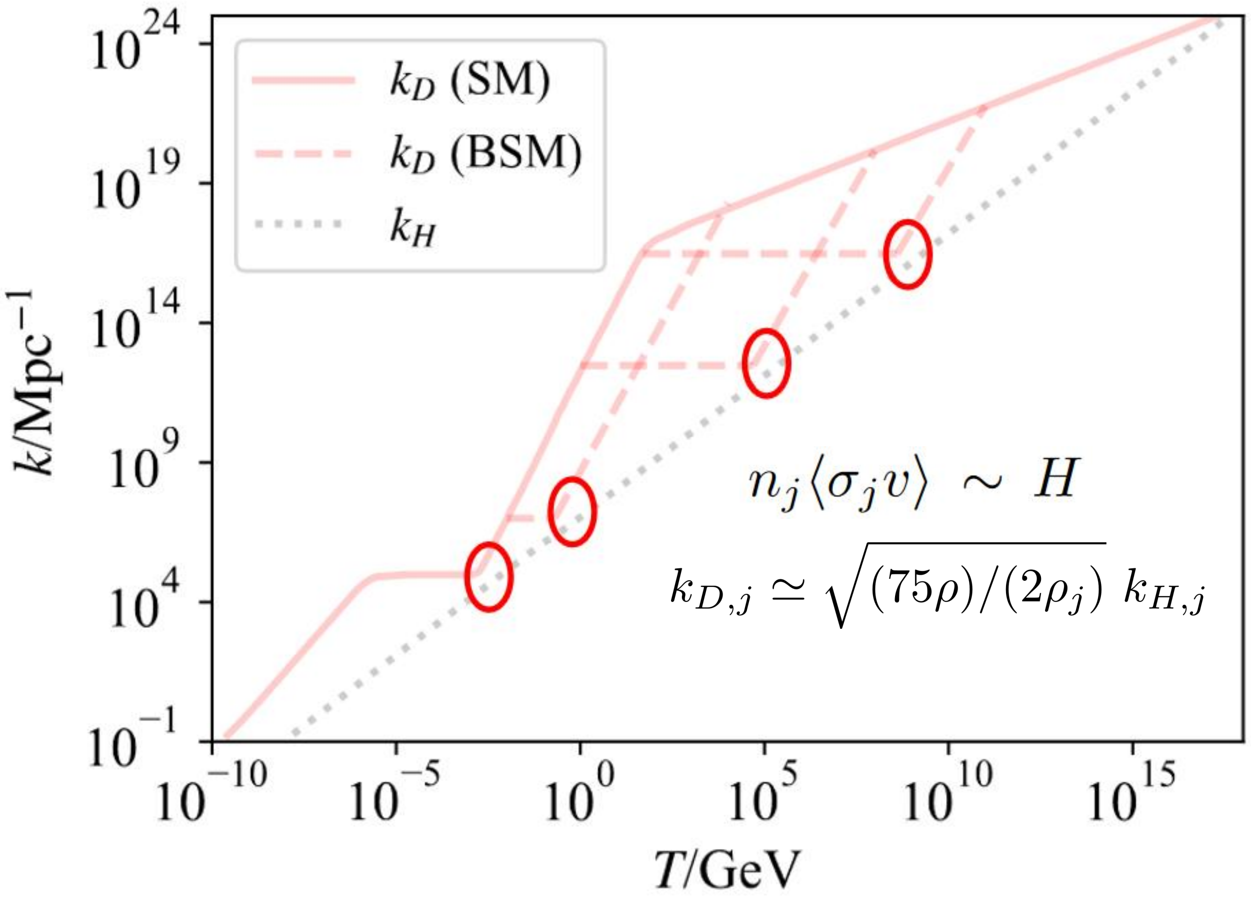


$$G \simeq G_F (M_W/M')^2$$

specific BSM models can be considered

PRL 113 (2014) 061301: D. Jeong, J. Pradler, J. Chluba, and M. Kamionkowski
*SCPMA 68 (2025) 210412: **YHY** and S. Wang*

