NEW PROBES OF SUPERCOOL PHASE TRANSITIONS AND DOMAIN WALLS AT PTA FREQUENCIES

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PRISMA++

"Particle Physics in the Early Universe"

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Plan

PT and DW interpretation of PTA GWs

Ratzinger, PS, 2009.11875
Madge et al, 2306.14856

Model parameter reconstruction at NLO

Christiansen, Madge, Puchades-Ibañéz, Ramirez-Quezada, PS, 2511.02910
Puchades-Ibañéz, PS, 2609.12098

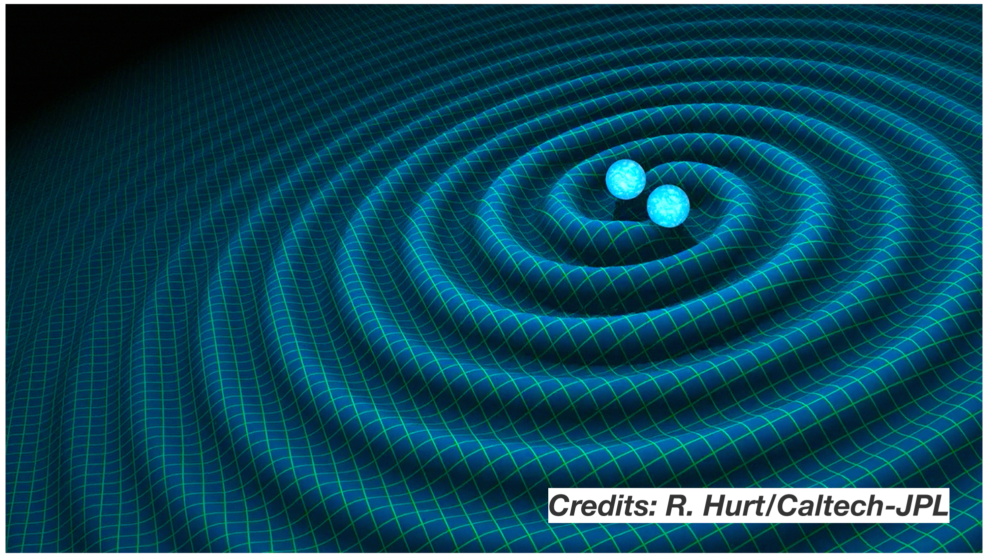
BBN Constraints on GW sources below TeV scale

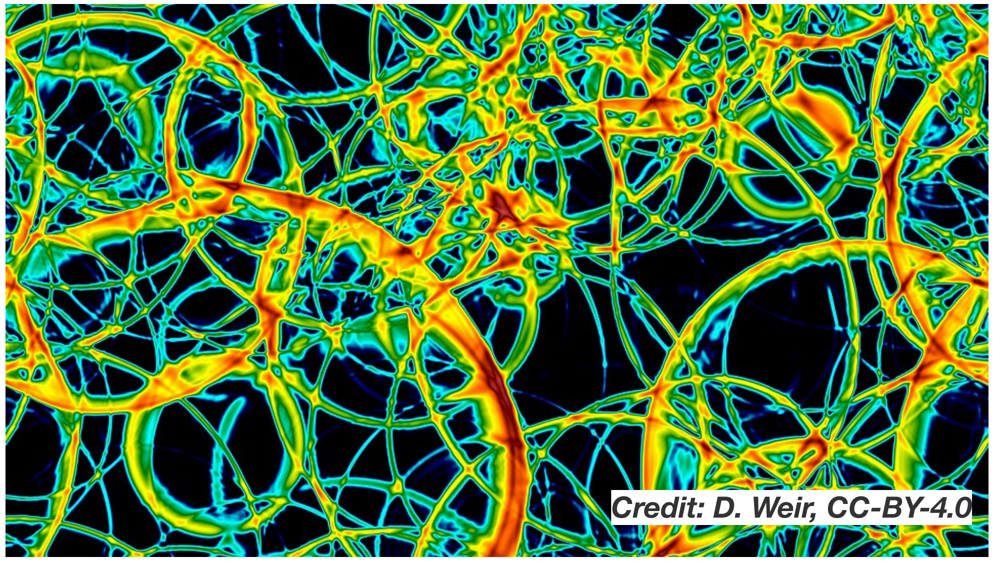
Elahi, Fortini, Gouttenouire, Leister, PS, 26XX to appear

Gravitational waves as messengers from the early Universe

Radiation is sourced by accelerated charges

Wavelength set by size of the dynamical system



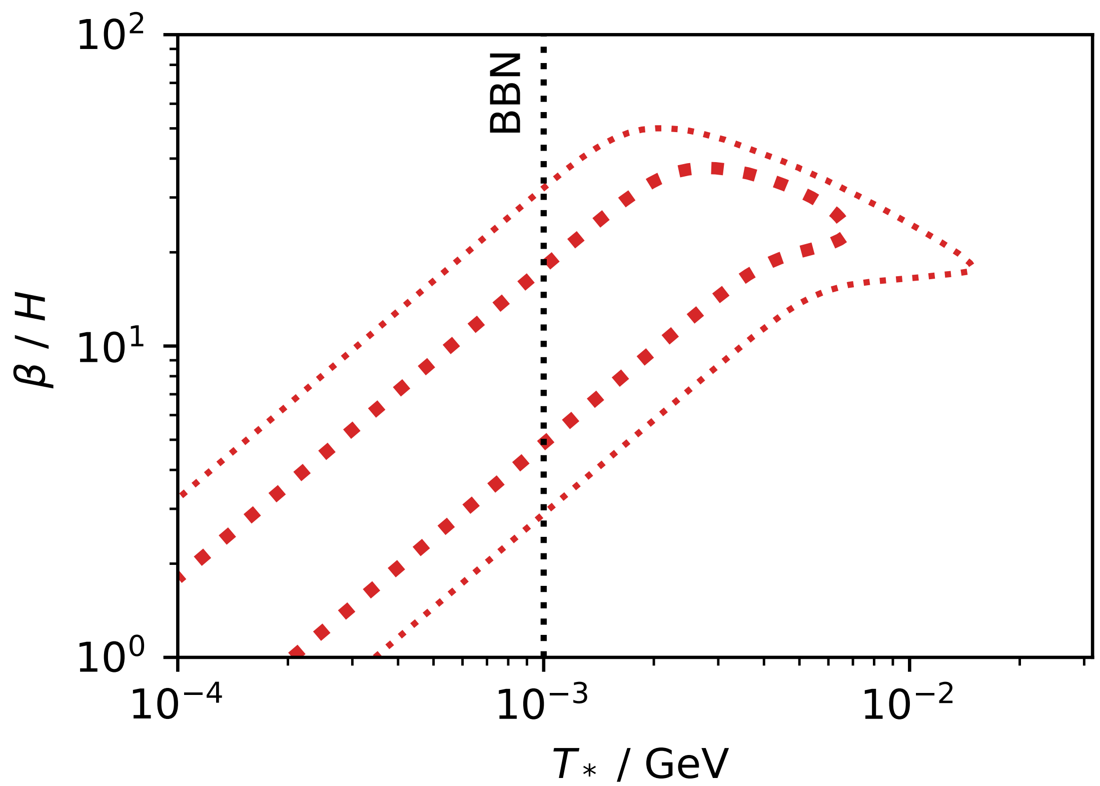


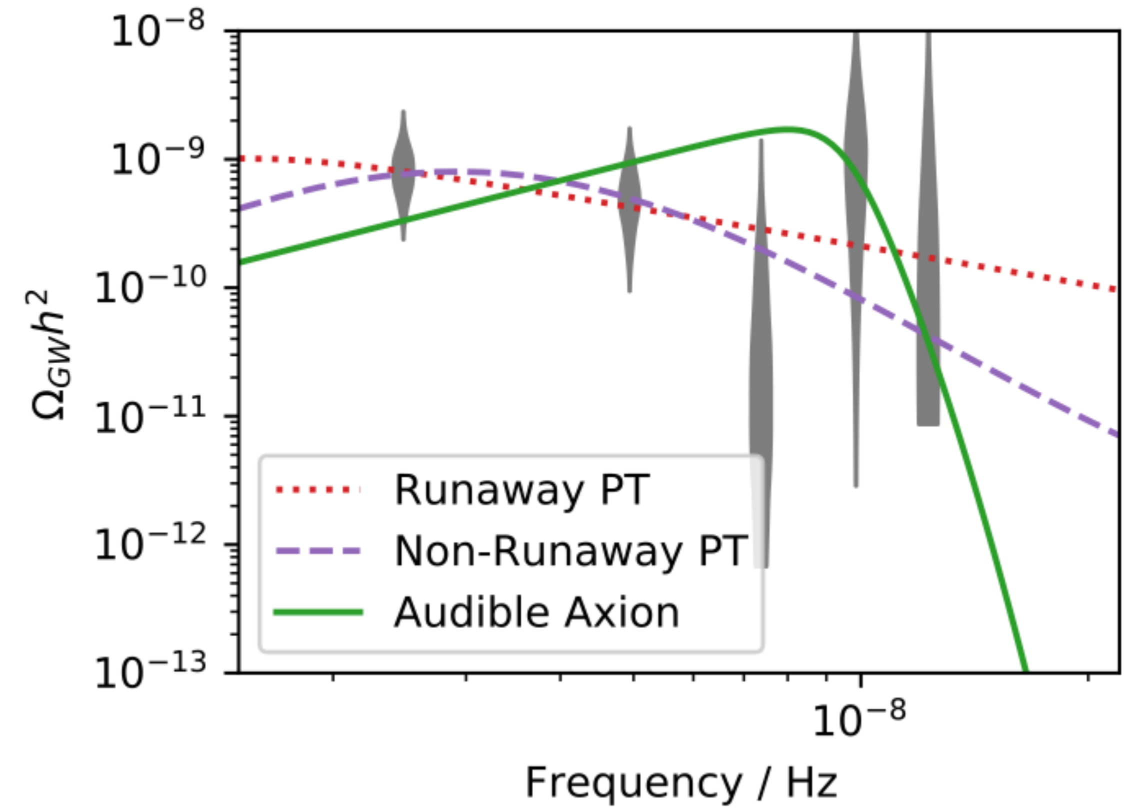
Early universe: Hubble radius ↔ GW wavelength

