Focus Workshop on Cosmological Phase Transitions

MeV First-Order Dark Phase Transitions

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JSPS

S. Kanemura, **Lisp**, K-P. Xie, arXiv: 2504.08304

S. Kanemura, **Lisp**, arXiv: 2308.16390

Lisp, K-P. Xie, arXiv:2307.01086

Outline

- Observational windows of MeV-scale dark FOPT
- Close complementarity in cosmology
- Close consequences at colliders
- Dark matter production in minimal dark FOPT
- Summary

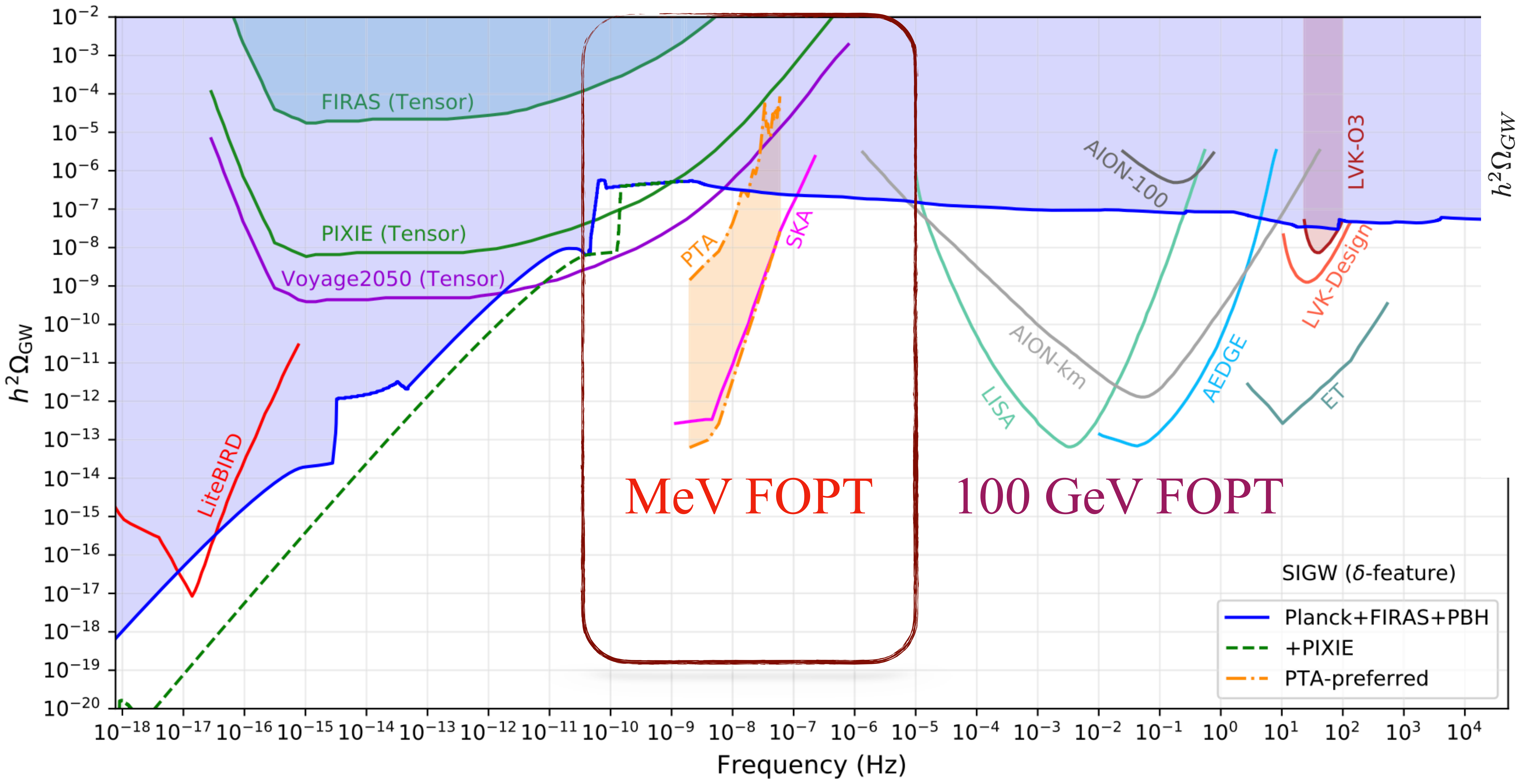
Cosmology

Observation windows for dark FOPT

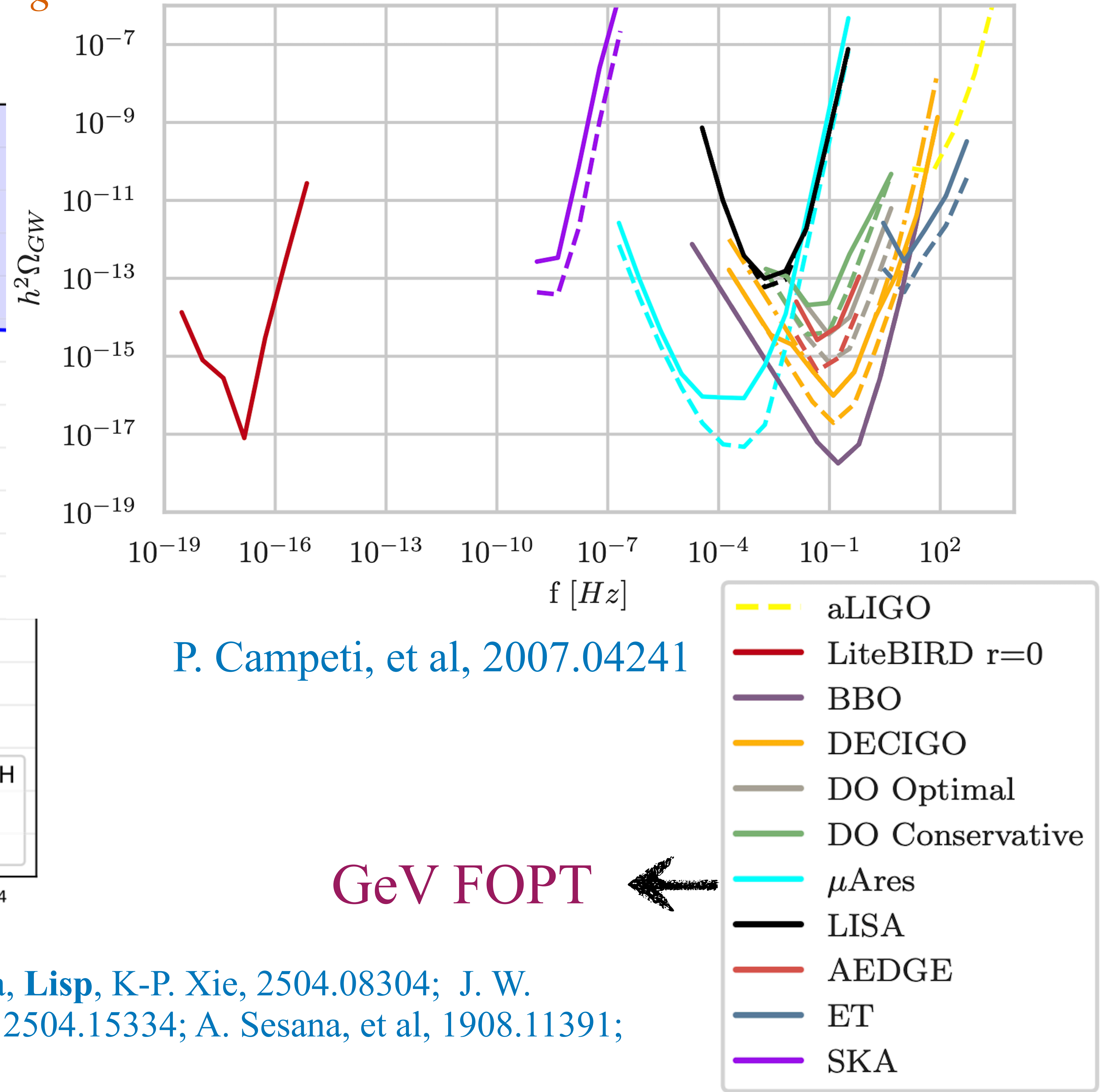
- Frequency of sound-wave dominated stochastic gravitational waves (GW) and FOPT temperature (scale)

$$f_{\rm sw}^{\rm peak} \approx 1.9 \times 10^{-5}\,{\rm Hz} \left(\frac{g_\rho(T_n)}{100}\right)^{1/6} \left(\frac{T_n}{100\ {\rm GeV}}\right) \left(\frac{\beta/\mathcal{H}}{v_w}\right) \qquad T_n \sim \frac{\lambda}{g} v$$