Silk damping scale



- **Microscopic origin:**

  particle interaction in cosmic fluid

- **Within the SM:**

  dominated by neutrinos

- **Beyond the SM:**

  dominated by weakest-interacting particles

- **At particle decoupling:**

  Silk damping scale ~ horizon scale

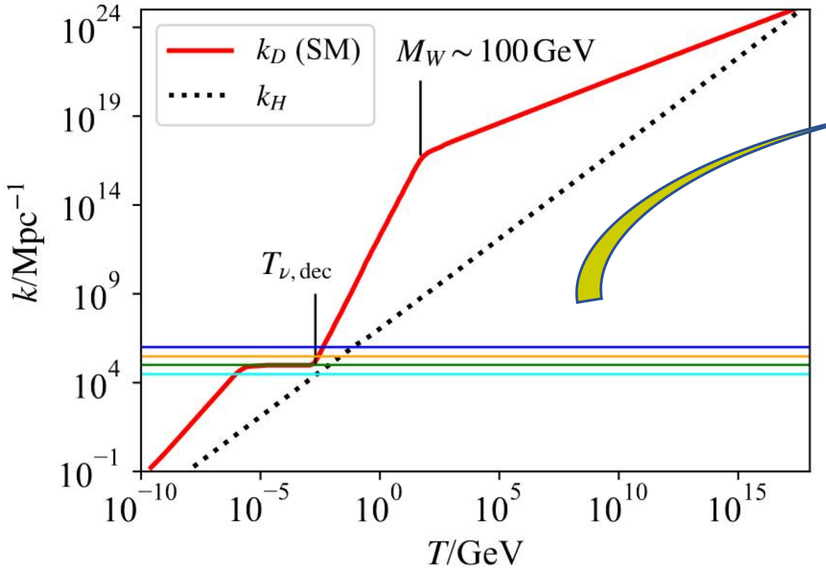
important for induced GWs

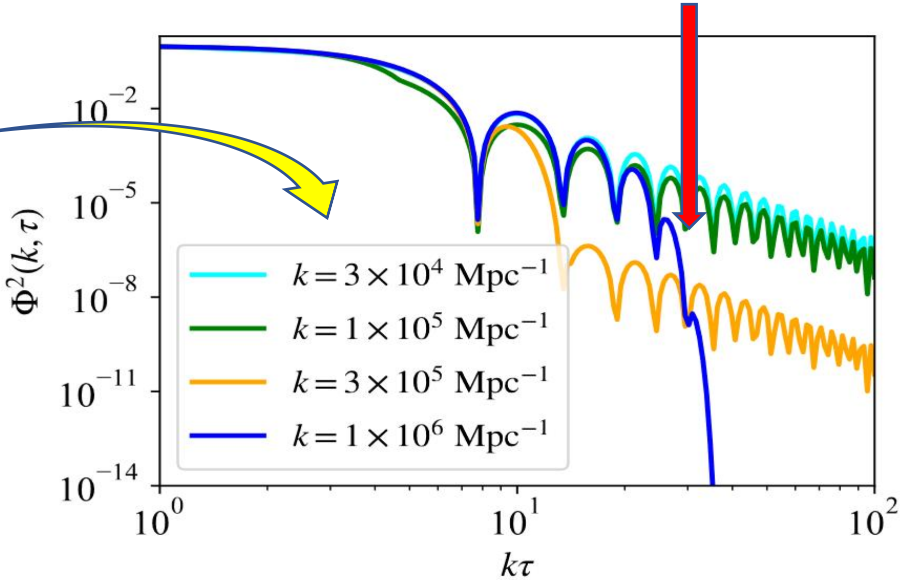
PRL 113 (2014) 061301: D. Jeong, J. Pradler, J. Chluba, and M. Kamionkowski
SCPMA 68 (2025) 210412: ***YHY*** *and S. Wang*

Silk damping in induced GWs

SCPMA 68 (2025) 210412: ***YHY*** *and S. Wang*

notable only for k ~ k_D (t_{dec})