GW frequency $\quad f_{\mathrm{GW}} \sim T_* \quad$ Age of Universe

Pulsar Timing Array

A tiny bit of history: The 2020 NANOGrav data





PT parameters

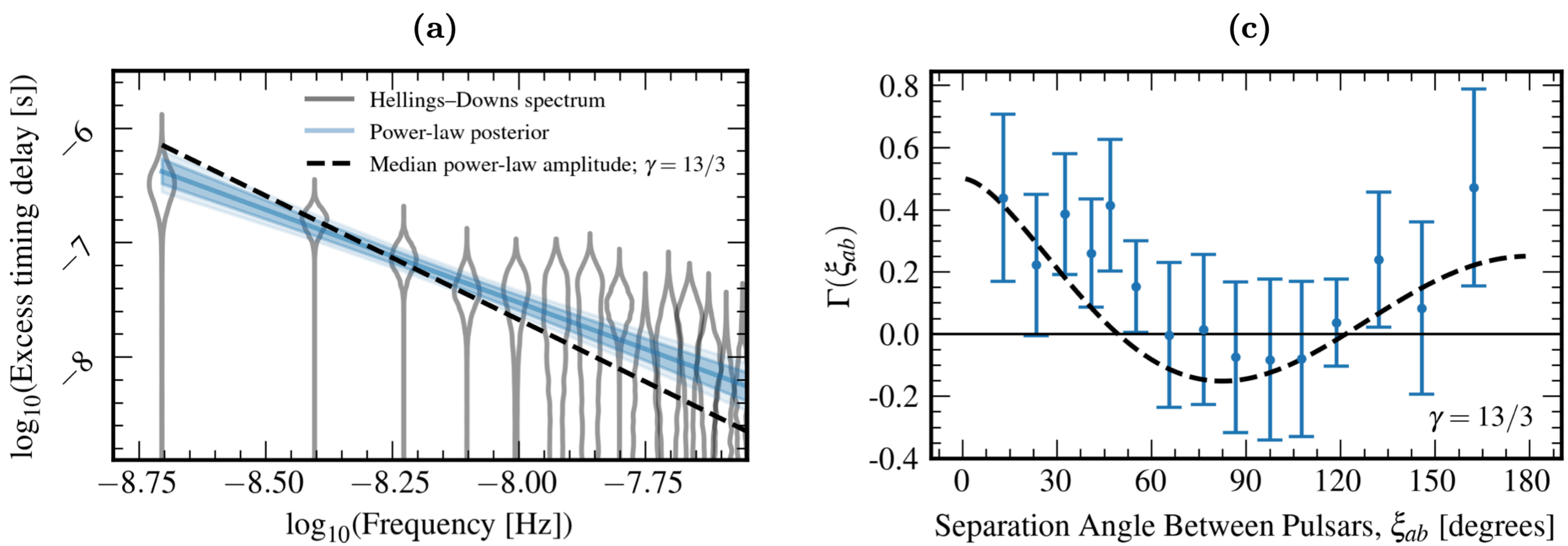
- Strength: $\alpha \sim \mathcal{O}(1)$ Duration: $\beta/H_* \sim 10$ (slow!)

First fit of GWs from PTs to NANOGrav spectrum

Ratzinger & PS, 2009.11875

Pulsar timing arrays 2023

EPTA, NANOGrav PPTA, CPTA have observed evidence for a stochastic GW background at nano-Hz frequencies:



Strong evidence for Hellings-Downs correlation

NANOGrav Collaboration, 2306.16213, APJL 951

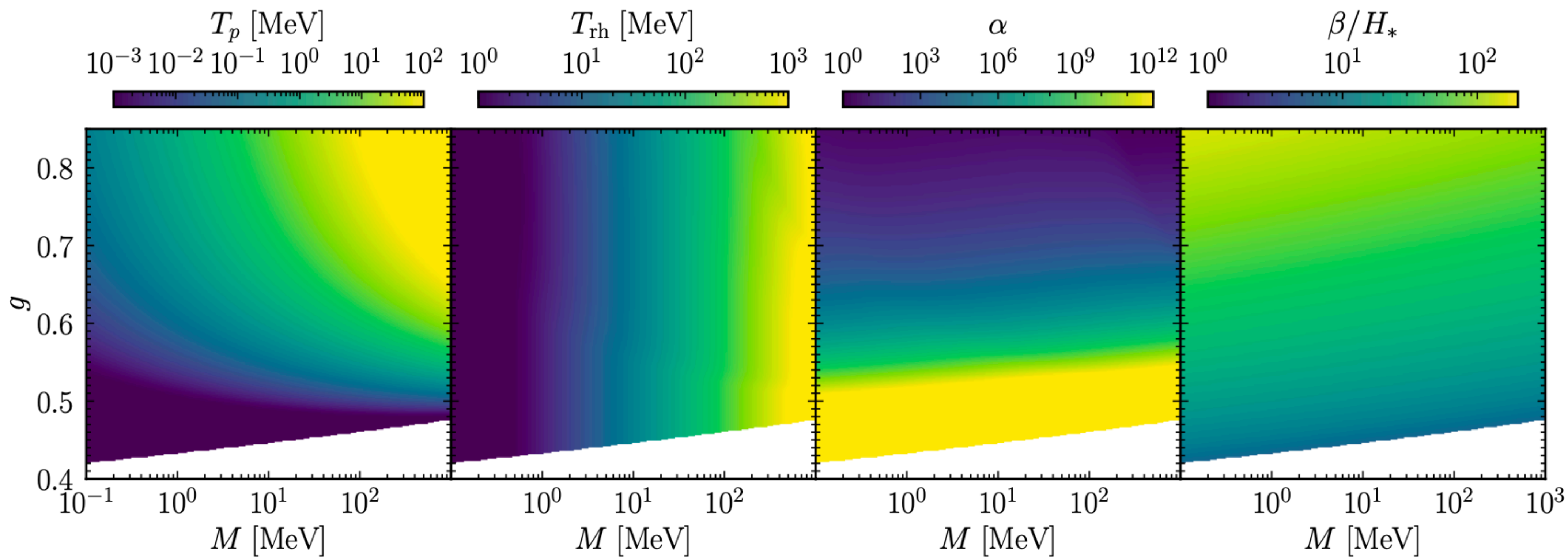
NanoHz: $T_* \sim \mathrm{MeV} - \mathrm{GeV}$

Supercooled phase transitions

Benchmark model: Coleman-Weinberg model with vanishing tree level potential

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi, T)$$

Two parameter model: Mass scale M and coupling g



Madge et al, 2306.14856

Signal dominated by colliding bubbles and sound shells

Simulated by Lewicki and Vaskonen, 2208.11697

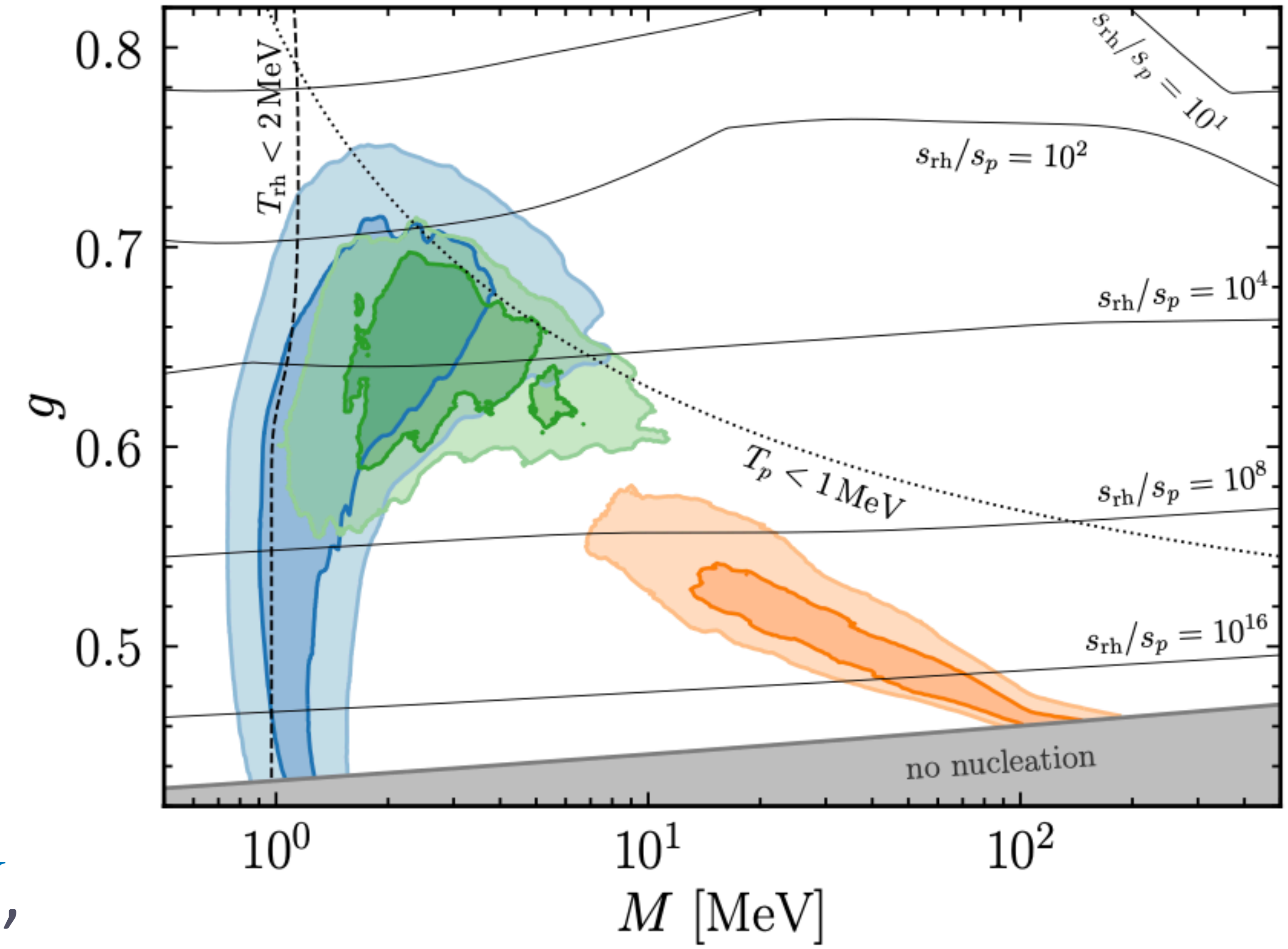
Supercooled phase transitions

Madge et al, 2306.14856

Comparison with 12 year data

Large supercooling and reheating

- Dilution of baryons, dark matter
- Two BBNs



Pheno: Light scalar $m_\phi \approx M$, decay to electrons and photons

Higgs portal not viable, instead

$$\mathcal{L} \supset c_{ee}\frac{|\Phi|^2}{\Lambda^2}LH\bar{e} + c_{\gamma\gamma}\frac{|\Phi|^2}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}$$

FCC? CEPC? Or low energy e+e- machine (MESA)

How robust are our predictions?

