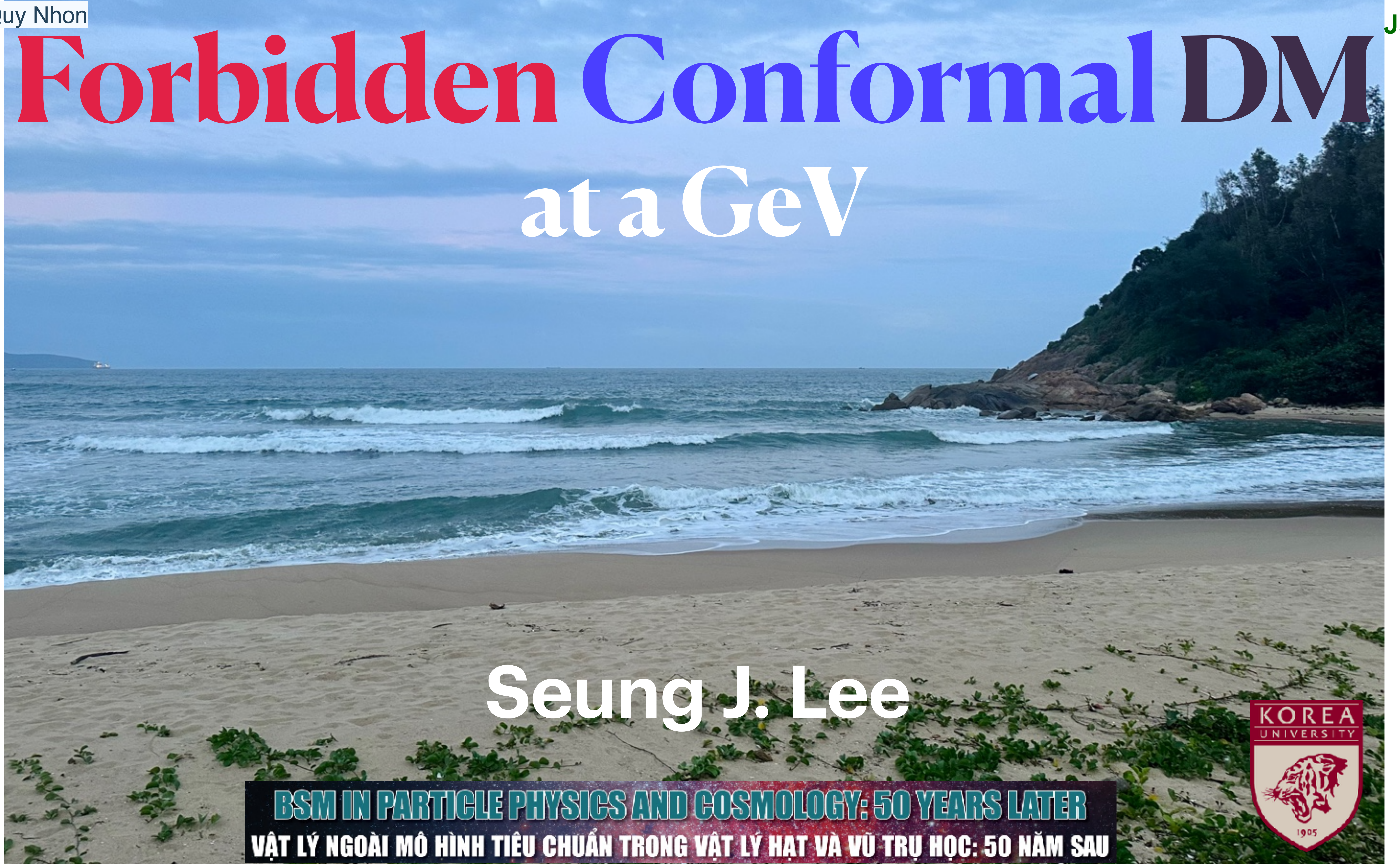
7-13 January 2024, Quy Nhon

Jan 11, 2024

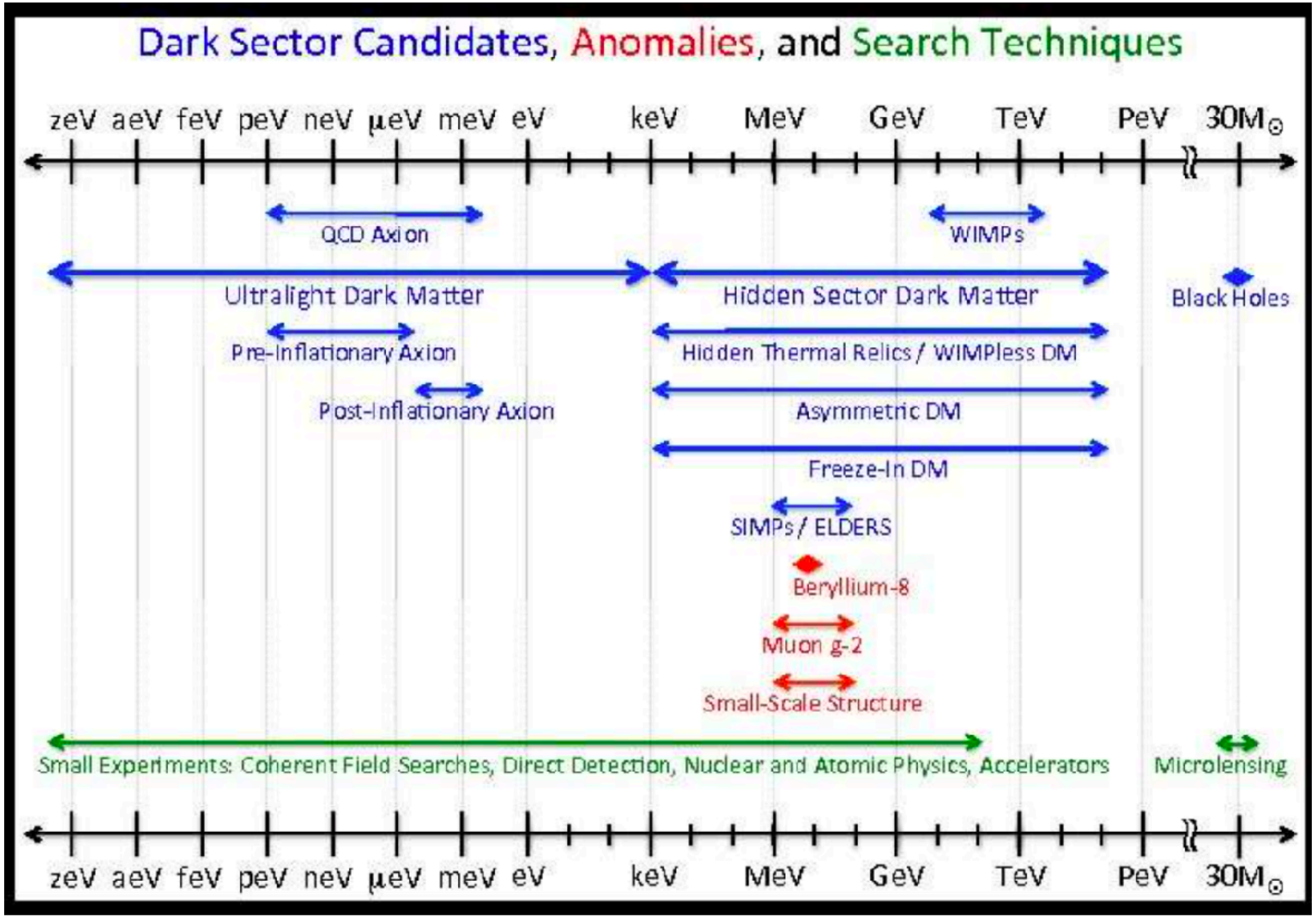
Forbidden Conformal DM at a GeV



Seung J. Lee

in collaboration with Steven Ferrante, Ameen Ismail and Yunha Lee

2308.16219; JHEP 11 (2023) 186



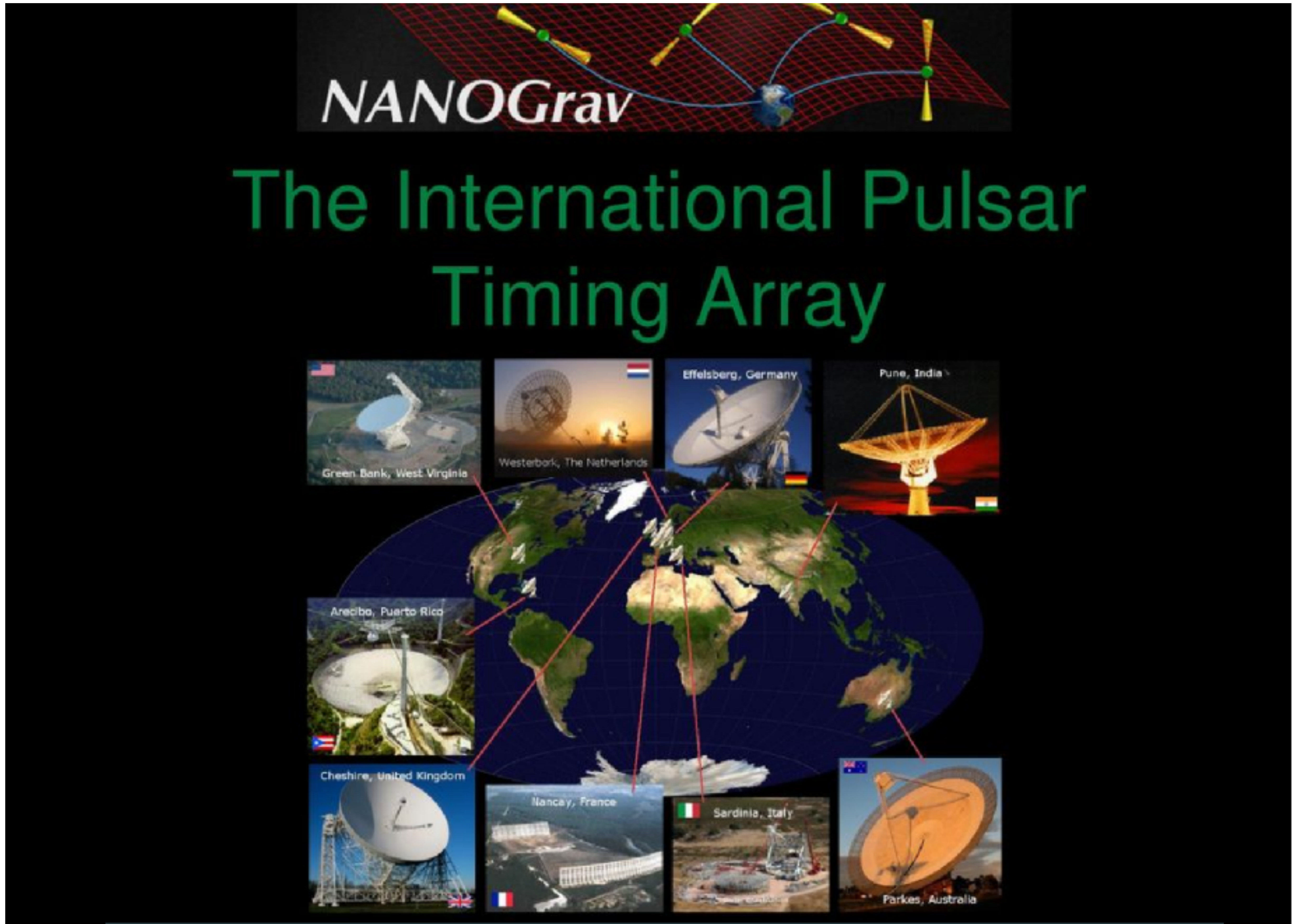
Dark Sector Candidates, Anomalies, and Search Techniques
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS
Beryllium-8
Muon g-2
Small-Scale Structure
Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
Microlensing
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙

Beyond WIMP, so many new ways to probe possible DM, But mostly for (ultra)light DM

- Table Top experiments (nuclear or electron scatteribg/absorption) for direct detection
- Cavity experiments for axion like particles, Beam Dump Experiments, Quantum Sensing (atomic physics)
- Cosmological Probes (indirect, CMB, star cooling, LSST,…)
- At colliders (including facilities for LLP such as FASER II, SHiP,…)
- etc

Dark Matter: where are we?