C. Caprini, et al, 1512.06239



B. Cyr, et al, 2309.02366



P. Campeti, et al, 2007.04241

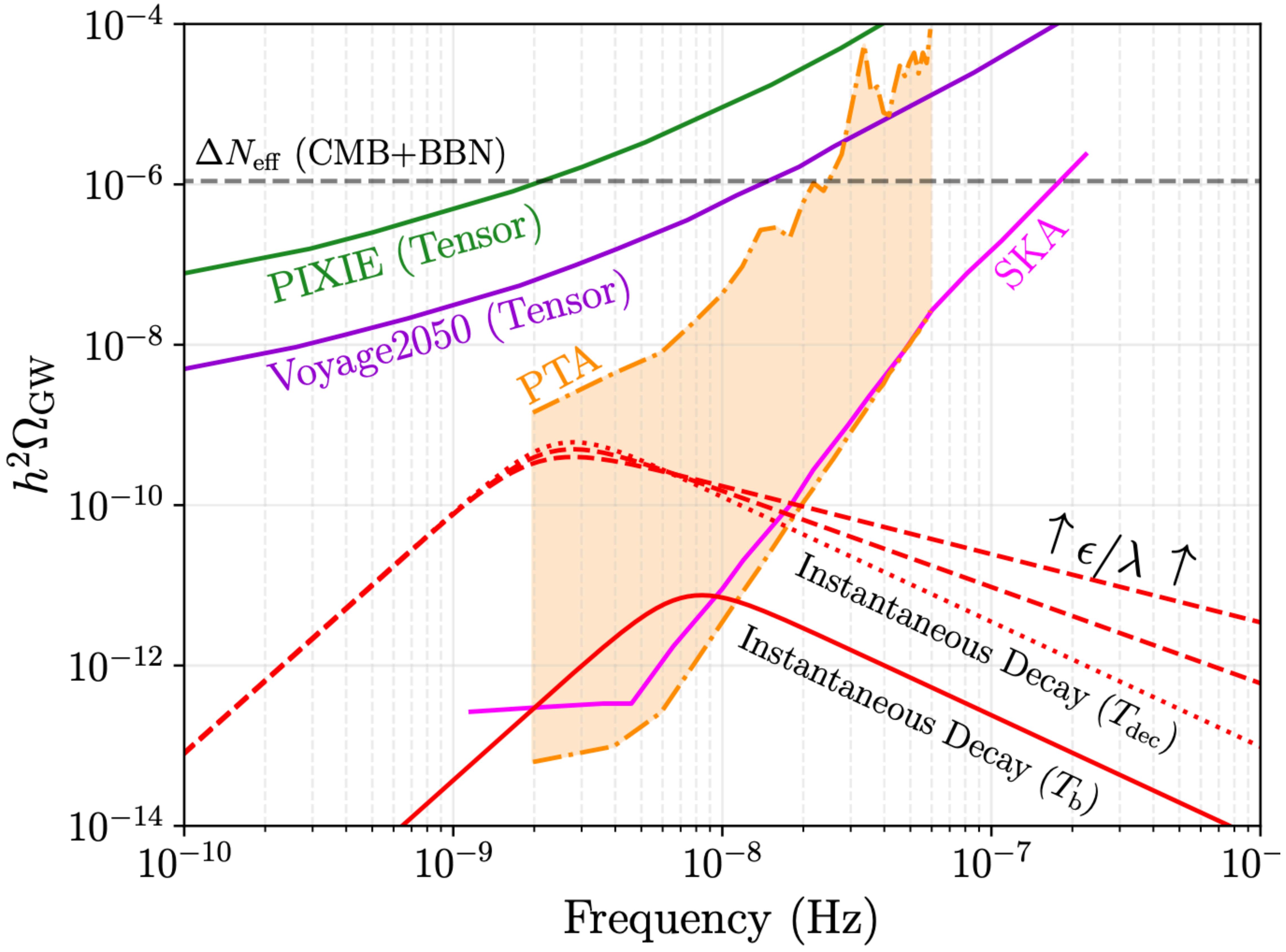
GeV FOPT

S. Kanemura, **Lisp**, K-P. Xie, 2504.08304; J. W. Foster, et al, 2504.15334; A. Sesana, et al, 1908.11391;

MeV dark FOPT in cosmology

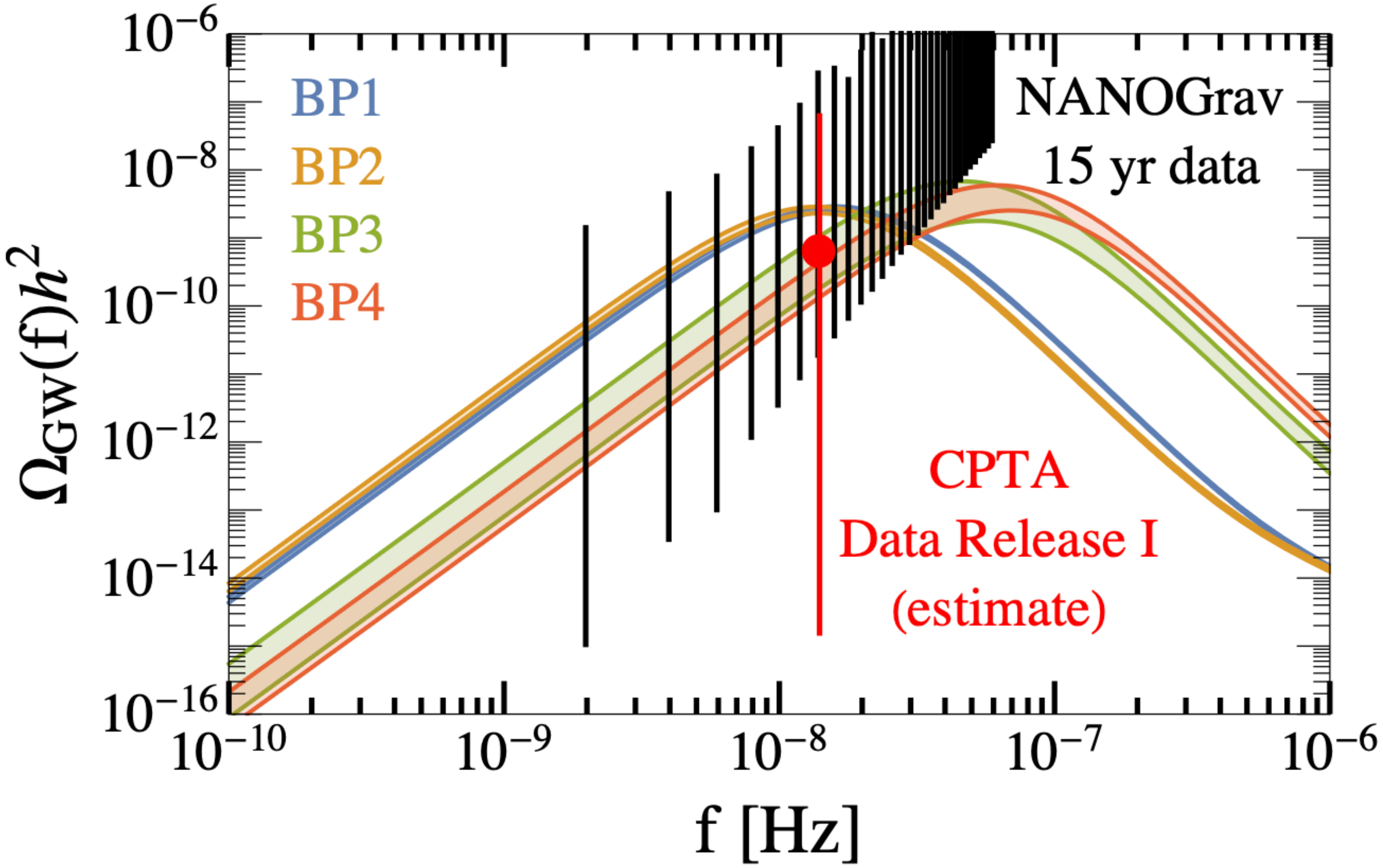
- Complementary probes from effective number of neutrinos N_{eff}, CMB spectral distortions, nanohertz GW