Christiansen, Madge, Puchades-Ibáñez, Ramirez-Quezada, PS, 2025

Compare approximations to effective potential and tunneling rates

- Semi-analytic one-parameter approximation (OPA)
- 4D thermal field theory with Daisy resummation
- Dimensional reduction with DRalgo

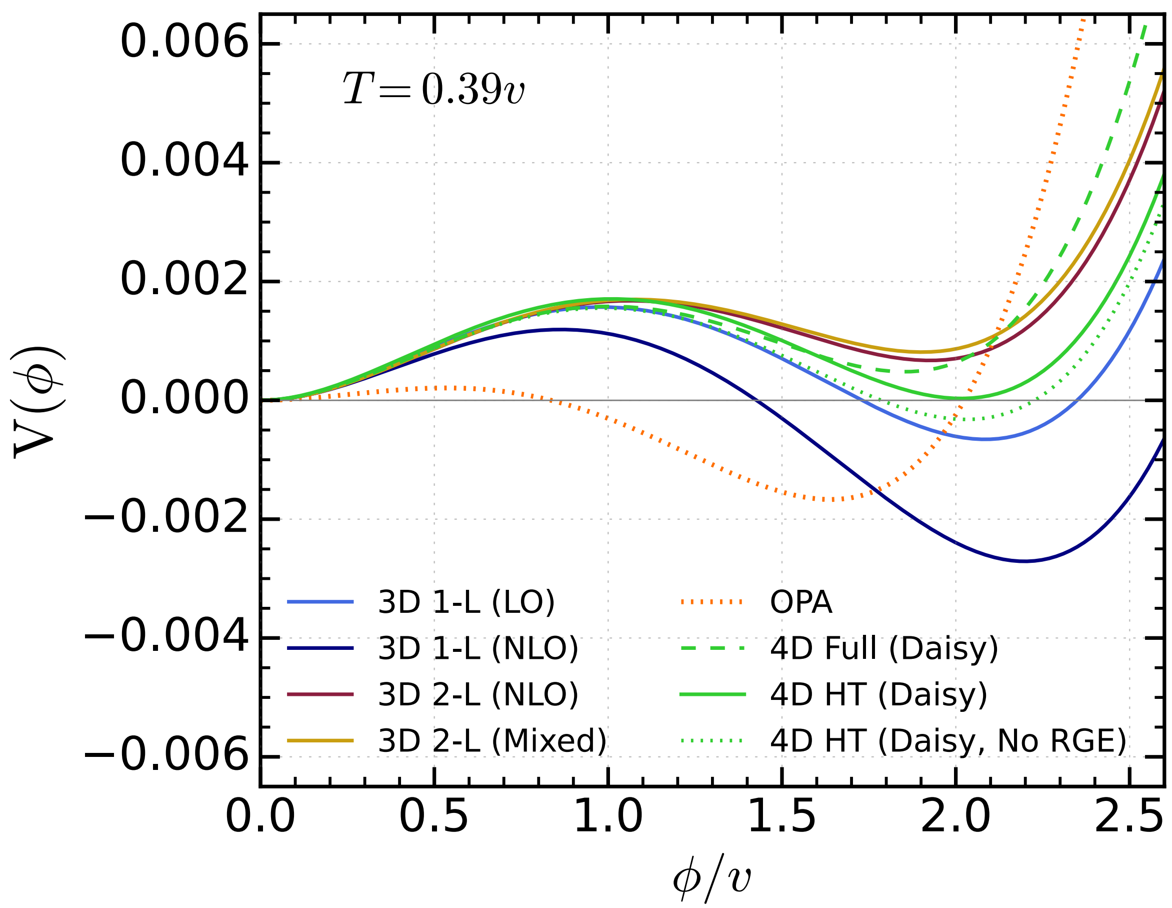
$$\mathcal{L}_{3D} = \frac{1}{4} F_{ij}^{3D\,2} + \frac{1}{2}\left(\partial_i A_0^{3D}\right)^2 + \frac{1}{2}\left|\left(\partial_i - i g_{3D} A_i^{3D}\right)\Phi^{3D}\right|^2 - m_{3D}^2 \left|\Phi^{3D}\right|^2 + \frac{1}{2}\mu_D^2 A_0^{3D\,2} - \lambda_{3D}\left|\Phi^{3D}\right|^4 + \frac{\lambda_A}{4!} A_0^{3D\,2} + \frac{\lambda_{A\Phi}}{2} A_0^{3D\,2}\left|\Phi^{3D}\right|^2 \,.$$

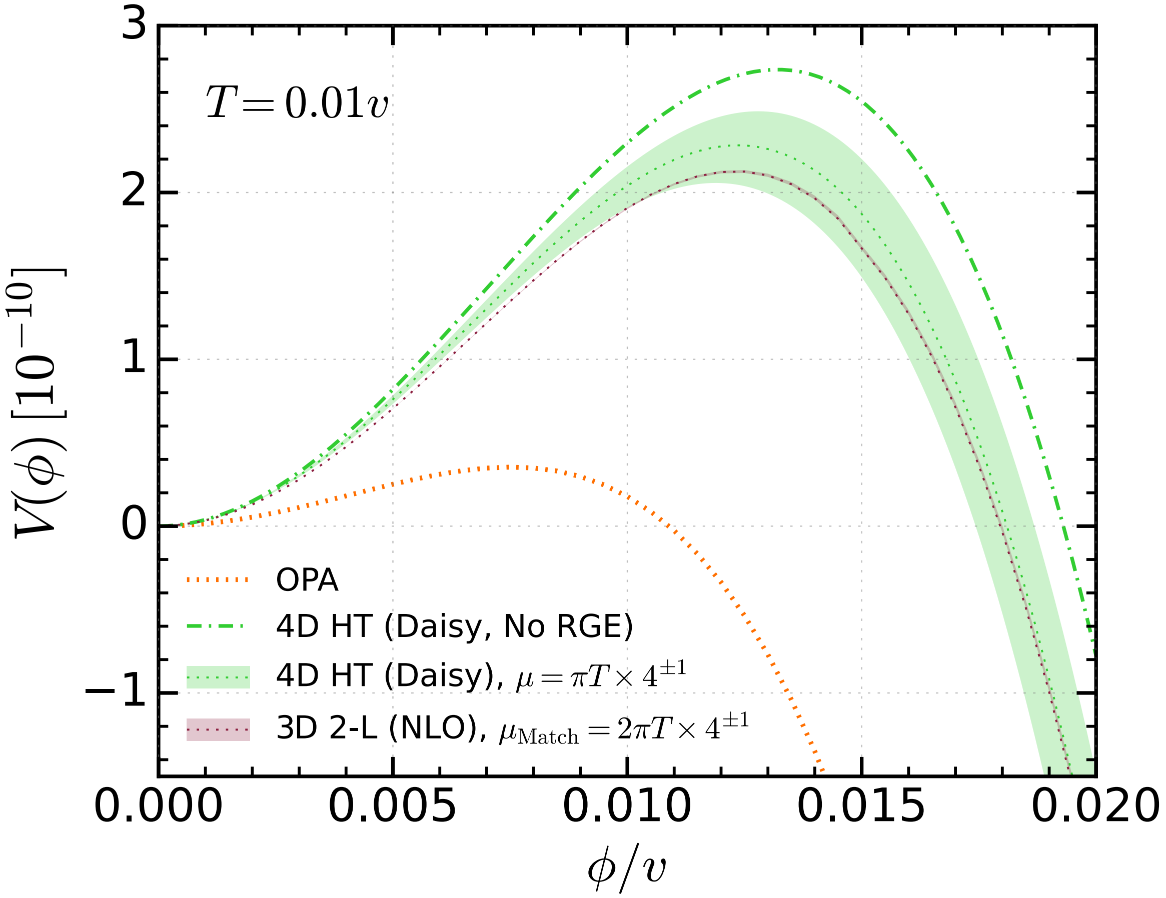
- One-loop matching relations

$$g_{3D}^2 = g^2 T - \frac{g^4 L_b T}{48\pi^2}\,, \qquad \lambda_{3D} = \lambda T + \frac{T}{16\pi^2}\left[g^4\left(2 - 3L_b\right) + 6 g^2 \lambda L_b - 10\lambda^2 L_b\right]\,,$$

$$\lambda_A = 0 + \frac{g^4 T}{\pi^2}\,, \qquad \lambda_{A\Phi} = 2 g^2 T + \frac{g^2 T}{24\pi^2}\left[24\lambda - g^2\left(L_b - 4\right)\right]\,,$$

Results





3D EFT greatly reduces scale dependence

OPA quite off, 4D high-T expansion works well if couplings evaluated at $\mu = \pi T$

Christiansen, Madge, Puchades-Ibáñez, Ramirez-Quezada, PS, 2025

Full NLO nucleation rates

Puchades-Ibáñez, PS, 2026

LO: $\Gamma = A e^{-S_3/T} \approx T^4 e^{-S_3/T}$

At NLO: $\Gamma_{\mathrm{NLO,det}}(T) = A_{\mathrm{dyn}}(T)\ \mathrm{det}_{\mathrm{s}}[\phi_b^{\mathrm{LO}}]\ \mathrm{det}_{\mathrm{V}}[\phi_b^{\mathrm{LO}}] \times$

$$e^{-S_{\mathrm{LO}}(T)}\, e^{-\Delta S_{V,\mathrm{NLO}}(T)}\, e^{\mathcal{C}_{\mathrm{sub}}[\phi_b^{\mathrm{LO}}]}$$

Complications:

- Prefactors contribute at same order as NLO corrections to exponent
- Gradient expansion breaks down for fields that change mass across the bubble profile (c.f. Bogumilas talk, and Kierkla et al, 2025)
- Compute fluctuation determinants using Gelfand Yaglom