perfect fluid, RD

Silk damping

$$\phi^{(1)}_{\mathbf{k}}(\tau) = \Phi(k,\tau)\,\zeta_{\mathbf{k}}$$

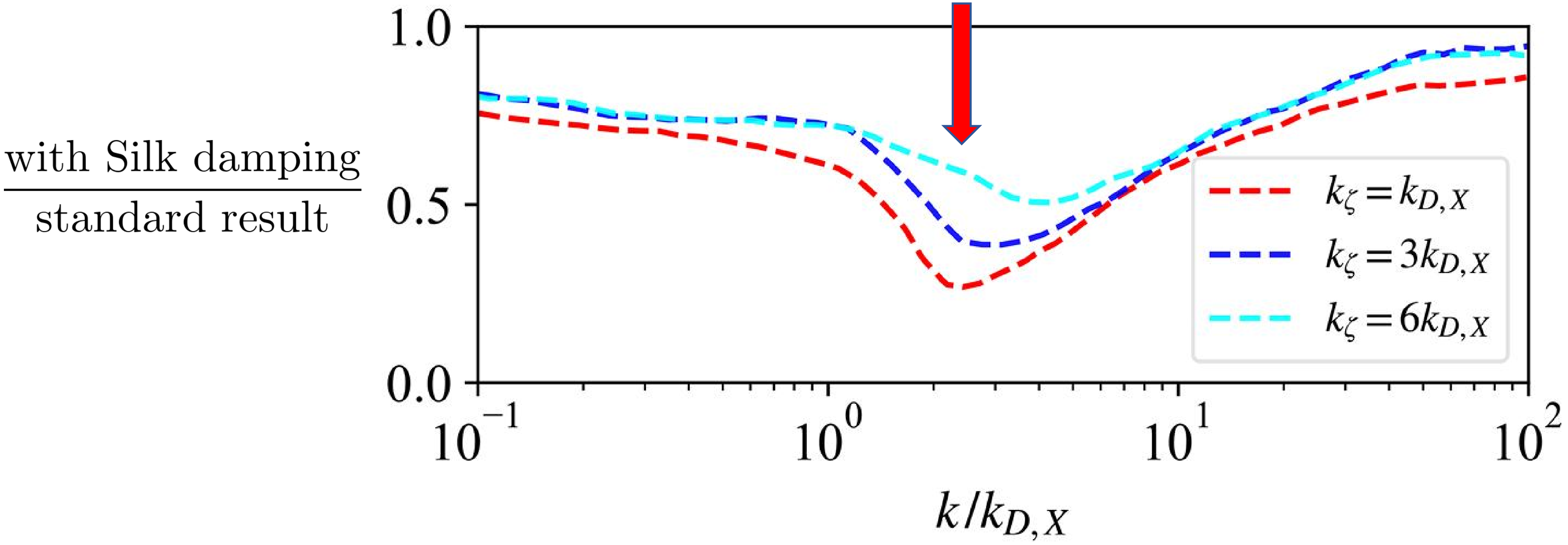
$$\Phi(k,\tau) \simeq \frac{9}{(k\tau)^2}\left(\frac{\sqrt{3}}{k\tau}\sin\frac{k\tau}{\sqrt{3}} - \cos\frac{k\tau}{\sqrt{3}}\right) \times e^{-k^2/k_D^2(\tau)}$$

$$\Omega_{\mathrm{gw}}(k) = \frac{k^2}{6a^2H^2}\int_0^\infty \mathrm{d}u \int_{|1-u|}^{|1+u|} \mathrm{d}v \left[\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right]^2 \times \overline{I^2(u,v,k,\tau)}\,\mathcal{P}_\zeta(uk)\mathcal{P}_\zeta(vk)$$