Nanohertz GW from Domain Wall



B. Cyr, et al, 2504.02076

Nanohertz GW from dark FOPT



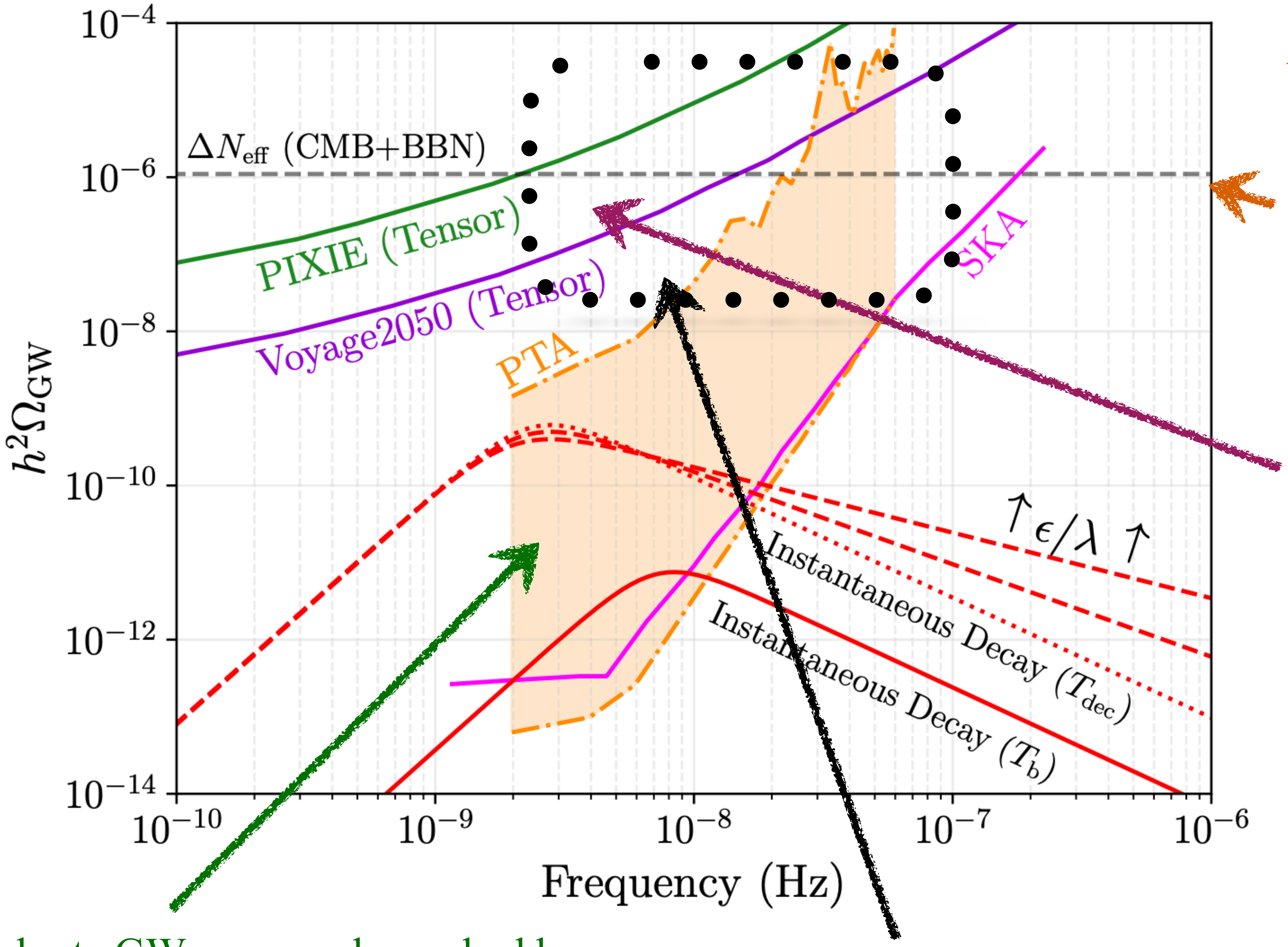
Lisp & K.-P. Xie, 2307.01086

Close complementarity in cosmology

- Complementary probes from effective number of neutrinos $N_{\rm eff}$, CMB spectral distortions, nanohertz GW

B. Cyr, et al, 2504.02076

T-H Yeh, et al, 2207.13133



$N_{\rm eff}$: GW as radiation contributing to cosmic expansion

$$\Omega_{{\rm GW},0}h^2 = \left(\frac{\rho_{\rm GW}}{\rho_\gamma}\right)\Omega_{\gamma,0}h^2 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Omega_{\gamma,0}h^2\Delta N_{\rm eff} \approx 5.6\times 10^{-6}\Delta N_{\rm eff}$$

*GW near neutrino decoupling may have not be considered yet… no simple analytic estimate

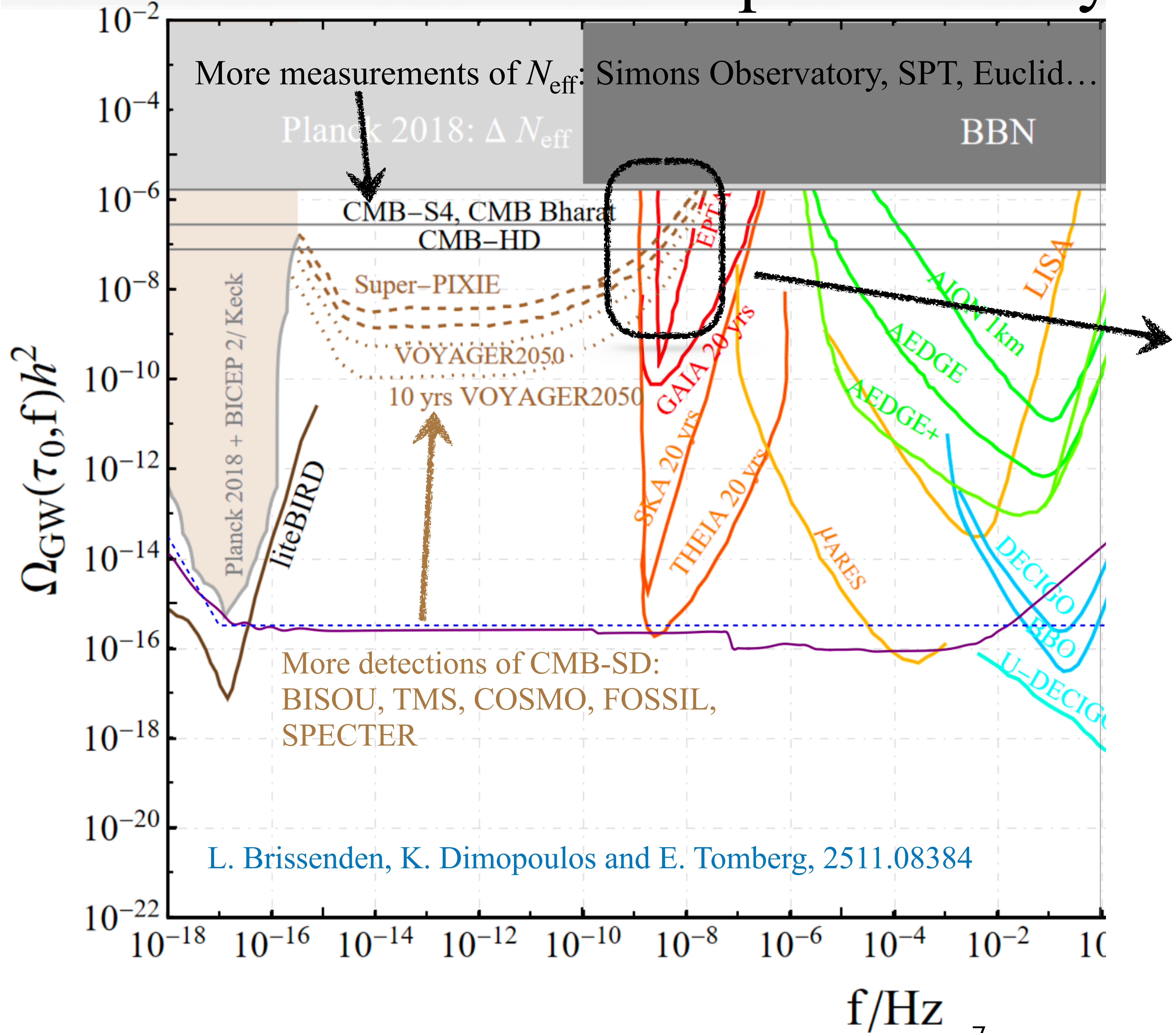
CMB spectral distortions: GW as a ***tensor*** perturbation, couples to photon perturbation evolution in Boltzmann hierarchy