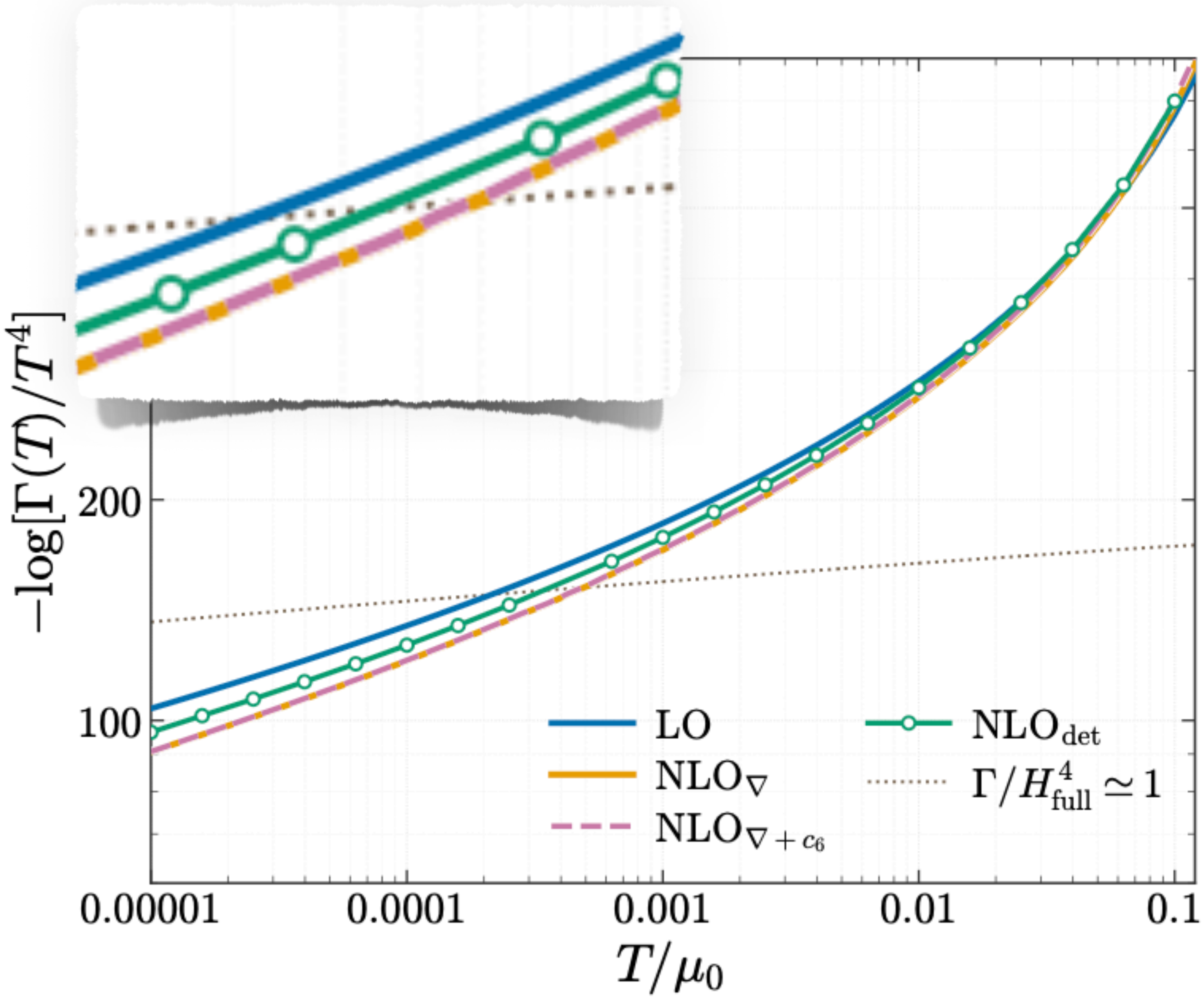
LO vs different NLO prescriptions

Puchades-Ibáñez, PS, 2026

NLO∇ is systematic in power counting but not precise enough

Nucleation temp. shift appreciable

Dim6 operators can be important at T_C, but suppressed at nucleation scale[1]



Use det corrected NLO∇ for numerical scans!

[1]see also Bernardo, Kierkla, Leister, Schicho, PS, in prep

Puchades-Ibáñez, PS, 2026

From PT to GW spectra

Compute α and β/H from $\Gamma(T)$, insert in GW formula, win

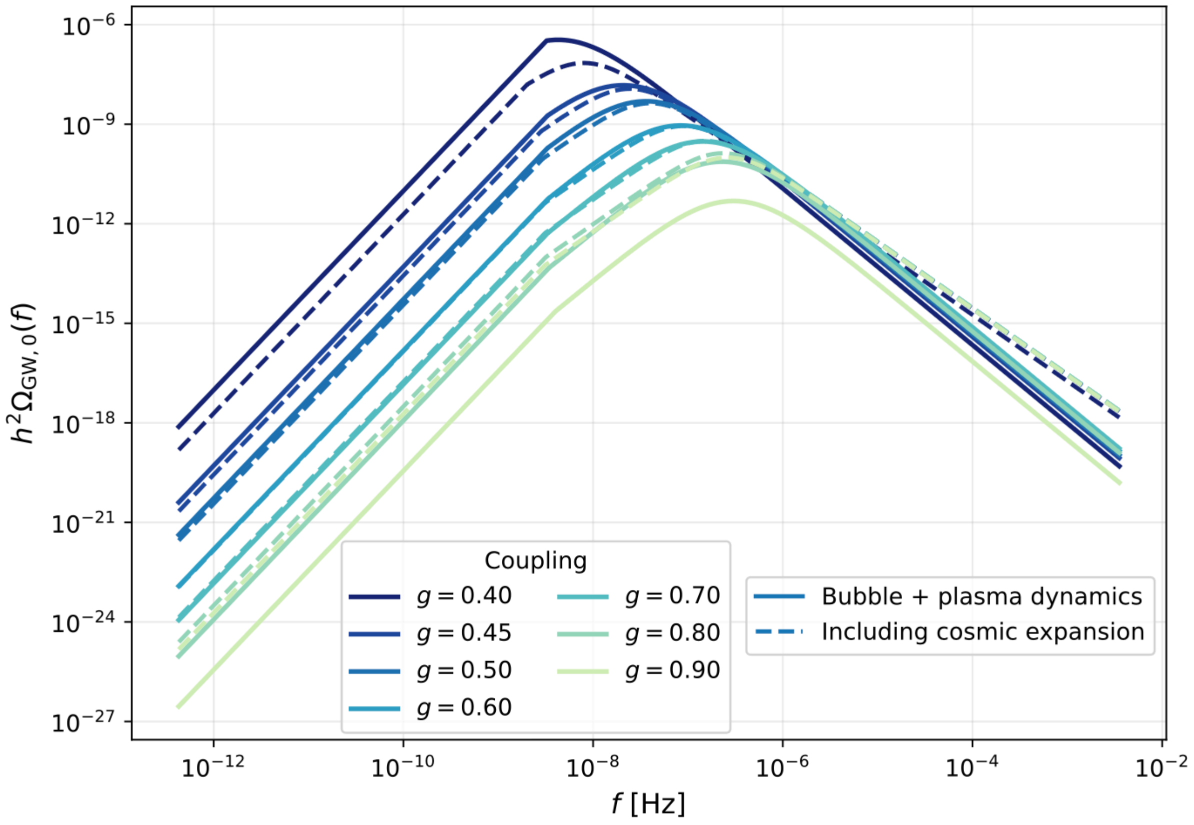
Improvements:

- Nucleation $\neq$ percolation $\neq$ completion in supercooling
- Compute β/H from average bubble separation R_*

$$\frac{\beta}{H} = \frac{(8\pi)^{1/3} v_w}{H R_* f_{\rm perc}^{1/3}}$$

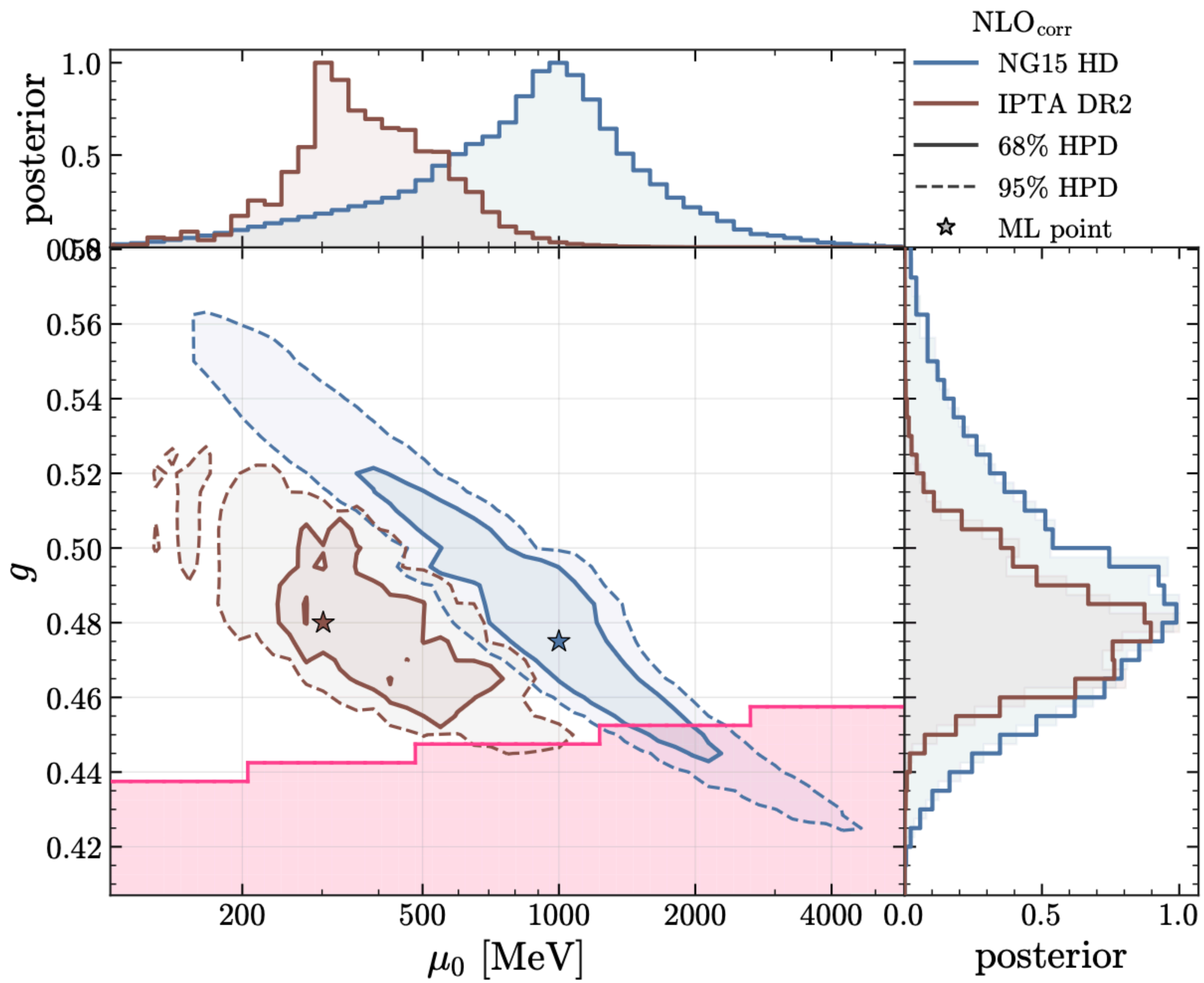
- Include $g_*(T)$ effects (QCD scale!)
- Cosmic expansion?