Results

SCPMA 68 (2025) 210412: **YHY** and S. Wang

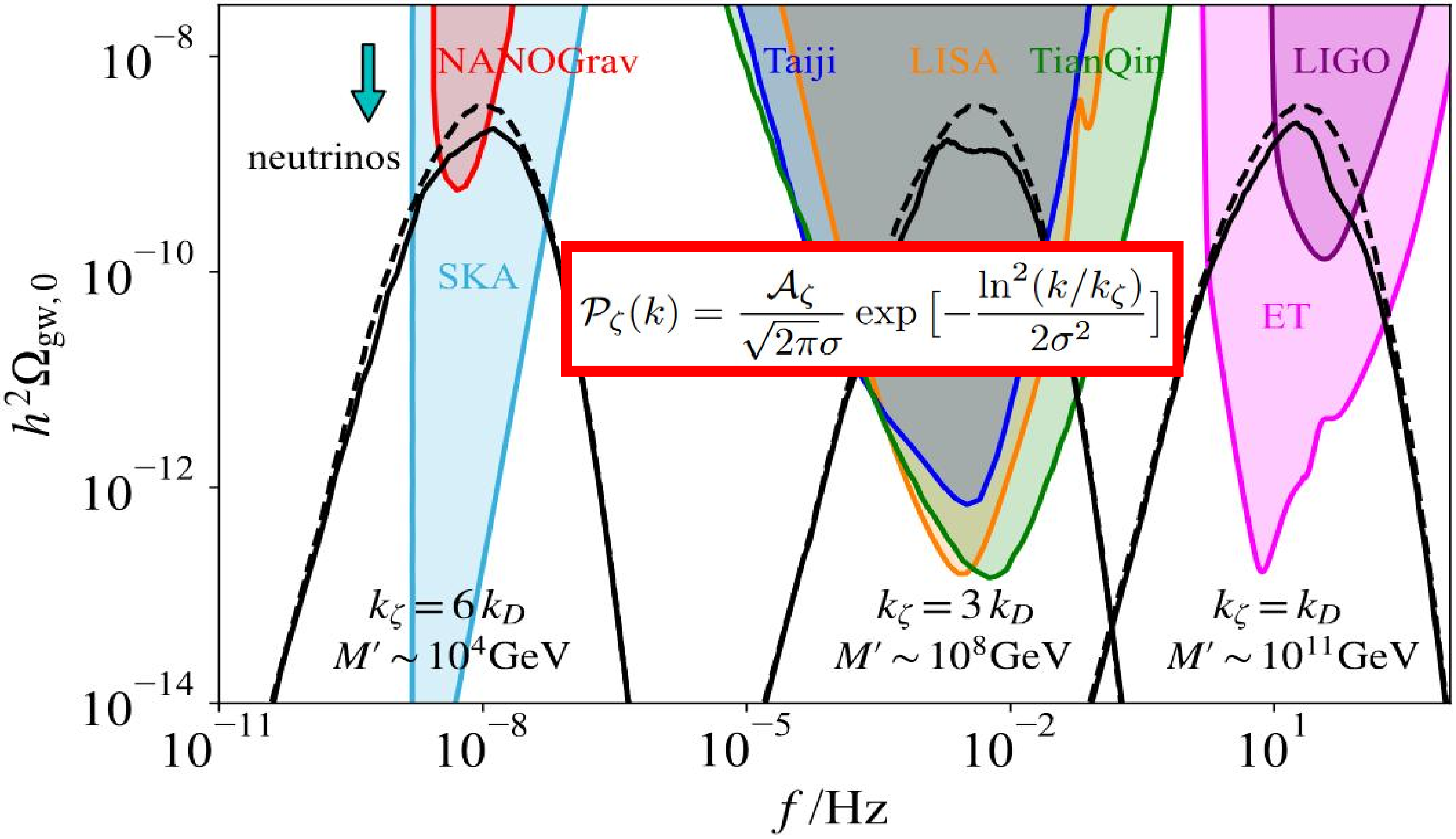
Silk damping effect



Silk damping can suppress the GW spectrum by ~70% at the scale $k \sim k_D(t_{dec,X})$ → decoupling time of weakly-interacting particles → particle interaction