analogous to the standard CMB μ distortion from Silk damping —diffusion damping of small-scale ***scalar*** perturbations dissipates and transfers energy to CMB monopole

Nanohertz GW can now be probed by PTA and upcoming SKA

A big question to consider: *can MeV dark FOPT create simultaneously the three observable signals?* → Could be a way to distinguish various GW sources

Close complementarity in cosmology



How MeV dark FOPT makes predictions here?

Still under consideration…

1. Correlations can be analyzed model-independently
2. Parameter space of particle physics should be specified model-dependently

Colliders

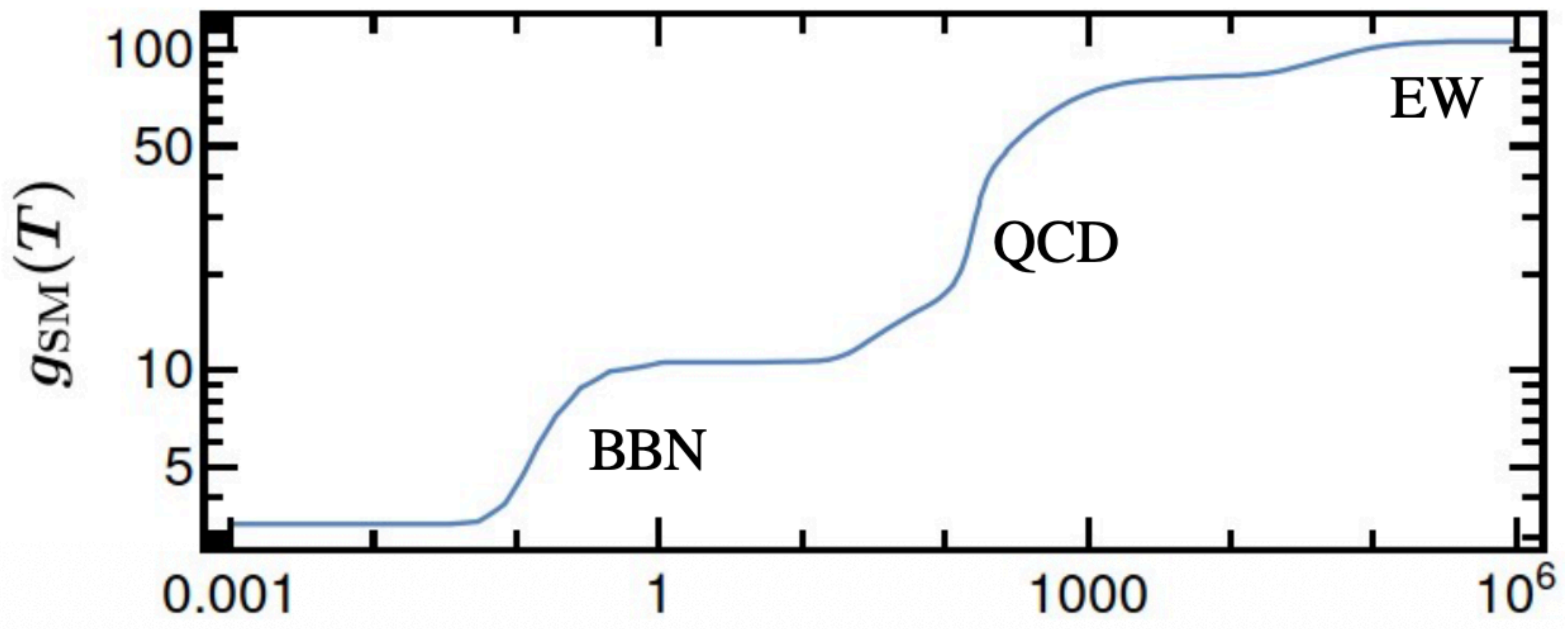
A close consequence of dark FOPT at colliders

- A close consequence in EW FOPT: Higgs trilinear coupling. What about MeV FOPT?

  GW from dark MeV FOPT sensitively depends on the temperature ratio between the SM and dark plasma. This sensitivity can be used to probe the portal connection at colliders

- Without portal coupling, the two temperatures evolve differently

Even from a symmetric reheating $T_{\rm dark,i} = T_{\rm SM,i}$



$$\left.\frac{T_{\rm dark}}{T_{\rm SM}}\right|_{\rm FOPT} = \left(\frac{g_*(T_{\rm FOPT})}{g_*(T_i)}\right)^{1/3} \left.\frac{T_{\rm dark}}{T_{\rm SM}}\right|_i \lesssim 1$$

- Without portal coupling, GW amplitude suppressed

C. Caprini, et al, 1512.06239

$$\Omega_{\rm sw}^{\rm peak} h^2 \approx 2.65 \times 10^{-6} (\mathcal{H}\tau_{\rm sw}) \left(\frac{v_w}{\beta/\mathcal{H}}\right) \left(\frac{100}{g_\rho(T_n)}\right)^{1/3} \left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 \propto \left.\left(\frac{T_{\rm dark}}{T_{\rm SM}}\right)^{8-16}\right|_{\rm FOPT}$$

$$\kappa_{\rm sw} \approx \frac{\alpha}{0.73 + 0.083\sqrt{\alpha} + \alpha} \qquad \alpha \approx \frac{\Delta V_{\rm eff}}{\rho_R} \propto \left.\left(\frac{T_{\rm dark}}{T_{\rm SM}}\right)^4\right|_{\rm FOPT}$$

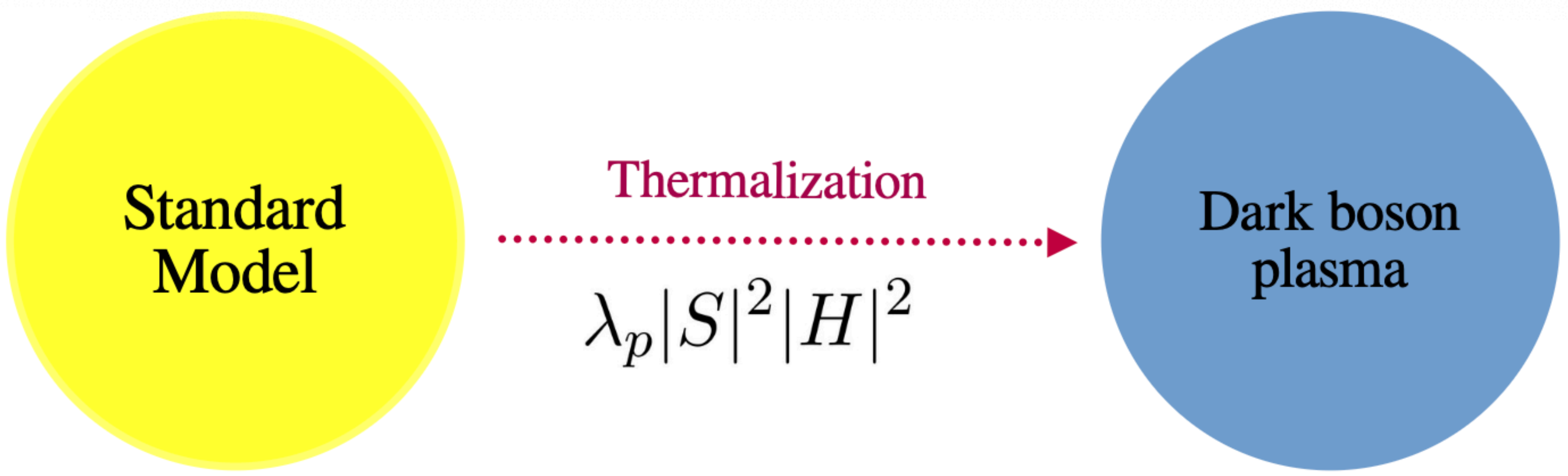
A close consequence of dark FOPT at colliders