Lewicki, Vaskonen, 2208.11697 vs. 2511.15687



Updated fit to PTA data

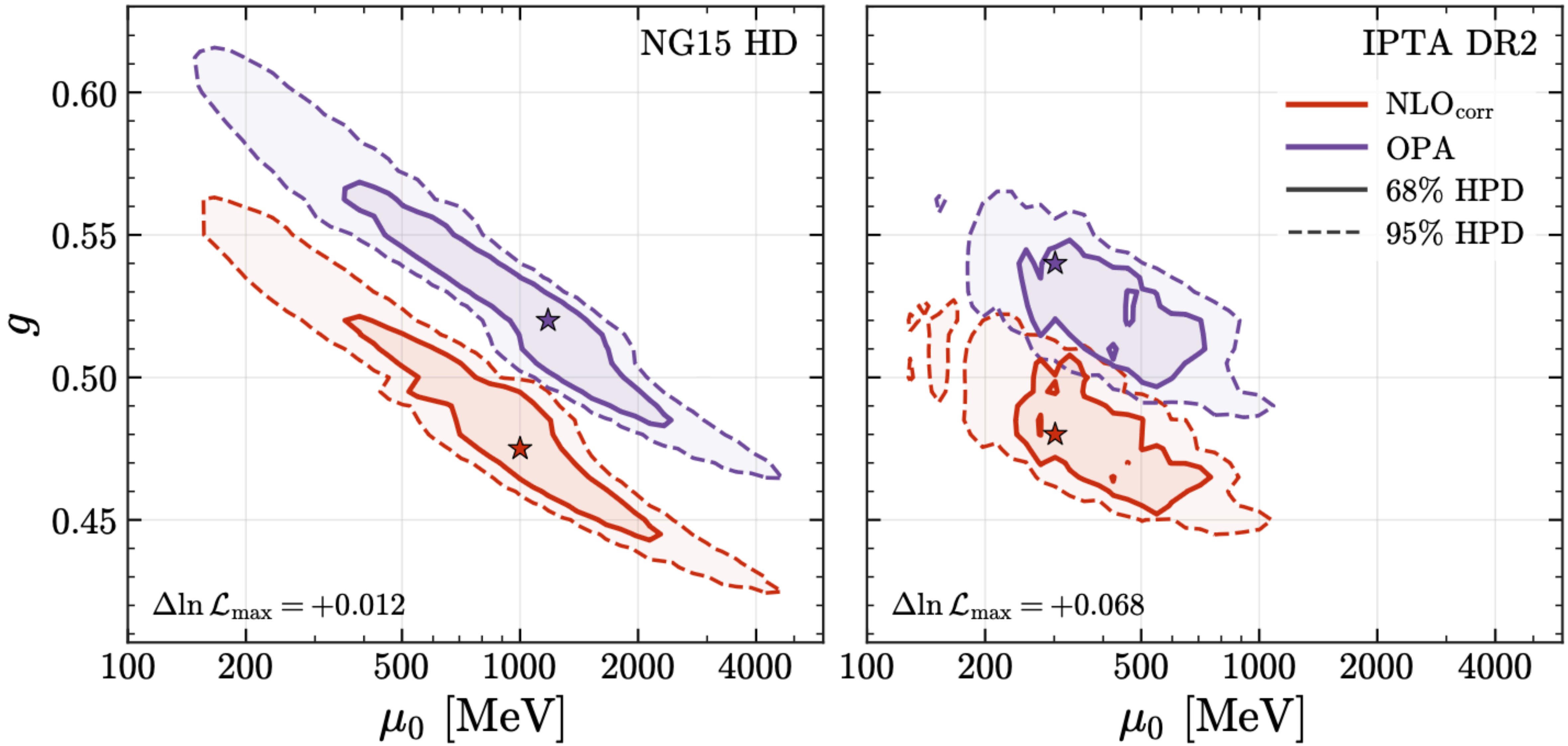
Puchades-Ibáñez, PS, 2026



Note: Red line has $\beta/H \approx 10$

Puchades-Ibáñez, PS, 2026

Comparison



NLO seems important for parameter reconstruction!

BBN constraints on GW sources at nHZ frequencies

BBN constraints on fluctuations in $\eta = n_b/n_\gamma$

D/H depends non-linearly on η

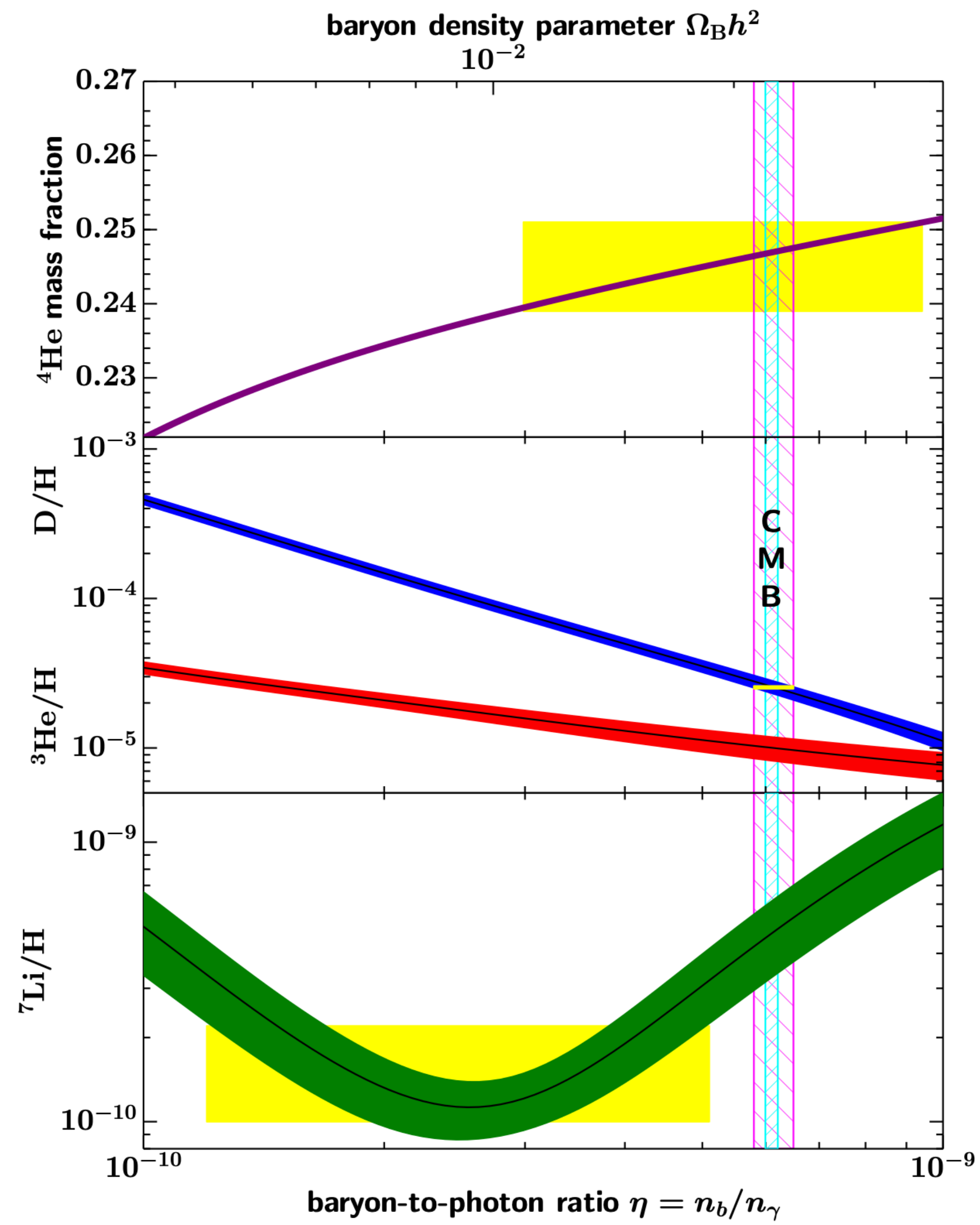
- Sensitive to fluctuations $\eta = \eta_{\text{CMB}}(1+\delta)$

$$\frac{\langle D \rangle}{\langle H \rangle} \simeq 2.53 \cdot 10^{-5} \left[1 + 0.8\delta^2 + \dots\right]$$

- Gives: $\delta \lesssim 0.22$

But: Protons are slow!

Probes inhomogeneities induced as early as 3 TeV



Bagherian, Ekhterachian, Stelzl, 2025

Baryon isocurvature

PT or DW annihilation leads to anisotropic reheating

Fluctuations in η at scales $1/H$ or β/H

Baryon isocurvature: $$\frac{\delta\eta}{\eta} = \frac{\delta n_B}{n_B} - \frac{\delta n_\gamma}{n_\gamma} = \delta_B - \frac{3}{4}\delta_\gamma = S_B$$

Assume: GW source with energy $\alpha_S = \rho_S/\rho_{\rm SM}$ decays to photons. Then

$$S_B \approx -\frac{3}{4}\frac{\alpha_S}{1+\alpha_S}\delta_S$$

δ_S = source anisotropy

Elahi, Fortini, Gouttenoire, Leister, PS, 2026 (to appear)

Evolution of baryon isocurvature

Just use cosmic perturbation theory

- Caveat: GeV to MeV temperatures!