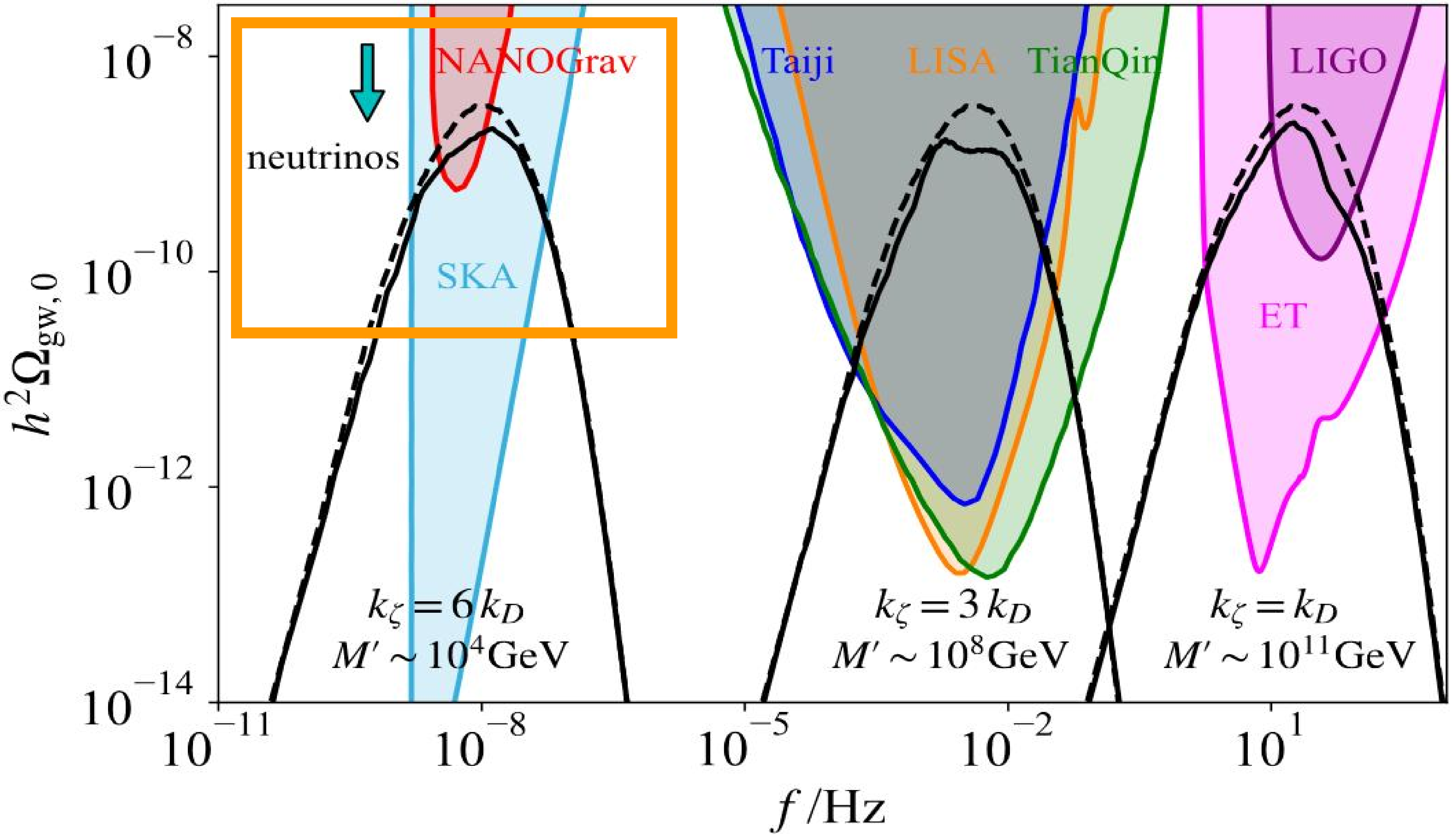
Observation

SCPMA 68 (2025) 210412: **YHY** and