- With portal coupling, $T_{\text{dark}} \approx T_{\text{SM}}$ can be maintained through the dark FOPT:

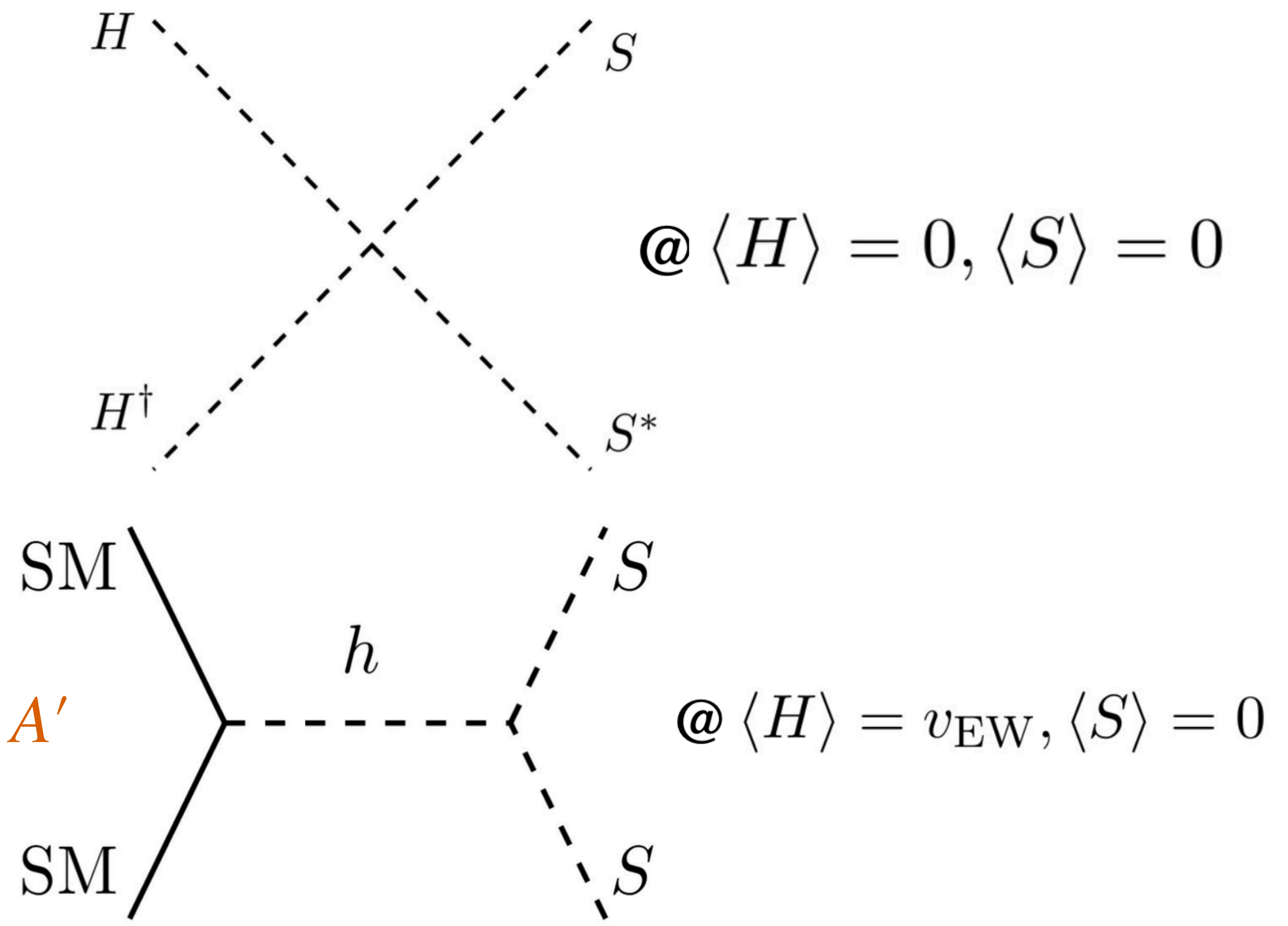
unsuppressed GW → significant portal couplings

→ large production rate of dark species at colliders

- A minimal and natural portal coupling—generic dark FOPT requires scalar particles



Gauged U(1): scalar S, gauge boson A'