Find:

$$S'_B = k(v_B - v_\gamma)$$

Baryon isocurvature is conserved as long as photons and baryons are tightly coupled

We also confirmed this persists through neutrino free-streaming: Photon fluctuations are erased, but they drag baryons with them, creating baryon "holes" so that S_B is conserved

Elahi, Fortini, Gouttenoire, Leister, PS, 2026 (to appear)

Constraints on phase transitions

Density perturbations:

$$\sqrt{\langle \delta^2_{\rm FOPT} \rangle} \simeq 4\,\frac{H_*}{\beta}$$

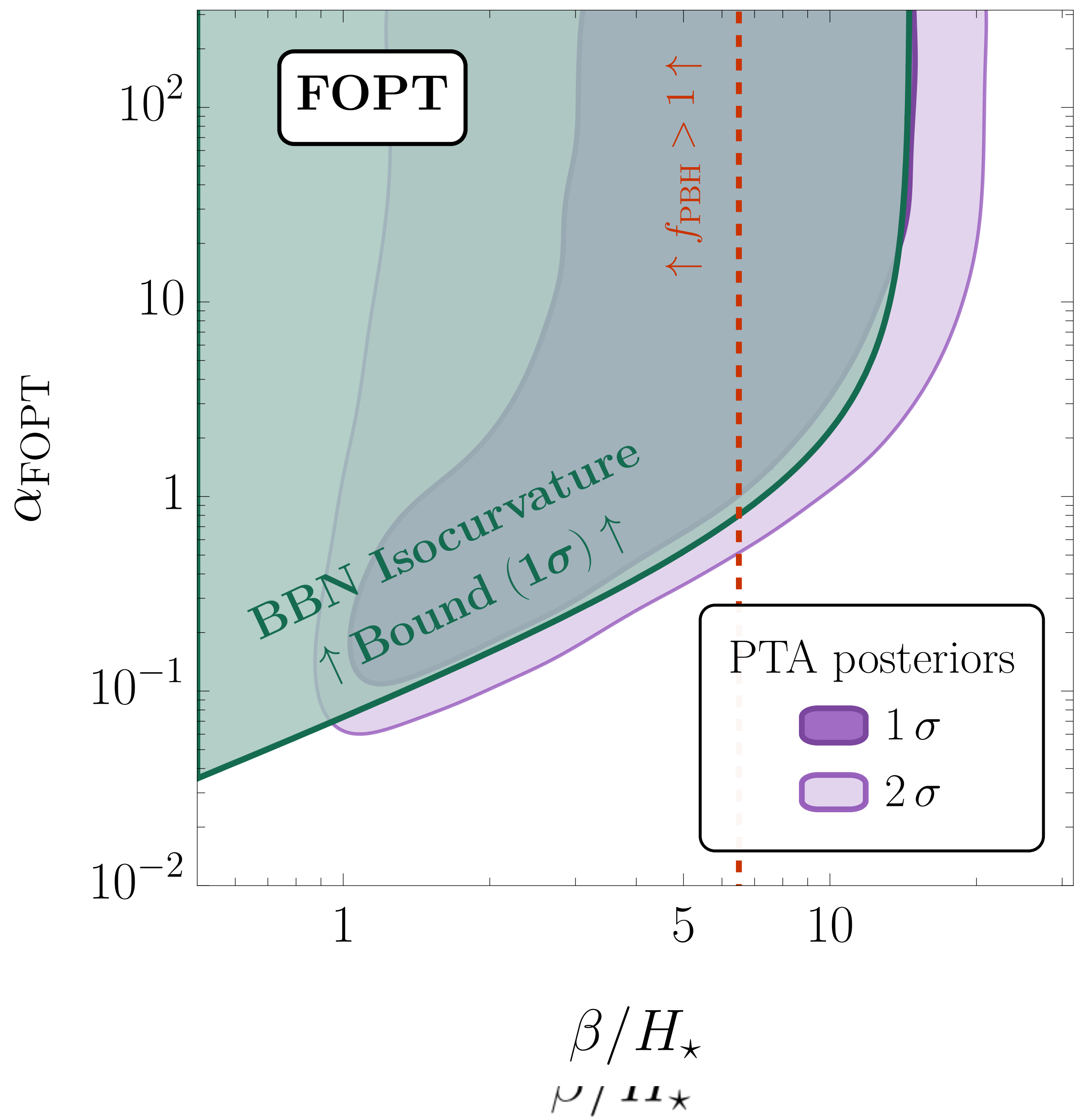
Elor et al, 2023

- From fluctuation of # bubbles inside Hubble patch

$$\sqrt{\langle S_B^2 \rangle} \simeq \frac{3}{4}\left(\frac{\alpha_{\rm FOPT}}{1+\alpha_{\rm FOPT}}\right)\left(3.9\frac{H_*}{\beta}\right) \leq 0.2$$

$$\frac{\beta}{H_*} \gtrsim 14.6\left(\frac{\alpha_{\rm FOPT}}{1+\alpha_{\rm FOPT}}\right).$$

- Using $\dfrac{\Delta\langle Y_D\rangle}{Y_D(\bar\eta_b)} \simeq C_D\,\langle S_B^2\rangle$ with C_D determined using PRIMAT



Elahi, Fortini, Gouttenoire, Leister, PS, 2026 (to appear)

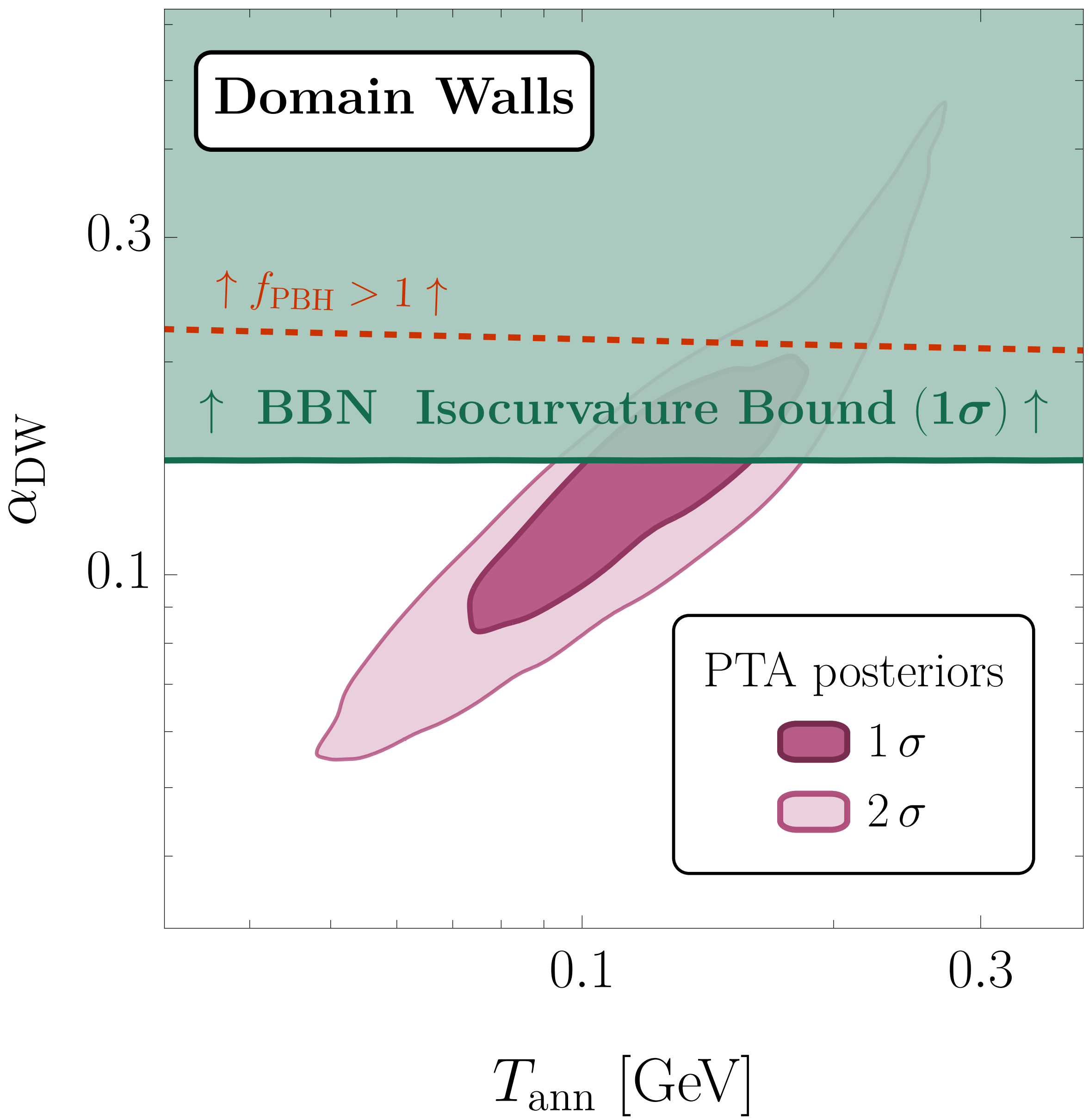
Constraints on DW scenarios

DWs are Hubble sized, naturally have order one density fluctuations

$$\sqrt{\langle (S_B^{\rm DW})^2 \rangle} \simeq \frac{3}{4} \frac{\alpha_{\rm DW+V}}{1+\alpha_{\rm DW+V}} \sqrt{\langle \delta^2_{\rm DW+V} \rangle} \lesssim 0.2,$$