- maybe another way to look at DM: Stochastic Gravitational Wave at a nanoHertz scale



PTAs are galaxy-sized GW detectors that allow us to search for nHz GWs

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Apart from astrophysical explanation:

-cosmic inflation

-first-order phase transitions

-topological defects

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- The only consistent scale invariant 4D theory with UV completion is: CFT
- Model-building: AdS/CFT allows explicit calculation for large N CFT

Dialton Portal Conformal DM

Bai, Careba, Lykken 09'
Agashe, Blum, SL, Perez 09'
Blum, Cliche, Csaki, SL 14'
Efrati, Kuflik, Nussinov, Soreq , Volansky 14'
Fuks, Goodsel, Kang, Ko, SL, Utsch 20'

- Embedding the SM partially or completely in a composite sector can solve the hierarchy problem, by making the Higgs boson composite. DM is a composite of the conformal sector and the SM fields are taken to be elementary

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$$-\frac{\sigma}{f}\mathrm{Tr}T$$

- Conformal phase transition can be 1st order phase transion- GW signals

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- For massive particles, coupling to dilaton is proportional to ~M/f

  1. A very economic way to couple the SM to the dark sector (singlet under SM gauge symmetry)

  2. DM coupling to SM resembles Higgs portal, but with an extra factor $(v/f)^2\ (m_h/m_\sigma)^4$ (for the case of $f > v$)

- In the minimal set-up, basically three parameters determine the dynamics of thermal freeze-out in the early universe: f, m_{DM}, m_σ (all three around 1-10 TeV)

Ferrante, Ismail, SL, Lee. 23'

Forbidden Conformal DM at a GeV

0.1 - 10 GeV

- a model of thermal GeV-scale DM from a dark sector with spontaneously broken conformal symmetry
- DM is a composite of the conformal sector and the SM fields are taken to be elementary
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✓ A GeV scale DM that gives a stochastic GW consistent w/ NANOGrav,

✓ A signal with future Direct Detection experiments

✓ A signal with future searches for Long Lived Particles such as FASER II and SHiP

Why "Forbidden DM" at a GeV?

D'Agnolo and Ruderman, 15'

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- The dark sector must contain a dilaton field σ, the Goldstone boson of broken scale invariance, so one might minimally consider a model where the dilaton is the DM $-\frac{\sigma}{f}\mathrm{Tr}T$
    - Dilaton has couplings to the light SM fermions → dilaton to decay to e^+e^- pairs, ruling out the dilaton as the DM unless its lifetime is larger than about 10^{25} s

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- What if Λ_{CFT} sufficiently high? feeble interaction means one can still have conformal freeze-in scenario; but no GW signals ☹️
  - An observable stochastic gravitational wave background is only generated if the dark sector temperature is comparable to or larger than the visible sector temperature.

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- So we need to do something slightly less minimal: adding composite DM field + dilaton

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  - What mechanism can set the relic abundance of ϕ? The simplest option: ϕ to be a canonical WIMP that freezes out through $2 \to 2$, via dilaton-portal.
    - But, @ $T \lesssim m_\phi$, $\langle\sigma v\rangle \sim m_\phi^2/\Lambda^4 \rightarrow \langle\sigma v\rangle \sim (1000\ \text{TeV})^{-2}$ with $m_\phi \sim$ GeV & $\Lambda \sim$ TeV c.f. what we need is $\langle\sigma v\rangle \sim (20\ \text{TeV})^{-2}$

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Why don't we just lower cutoff scale? i.e. setting $\Lambda \sim O(100)$GeV? $\rightarrow$ direct detection rules it out!