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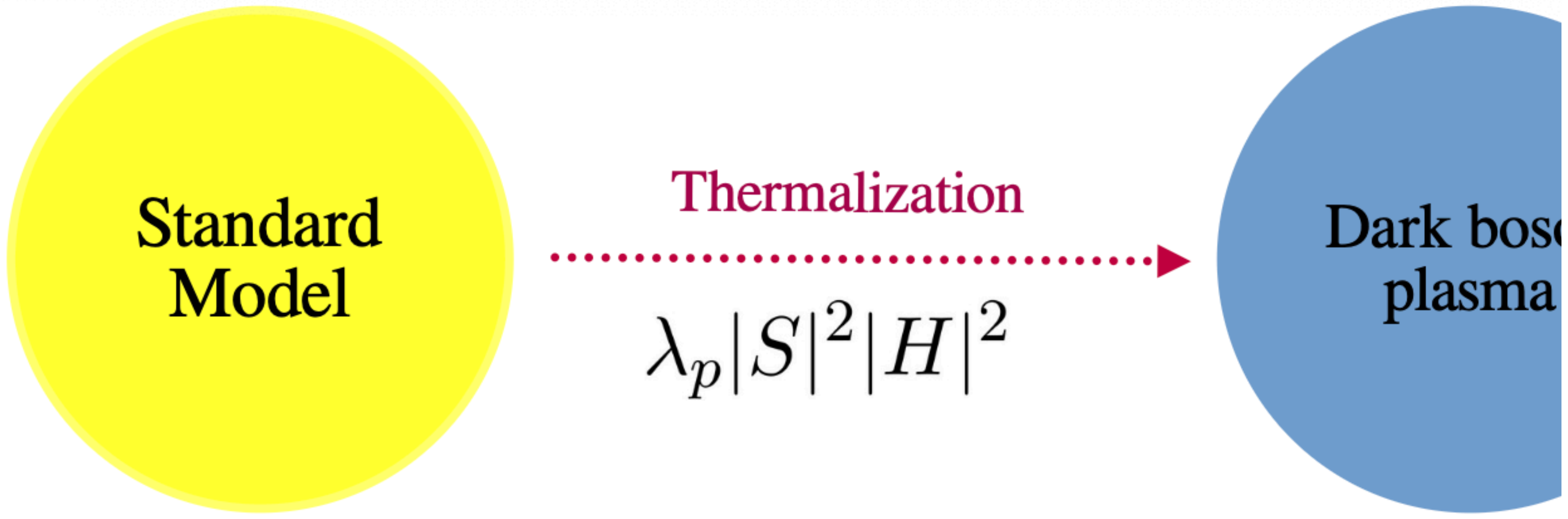
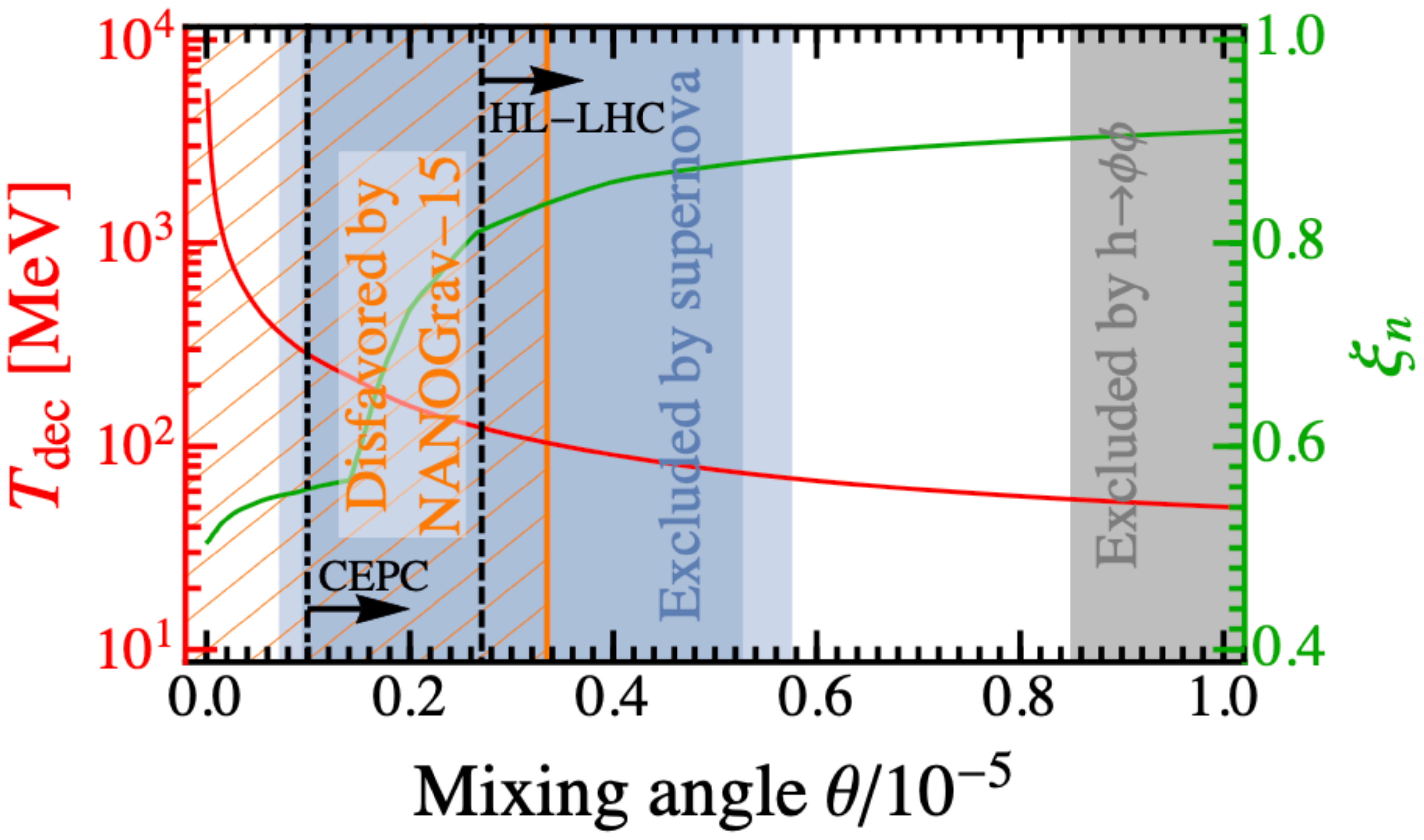
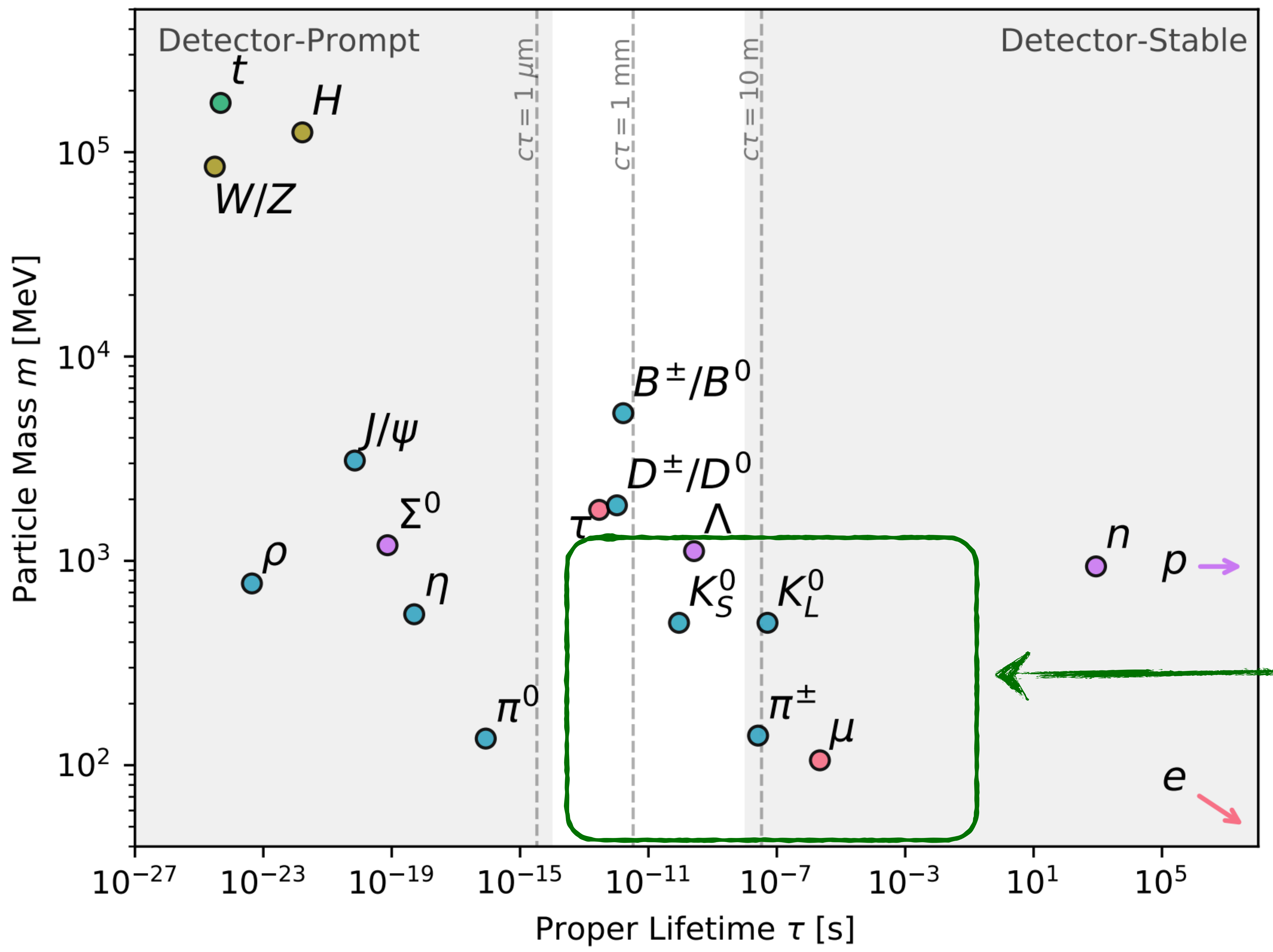