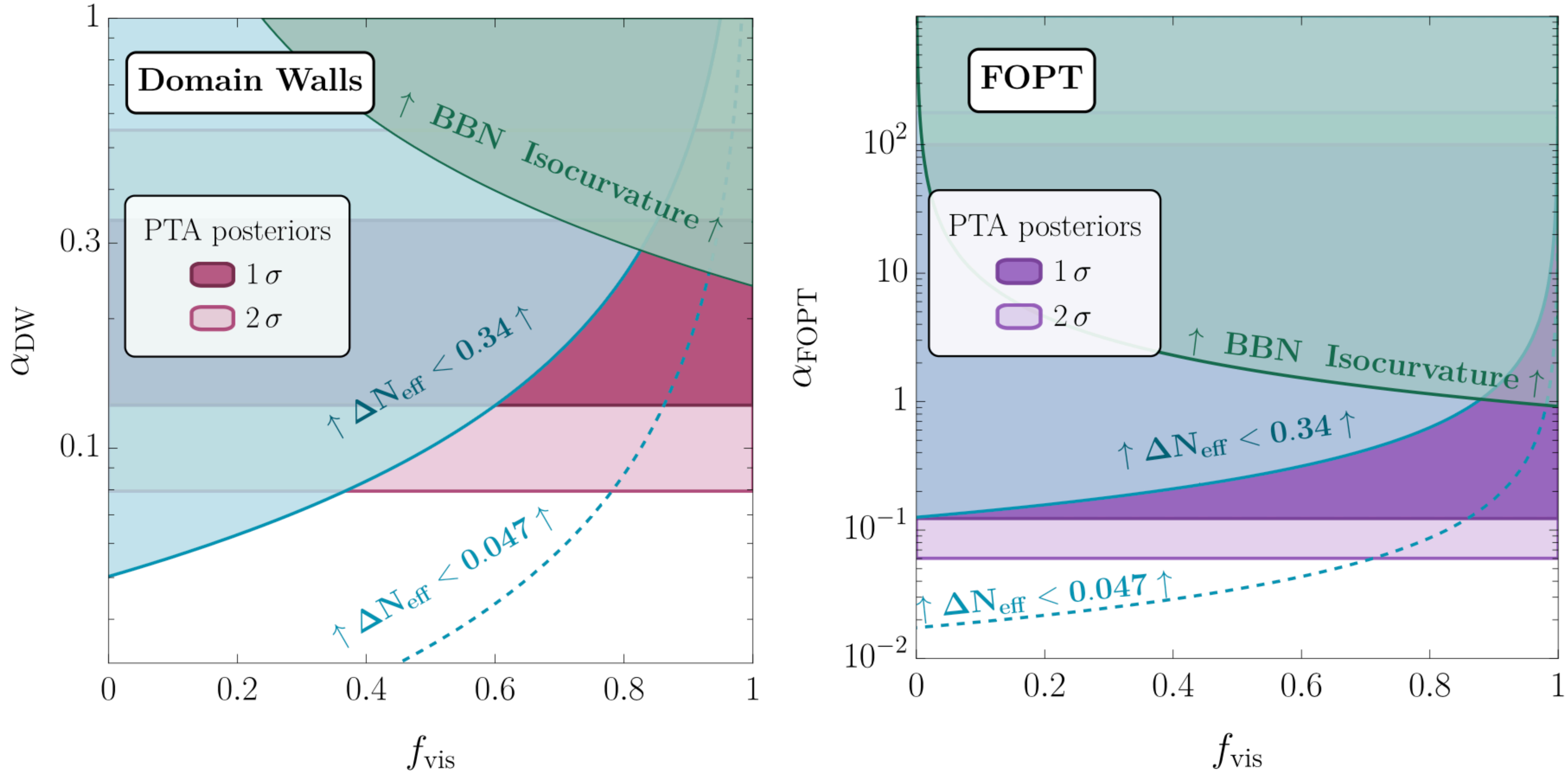
With:

- DW energy fraction $\alpha_{\rm DW}$ at time of annihilation $T_{\rm ann}$
- Including vacuum contribution, and NRT spectrum



Elahi, Fortini, Gouttenoire, Leister, PS, 2026 (to appear)

No hiding in the dark!



Assuming that $1 - f_{\mathrm{vis}}$ of energy goes to dark radiation

Elahi, Fortini, Gouttenoire, Leister, PS, 2026 (to appear)

Summary

GWs probe violent phenomena in the early Universe

Evidence for stochastic GW background at nHZ, corresponding to MeV - GeV new physics

Probing models of FOPT requires control over theory errors

- Focus on scenarios with strongest signals
- Obtained NLO precision for supercooled PT in conformal abelian Higgs dark sector
- Refit of IPTA and NANOGrav regions

BBN constraints

- BBN is sensitive to fluctuations in $\eta = n_B/n_\gamma$
- Constrains scenarios with late energy injection
- Excludes (part of) the PTA GW interpretation in terms of FOPT or DW

Extra slides :)

PTAs and Axion/ALP domain walls

Domain walls appear when discrete symmetries are spontaneously broken to degenerate ground states

Long lasting GW source, until DWs annihilate, before dominating the Universe ideally

Review: Saikawa, 1703.02576

Axion DW: $U(1)_{\mathrm{PQ}} \to Z_N$

Surface tension $\sigma = 8 m_a f_a^2$

Annihilation triggered by QCD instantons

$$T_{\mathrm{ann}} \sim 1\,\mathrm{GeV}\left(\frac{g_*(T_{\mathrm{ann}})}{80}\right)^{-\frac{1}{4}}\left(\frac{\Lambda_{\mathrm{QCD}}}{400\,\mathrm{MeV}}\right)^2\left(\frac{10^7\,\mathrm{GeV}}{f_a}\right)\sqrt{\frac{10\,\mathrm{GeV}}{m_a}}$$

Madge et al, 2306.14856

Axion/ALP domain walls

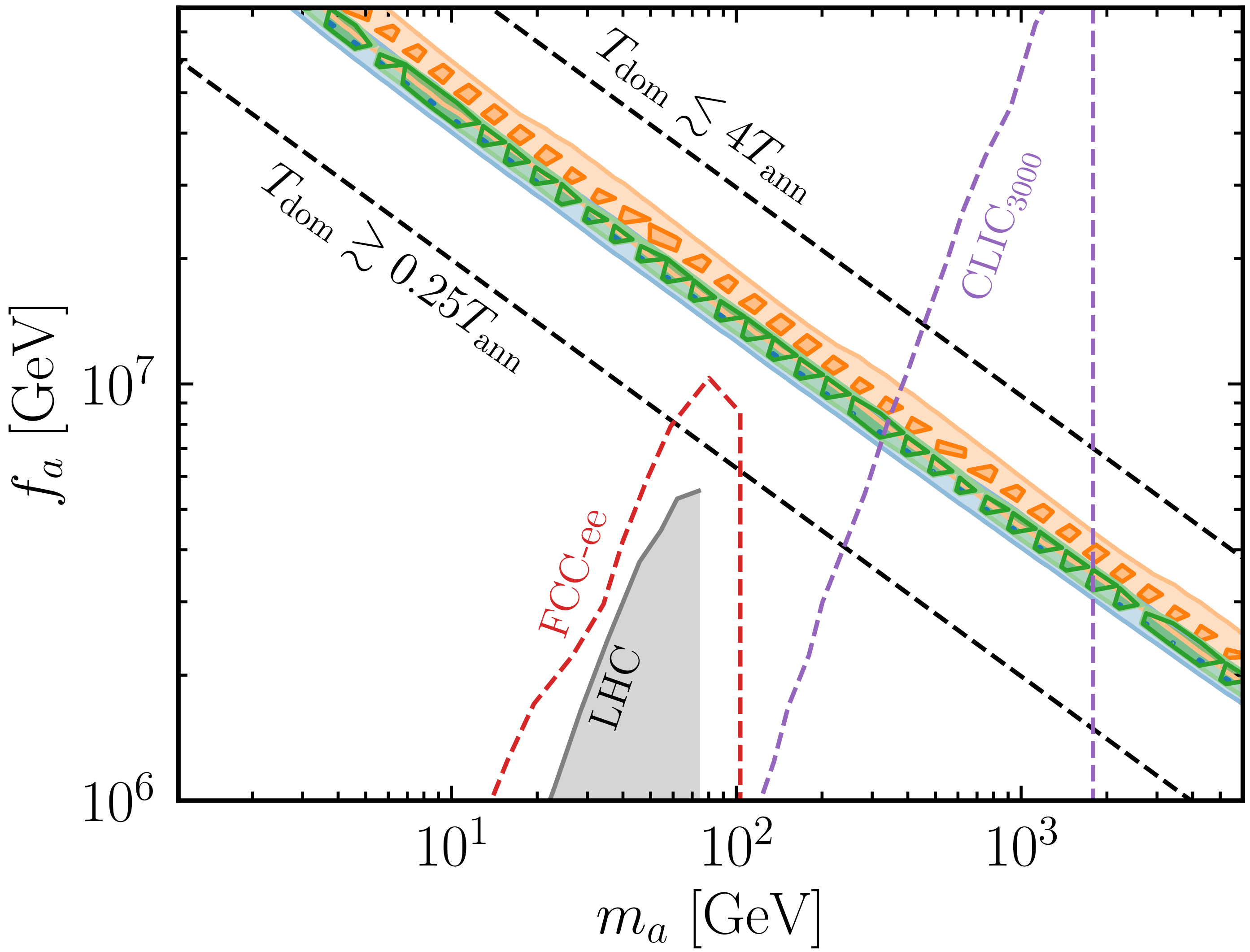
Madge et al, 2306.14856

Concrete model: Aligned/clockwork Axions Higaki et al, 1606.05552

Heavy axion “partners” at weak scale

In reach of future colliders Bauer et al, 1808.10323

- Maybe room for improvement (FCC-hh?)