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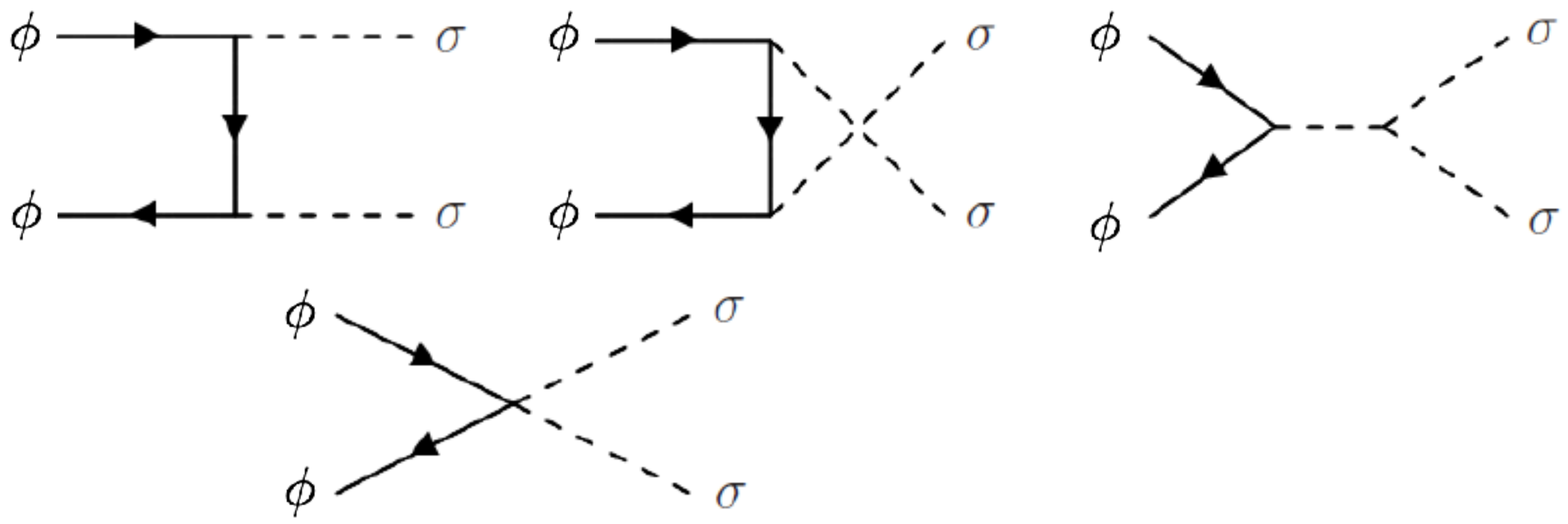
Why don't we just lower cutoff scale? i.e. setting $\Lambda \sim O(100)$GeV? $\to$ direct detection rules it out!

- Way out: SM interactions with the σ are suppressed by f, not by Λ, so the freeze-out of DM(ϕ) may be controlled by annihilations to dilaton(σ)
  - if $m_\phi < m_\sigma$, it is a forbidden DM scenario (D'Agnolo and Ruderman, 15'):
    the annihilation cross section is exponentially suppressed by Boltzmann factors
    $\phi\phi \to \sigma\sigma$ is the dominant process for the freeze-out process