S. Wang



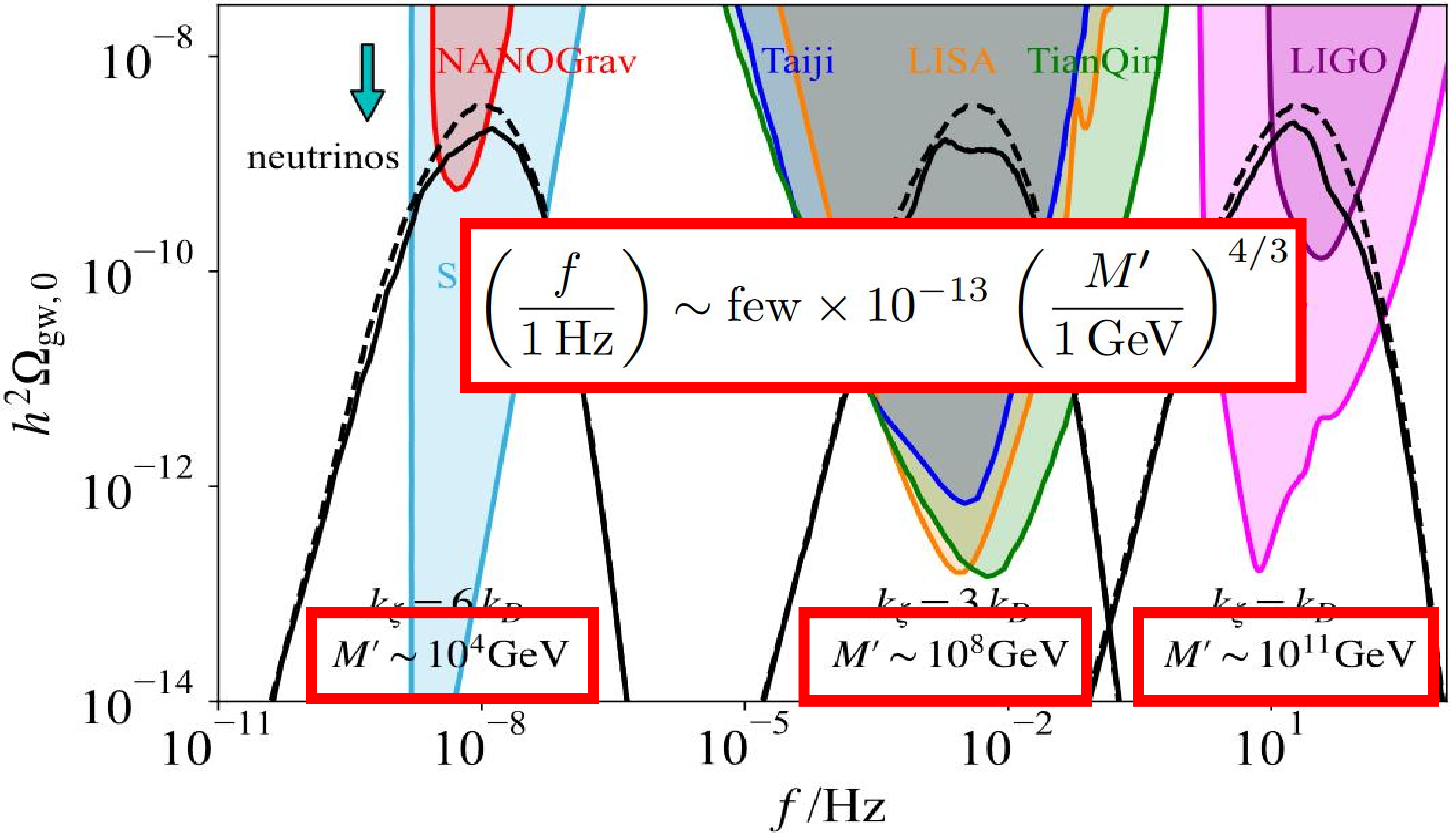
Observation (within the SM)