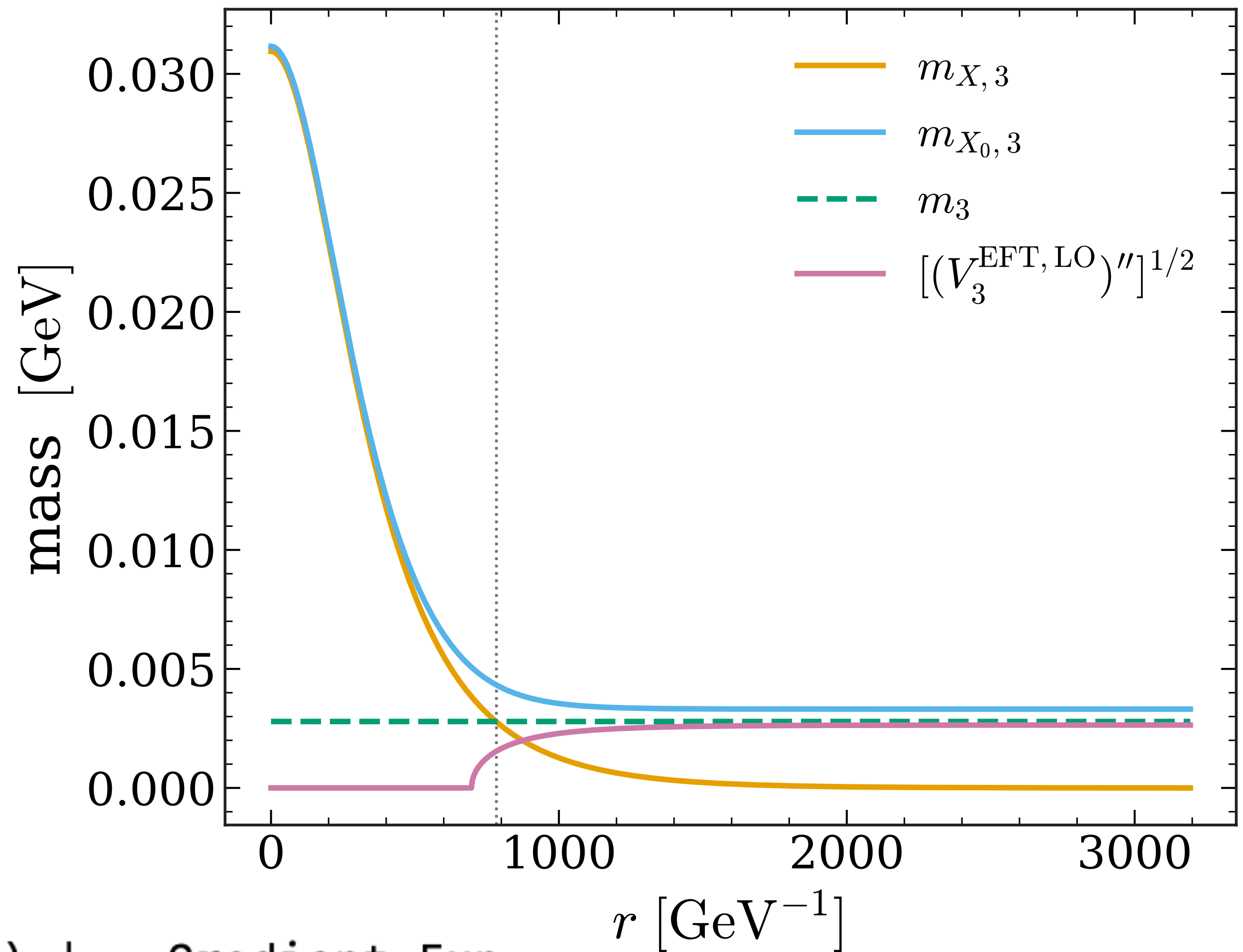


Scale shifters and gradient expansion

Numbers for

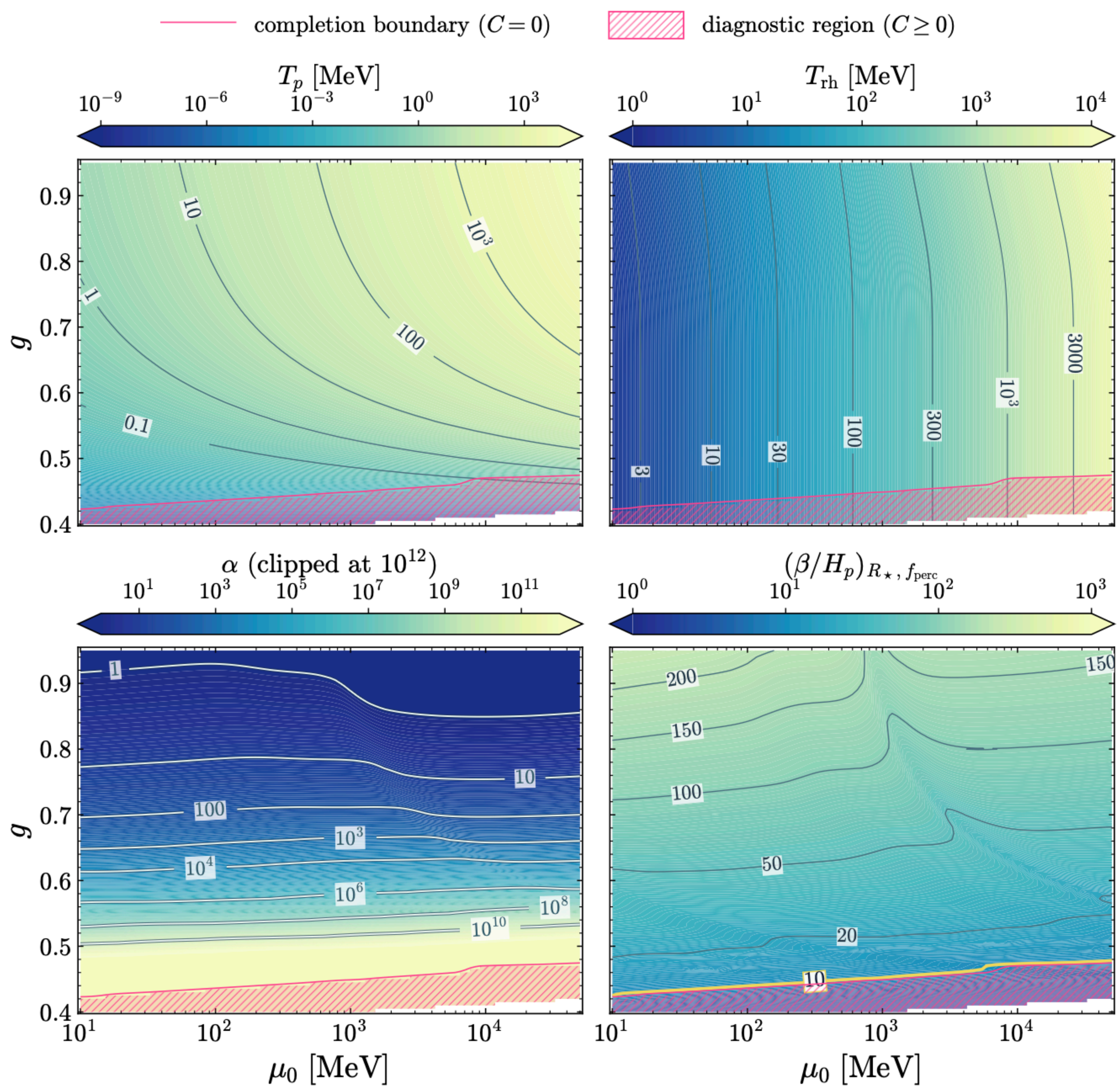
g = 0.5

T = 0.001



Contribution	Exact (GY)	Gradient Exp.
LO action	-185.727347	-185.727347
detH + zeroM/ 3 log(T)	-20.820170	-20.723266
temporal A0	49.763785	49.732103
vector-Goldstone	104.160369	111.558606
...	...	...
Total ln(Gamma/T^4)	-177.709668	-171.014384

PT parameters



Scale setting and dimensional transmutation

Tree level potential is not symmetry breaking

$$V(\phi) = \frac{\lambda}{4}\phi^4 + V_{\mathrm{CW}}(\phi, \mu)$$

$$V_{\mathrm{CW}}(\phi) \sim (g^2\phi^2)^2 \ \log\left[g^2\phi^2/\mu^2\right]$$

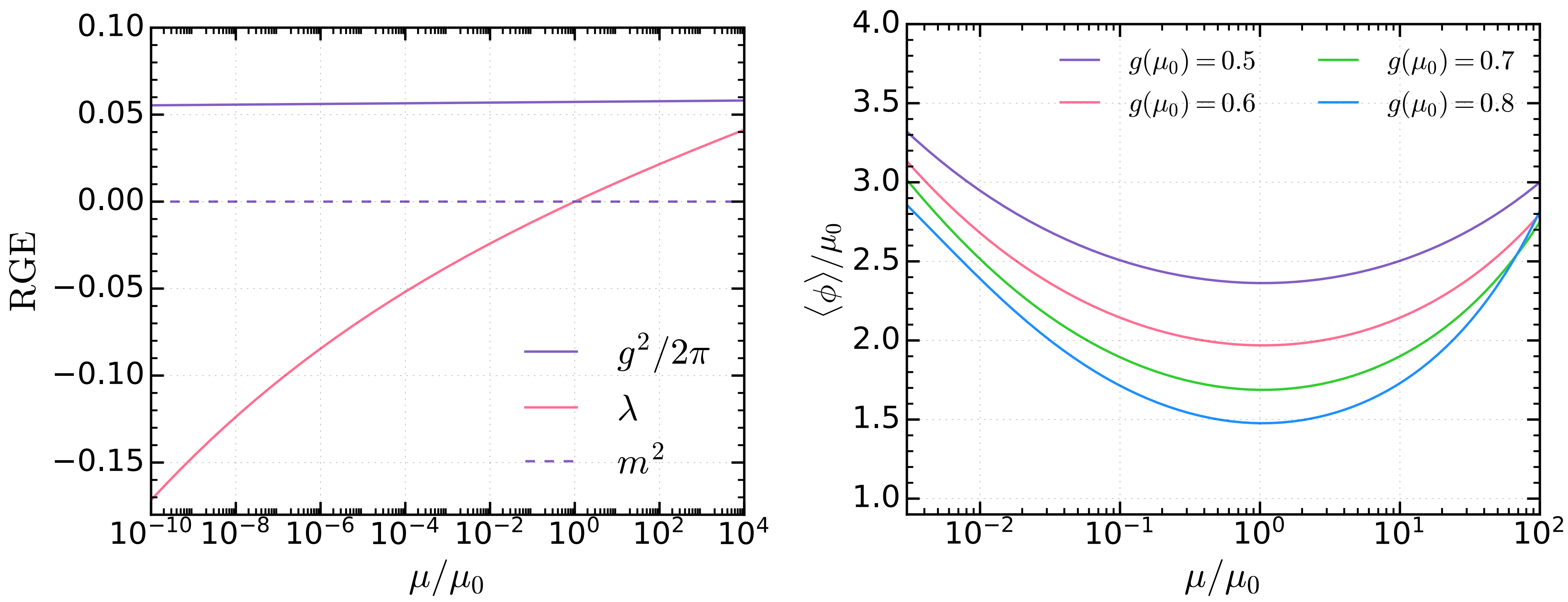
Minimum at $v = \langle \phi \rangle = \dfrac{e^{1/6}\mu}{g}$ for $\lambda = 0$

Unphysical? Particle masses $\sim gv$ should not depend on arbitrary RGE scale μ

Christiansen, Madge, Puchades-Ibáñez, Ramirez-Quezada, PS, 2025

Scale setting and dimensional transmutation

Need to take running of $\lambda = \lambda(\mu)$ into account



Input scale μ_0 with $\lambda(\mu_0) = 0$ turns out to be a good choice

Christiansen, Madge, Puchades-Ibáñez, Ramirez-Quezada, PS, 2025