Relic Abundance for a Forbidden Conformal DM

$m_\phi < m_\sigma$

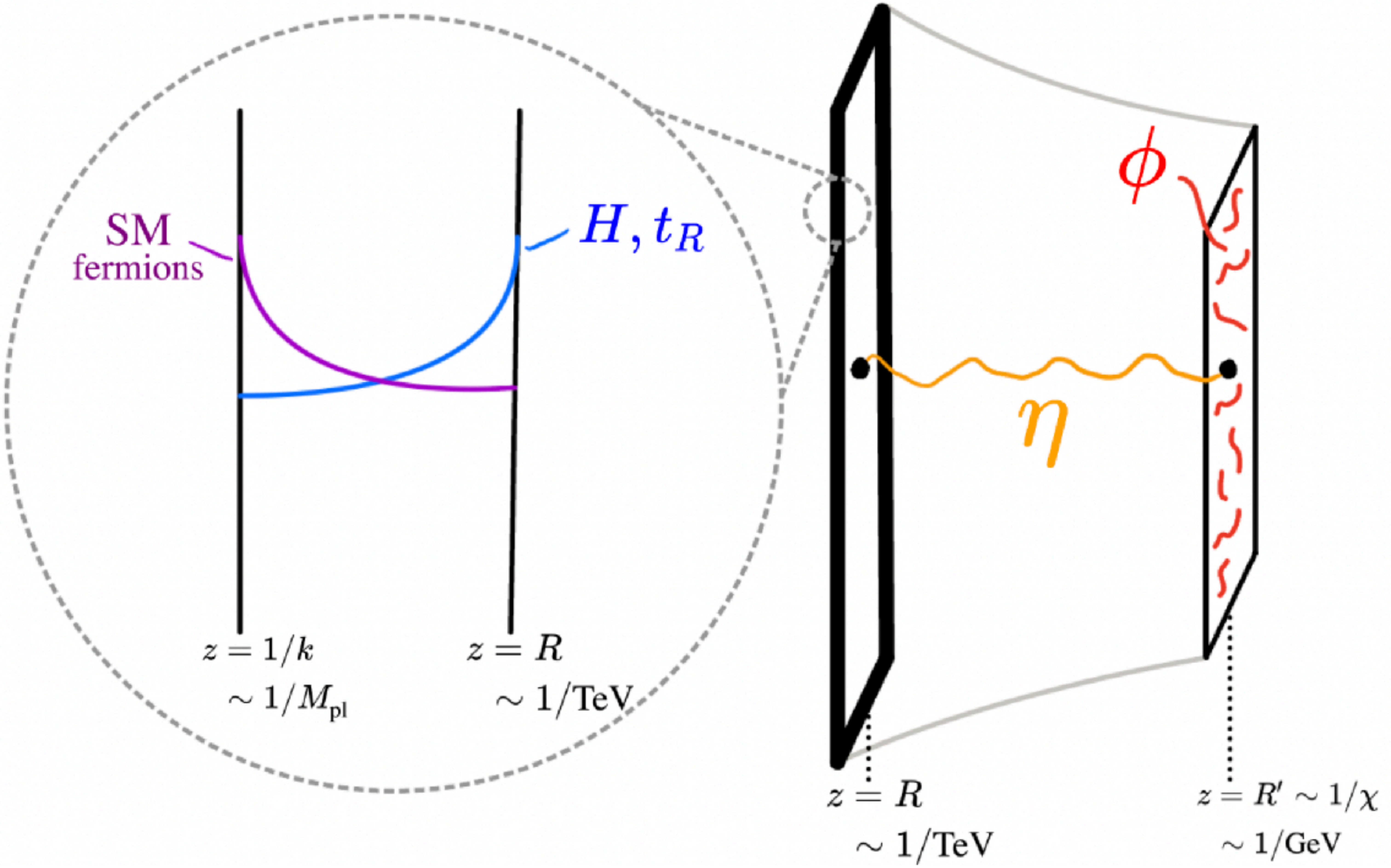
- Annihilations into SM states proceed via dilaton exchange.



Forbidden Conformal DM from 5D model

- ♦ modeling Conformal Forbidden DM at a GeV by Warped 5D model

$$ds^2 = \frac{1}{k^2 z^2}\left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$



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$$ds^2 = \frac{1}{k^2 z^2}\left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right) \qquad R \gg 1/k$$

$$S_{\rm EH} = \int d^5x \sqrt{g}\left(-2M_5^3 R - \Lambda_{\rm CC}\right) - \sqrt{\tilde{g}}\Lambda_{\rm CC}\frac{\delta(z-R)}{k} + \sqrt{\tilde{g}}\Lambda_{\rm CC}\frac{\delta(z-R')}{k}$$

Z2 symmetry

$$S_\phi = \int d^5x \sqrt{\tilde{g}}\delta(z-R')\left[\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{\lambda_\phi}{4!}\phi^4\right]$$

$$S_{\rm GW} = \int d^5x \sqrt{g}\left[\frac{1}{2}(\partial_M\eta)^2 - \frac{1}{2}m_\eta^2 k^2\eta^2\right] - \sqrt{\tilde{g}}\delta(z-R)V_{\rm UV}(\eta) - \sqrt{\tilde{g}}\delta(z-R')V_{\rm IR}(\eta)$$

$$V_{\rm UV}(\eta) = \beta\left(\eta^2 - k^3 v_\eta^2\right)^2, \quad V_{\rm IR} = \frac{1}{2}k m_{\rm IR}\eta^2$$