SCPMA 68 (2025) 210412: ***YHY*** *and S. Wang*



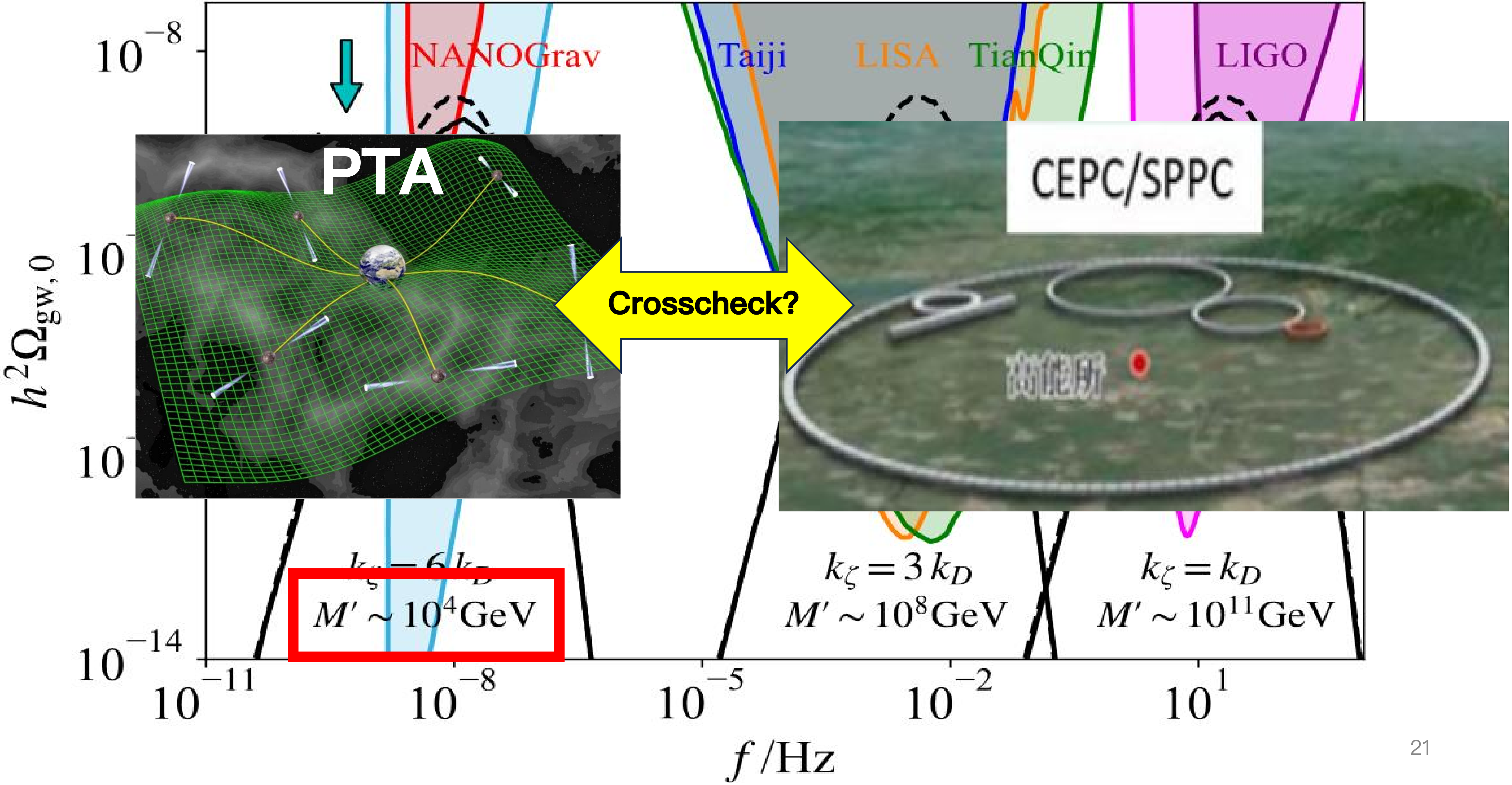
Observation (beyond the SM)