Gauged U(1): scalar S, gau



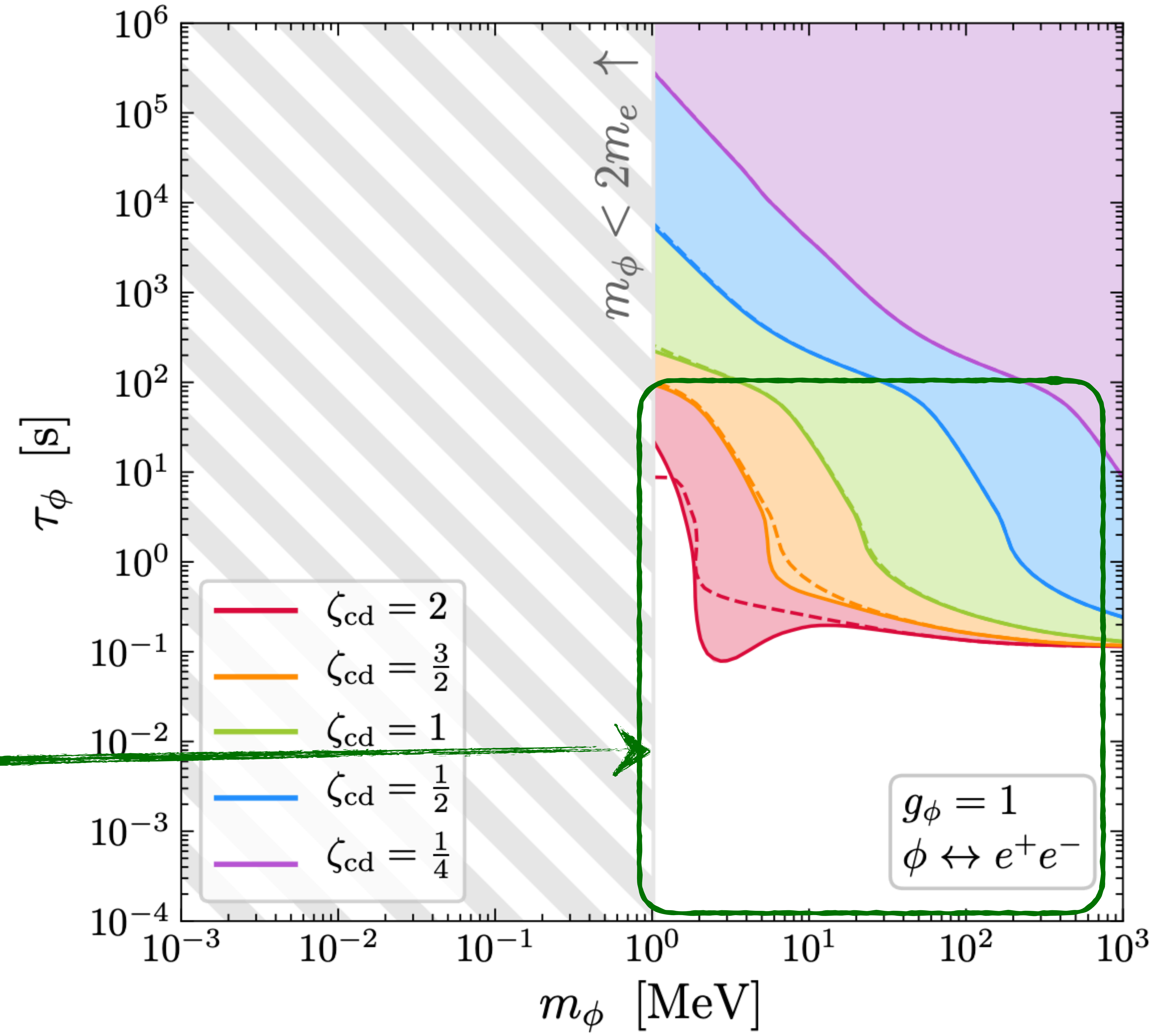
Collider searches of minimal dark FOPT

- Long-lived scalar particle at colliders and cosmology



Lawrence Lee, et al, 1810.12602

BBN bounds



P. F. Depta, et al, 2011.06519

Collider searches of minimal dark FOPT

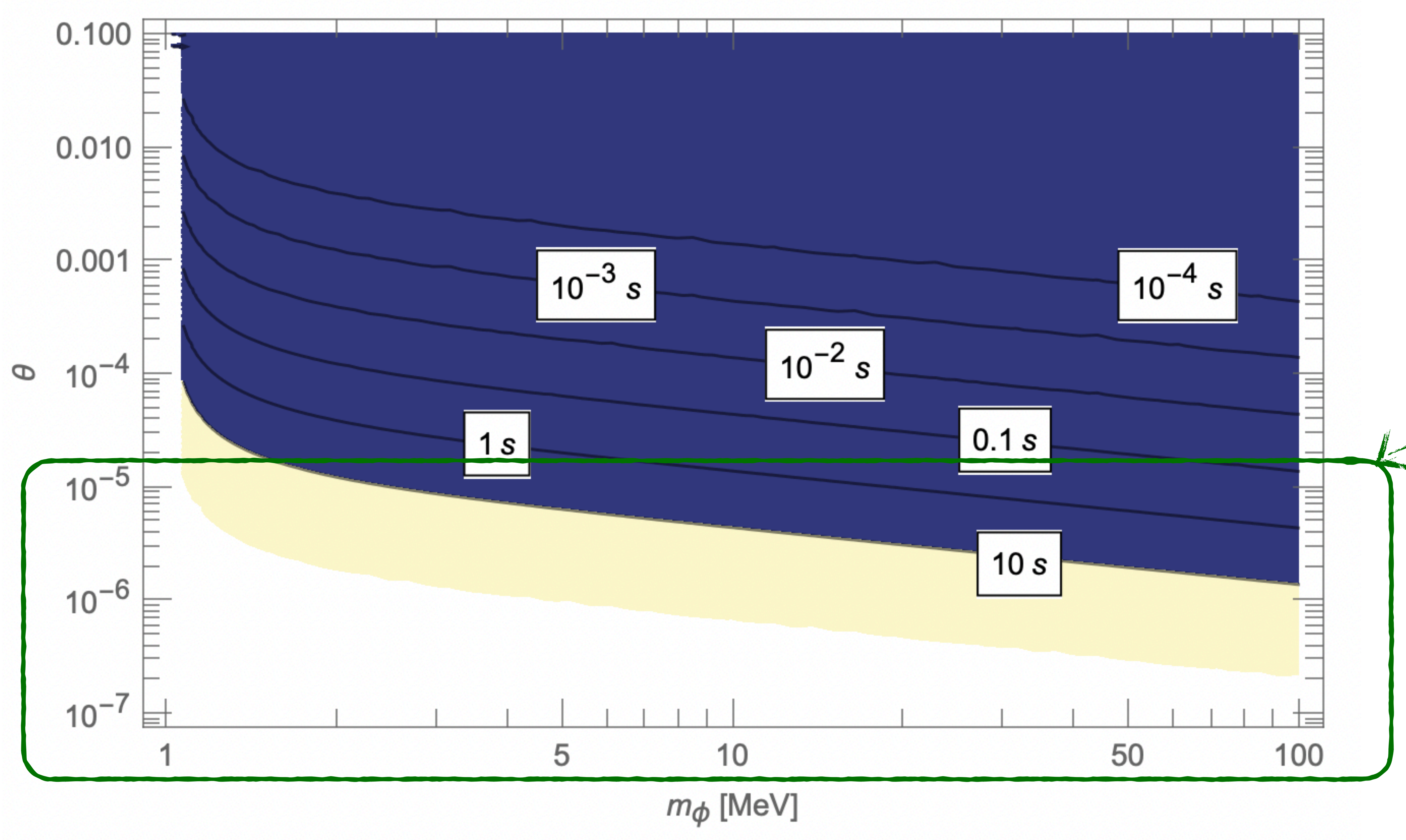
- $\phi \to e^+ + e^-$: lifetime converted into portal coupling