♦ modeling can be easily UV completed by three brane set-up to incorporate into a composite Higgs model which address the hierarchy problem

Forbidden Conformal DM from 5D model

♦ Dilaton 4D effective Theory

$$N^2 = 16\pi^2 (M_5/k)^3 \qquad \alpha = 2(\sqrt{4+m_\eta^2} - 2)$$

$$\int d^4x \frac{3N^2}{4\pi^2}(\partial_\mu \chi)^2 - V(\chi), \quad V(\chi) = \frac{3N^2}{2\pi^2}\left[-\lambda\chi^4 + \lambda_{\rm GW}\frac{\chi^{4+\alpha}}{R^{-\alpha}}\right] + V_0.$$

Potential induced by the vev of GW bulk field

$$\langle\chi\rangle = R^{-1}\left(\frac{\lambda}{\lambda_{\rm GW}}\right)^{1/\alpha}$$

$$V(\chi) = \frac{3N^2}{2\pi^2}\lambda\langle\chi\rangle^4\left[1 - (\chi/\langle\chi\rangle)^4 + \frac{-1 + (\chi/\langle\chi\rangle)^{4+\alpha}}{1+\alpha/4}\right]$$

$$\chi = \langle\chi\rangle + \sqrt{2\pi^2/3N^2}\sigma$$

$$\Lambda = \sqrt{3N^2/2\pi^2}R^{-1}$$

$$f = \sqrt{3N^2/2\pi^2}\langle\chi\rangle$$

$$m_\phi \to m_\phi \cdot \chi/\langle\chi\rangle \;:\; \int d^4x \frac{1}{2}(\partial_\mu\phi)^2 - \frac{\chi^2}{2\langle\chi\rangle^2}m_\phi^2\phi^2$$

Forbidden Conformal DM at a GeV

- 4D effective Lagrangian at O(1/Λ)

$$m \to m \cdot \chi/\langle\chi\rangle \cdot (R\langle\chi\rangle)^2$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{5}{6}\frac{m_\sigma^2}{f}\sigma^3 - \frac{11}{24}\frac{m_\sigma^2}{f^2}\sigma^4$$
$$+ \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4!}\lambda_\phi^4 - \left(\frac{2\sigma}{f} + \frac{\sigma^2}{f^2}\right)\frac{1}{2}m_\phi^2\phi^2$$
$$- \frac{\sigma}{\Lambda^2/f}\left[\sum_{\rm fermions} m_\psi\overline{\psi}\psi + m_h^2h^2 - 2m_W^2W_\mu^+W^{-\mu} - m_Z^2Z_\mu Z^\mu\right]$$
$$- \frac{\sigma}{\Lambda^2/f}\left[\frac{\beta_e(e)}{2e^3}F_{\mu\nu}^2 + \frac{\beta_3(g_3)}{2g_3^3}\left(G_{\mu\nu}^a\right)^2 + \sum_{\rm fermions}\gamma_\psi\overline{\psi}\psi\right]$$