*SCPMA 68 (2025) 210412: **YHY** and S. Wang*



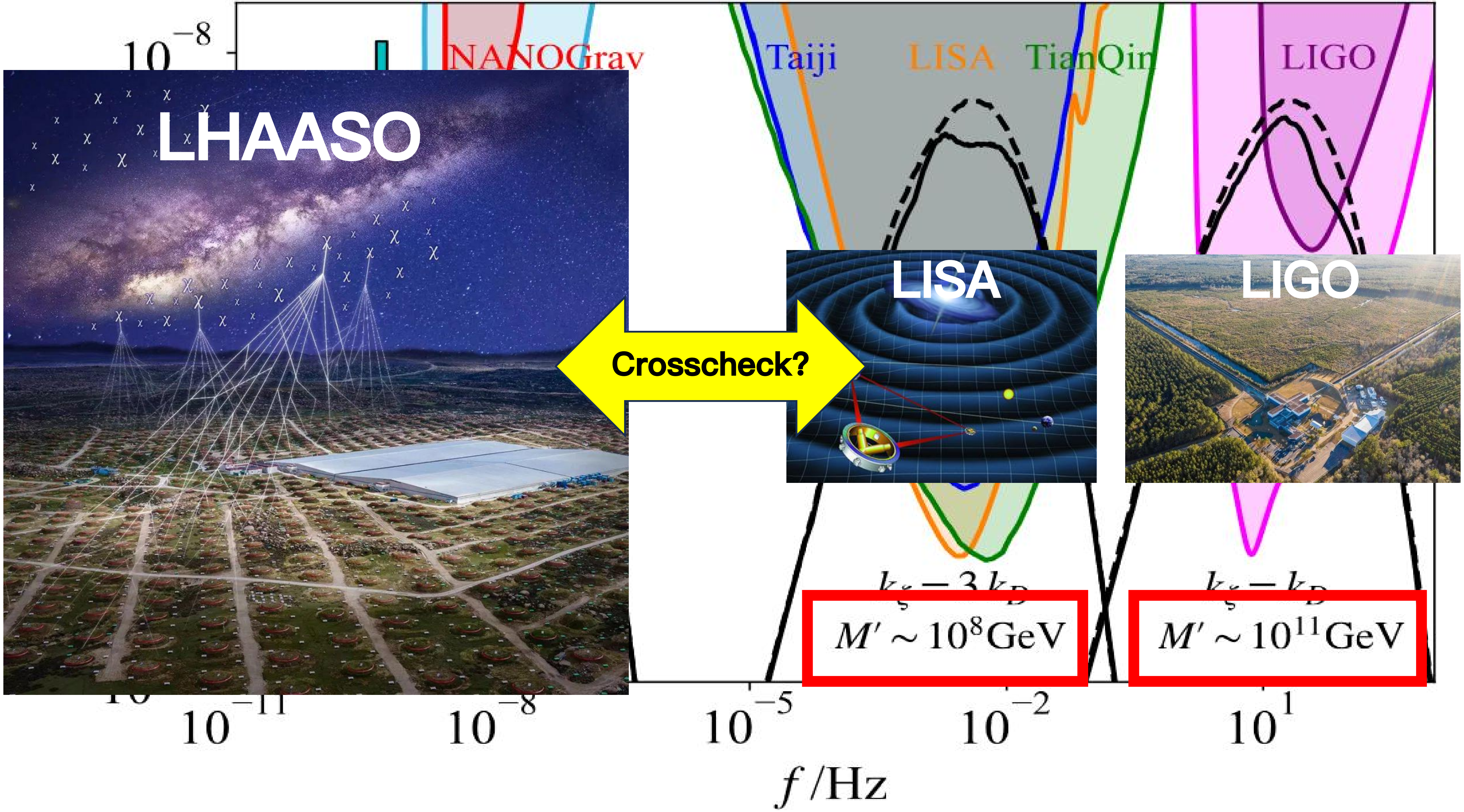
Future detection

SCPMA 68 (2025) 210412: **YHY** and S. Wang



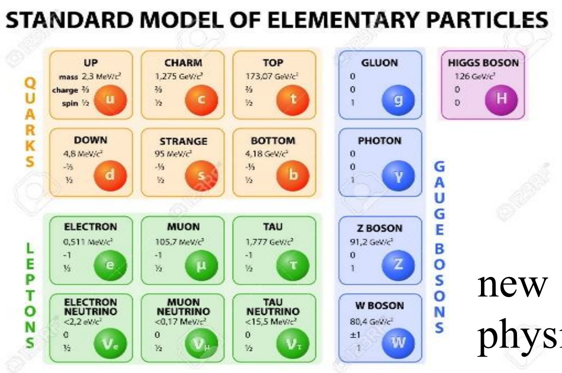
Future detection

*SCPMA 68 (2025) 210412: **YHY** and S. Wang*



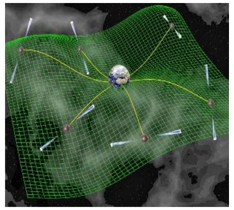
Conclusion

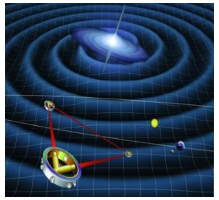
Particle interaction



new physics?

GW observation





We find a basic relation

$$\left(\frac{f}{1\,\mathrm{Hz}}\right) \sim \text{few} \times 10^{-13} \left(\frac{M'}{1\,\mathrm{GeV}}\right)^{4/3}$$

Dissipation in cosmic fluid

shear viscosity   bulk viscosity

$$\Delta T_{ij} = -\eta\left(\frac{\partial u_i}{\partial x^j} + \frac{\partial u_j}{\partial x^i} - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{u}\right) - \xi\,\delta_{ij}\nabla\cdot\mathbf{u}\,,$$

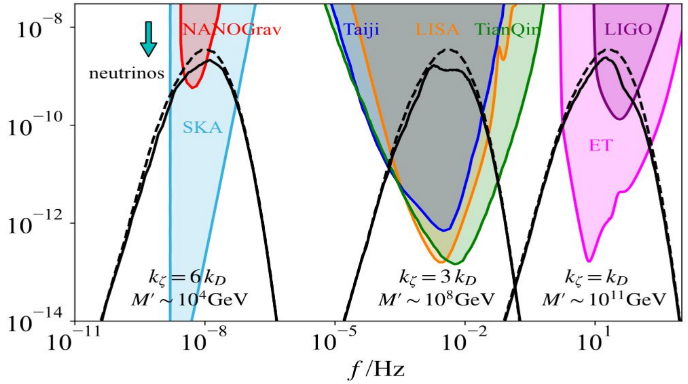
$$\Delta T_{0i} = -\chi\left(\frac{\partial T}{\partial x^i} + T\frac{\partial u_i}{\partial t}\right)\,,$$

$$\Delta T_{00} = 0$$

thermal conduction

Silk damping

Induced GWs



Conclusion

- Silk damping is an essential yet unexplored effect for GW observations.
- Silk damping notably suppresses the spectrum of induced GWs at the frequencies related to the decoupling of weakly-interacting particles.
- Within the SM, Silk damping caused by neutrinos will help to determine the origin of the GWB reported by PTA.
- Beyond the SM, Silk damping in induced GWs opens a new road to detect new physics, especially for those at extremely high energy scales.

Thanks!