Higgs-dark scalar mixing angle

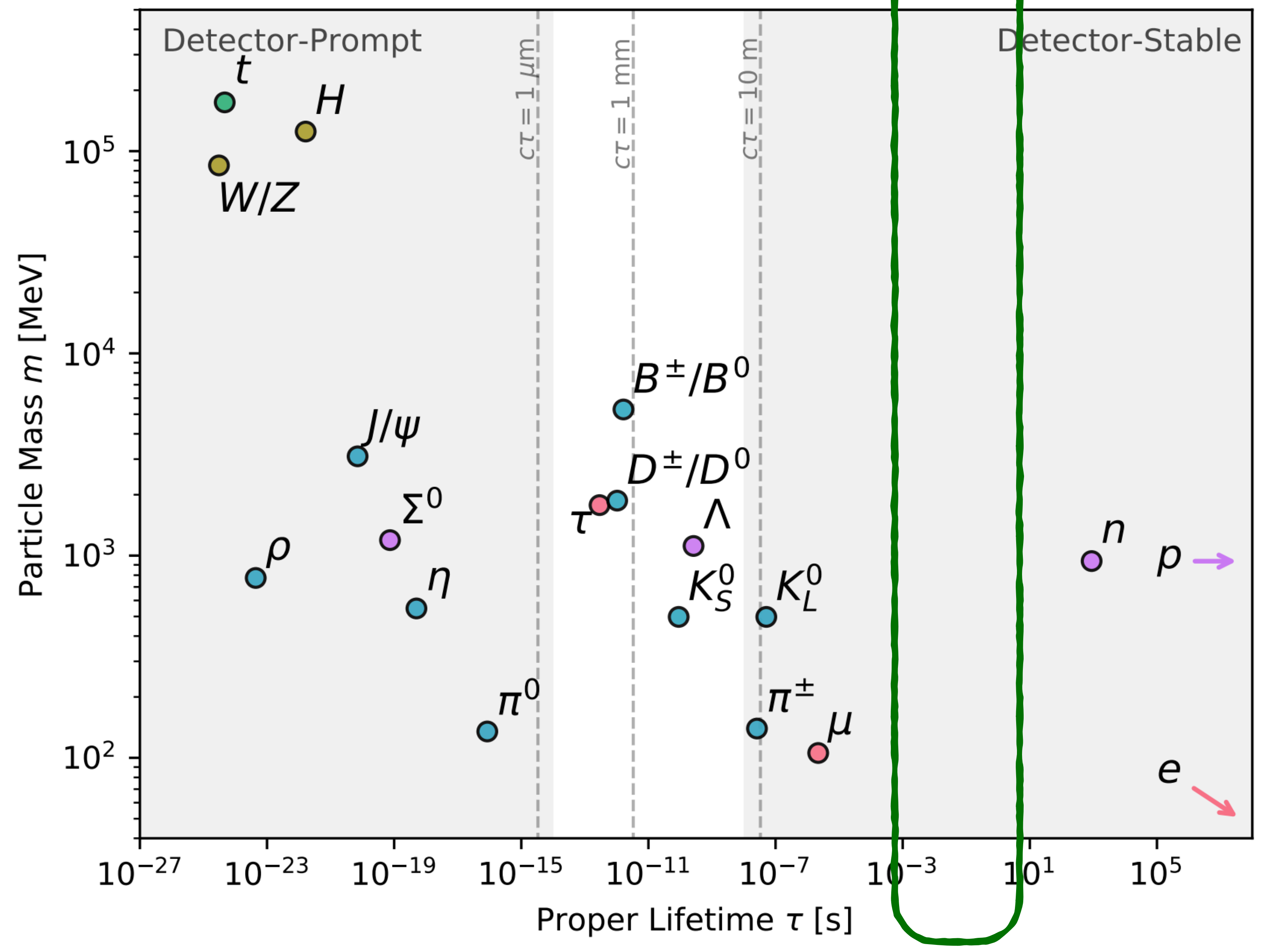
$$\theta \approx \frac{v_{EW} v_s}{m_h^2} \cdot \lambda_{portal}$$

$10^{-4} - 10^{-3}$

Some overlap



LHC detection regions for Higgs invisible decay



Collider searches of minimal dark FOPT

- Higgs invisible decay $h \to 2\phi$

$$\Gamma(h \to 2\phi) = \frac{\theta^2 m_h}{32\pi} \frac{m_h^2}{v_s^2} \left(1 + \frac{2m_\phi^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_\phi^2}{m_h^2}}$$

- Bounds & forecast sensitivities

J. de Blas, et al, 1905.03764

Current LHC bound: $|\theta| \simeq 10^{-5}$

CMS, 1809.05937

HL-LHC forecast: $|\theta| \simeq 10^{-6}$

CEPC, ILC, FCC-ee, muon collider:

$|\theta| \simeq 10^{-7}$

O.Cerri, et al, 1605.00100; Y. Tan, et al, 2001.05912;
C.Potter, et al. 2203.08330; M. Ruhdorfer, et al, 2303.14202

Dark matter production

Dark matter candidate in minimal dark FOPT

- Scalar S decays while gauge boson A' can be stabilized by unbroken Z_2 symmetry: $Z_2 \times U(1) \to Z_2$; no kinetic mixing $\epsilon F'_{\mu\nu} F^{\mu\nu}$; too small relic density

$$\left(\frac{\Omega_{\rm DM} h^2}{0.12}\right) \approx 0.33 \left(\frac{0.1}{g_X}\right)^4 \left(\frac{m_{A'}}{100\ \rm GeV}\right)^2$$

S. Kanemura & **Lisp**, 2308.16390

- A simple way out: adding fermions to the dark boson plasma, hard to know if this fermion DM is from MeV FOPT

- An ambitious and more predictable way out: non-perturbative A' production

Non-perturbative dark matter production in FOPT

- Bubble collisions: R. Watkins and L. M. Widrow, NPB 374 (1992), 446; A. Falkowski and Jose M. No, 1211.5615; see also Hyun Min's talk on Saturday
- Preheating-like production (parametric resonance, tachyonic instabilities) during (thermal) inflation… references ???
- Gravitational particle production in de Sitter spacetime…references ???

- Challenge I: thermal inflation also dilute densities; T. Hambye, A. Strumia, and D. Teresi, 1805.01473
- Challenge II: the scalar field usually does not oscillate around the minimum-preheating could be difficult (no parametric resonance production)
- A Big Question: which one matters, bubble wall collisions, parametric resonance, or gravitational particle production? To be continued…

Summary

- MeV-scale dark FOPT can be probed by various experiments in cosmology, including nanohertz GW (PTA), CMB spectral distortions (FOSSIL), $N_{\rm eff}$ (CMB upgrades)

- MeV-scale dark FOPT can also be probed at colliders, long-lived particles, Higgs invisible decay

- No bosonic MeV-scale DM available yet, one interesting possibility: non-perturbative gauge boson production in supercooled dark FOPT

Thank you

DM production in supercooled FOPT: under consideration

- Condition I: a short (but not too short) time period of vacuum energy domination—thermal inflation

$$\alpha(g_X, T_{\rm dark}, T_{\rm SM}) \approx \frac{\Delta V_{\rm eff}}{\rho_R} \gg 1\text{: large gauge coupling } g_X \text{ and/or large ratio } T_{\rm dark}/T_{\rm SM}$$

- Condition II: in the end of thermal inflation, large energy release heats the bath; avoid A' re-thermalization

$$T_{\rm rh} \ll m_{A'}$$

DM production in supercooled FOPT: under consideration

- Some basic formulas N. Herring, et al, 1912.10859

Quantization

$$\chi(\vec{x},\eta) = \frac{1}{\sqrt{V}} \sum_{\vec{k}} \left[a_{\vec{k}} g_k(\eta) e^{-i\vec{k}\cdot\vec{x}} + a^\dagger_{\vec{k}} g^*_k(\eta) e^{i\vec{k}\cdot\vec{x}} \right]$$

Mode function EoM in de Sitter space

exact solution

$$\frac{d^2}{d\tau^2} g_k^<(\tau) + \left[k^2 - \frac{\nu^2 - 1/4}{\tau^2} \right] g_k^<(\tau) = 0, \longrightarrow g_k^<(\tau) = \frac{1}{2}\sqrt{-\pi\tau}\, e^{i\frac{\pi}{2}(\nu+1/2)} H_\nu^{(1)}(-k\tau)$$

τ conformal time, $\nu = \frac{9}{4} - \frac{m_{A'}^2}{H_{\rm ds}^2}$

Calculate the Bogoliubov coefficients & particle number density