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dilaton-portal

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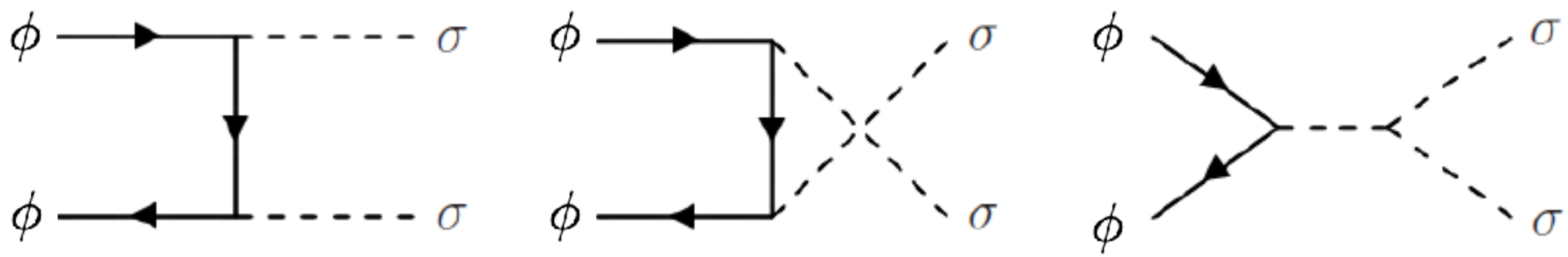
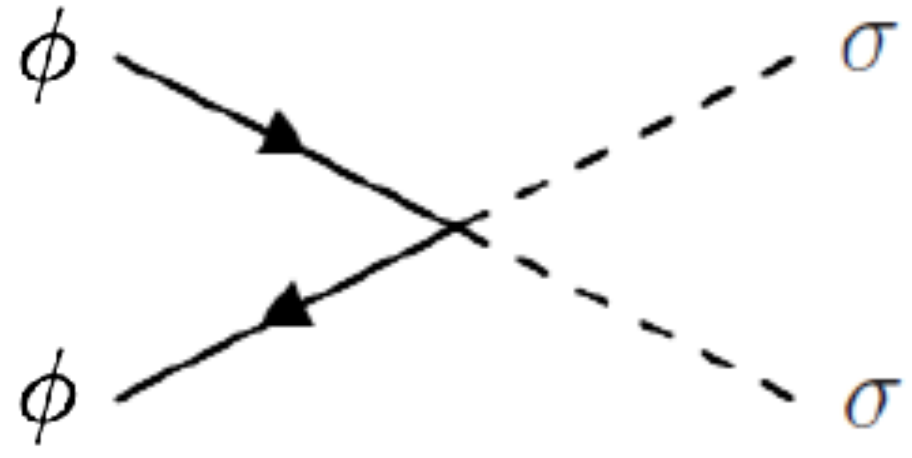
Relic Abundance

- Annihilations into SM states proceed via dilaton exchange.

- The dominant DM annihilation channels:





$$\dot{n}_\phi + 3Hn_\phi = n_\sigma^2 \langle \sigma v(\sigma\sigma \to \phi\phi)\rangle - n_\phi^2 \langle \sigma v(\phi\phi \to \sigma\sigma)\rangle,$$
$$\dot{n}_\sigma + 3Hn_\sigma = n_\phi^2 \langle \sigma v(\phi\phi \to \sigma\sigma)\rangle - n_\sigma^2 \langle \sigma v(\sigma\sigma \to \phi\phi)\rangle + \text{SM interactions.}$$

Relic Abundance

$$\Delta = (m_\sigma - m_\phi)/m_\phi$$

$$\langle \sigma v(\sigma\sigma \to \phi\phi)\rangle = \frac{1}{9\pi m_\phi^2}\left(\frac{m_\phi}{f}\right)^4 \frac{\sqrt{\Delta(2+\Delta)}}{(1+\Delta)^7}\left(1 - 4\Delta - 2\Delta^2\right)^2$$

$$\langle \sigma v(\phi\phi \to \sigma\sigma)\rangle = \left(\frac{n_\sigma^{\rm eq}}{n_\phi^{\rm eq}}\right)^2 \langle \sigma v(\sigma\sigma \to \phi\phi)\rangle$$

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$$\Omega_\phi h^2 \sim 0.1 g_\Delta(x_f) \frac{9\pi (f/m_\phi)^4 m_\phi^2}{(20\ \mathrm{TeV})^2} e^{2\Delta x_f},$$

$$x = m_\phi/T$$

$$g_\Delta(x_f) = \frac{2(1+\Delta)^4}{\sqrt{\Delta(2+\Delta)}\left(1-4\Delta-2\Delta^2\right)^2}\left[1 - 2\Delta x_f e^{2\Delta x_f}\int_{2\Delta x_f}^{\infty} dt \frac{e^{-t}}{t}\right]^{-1}$$

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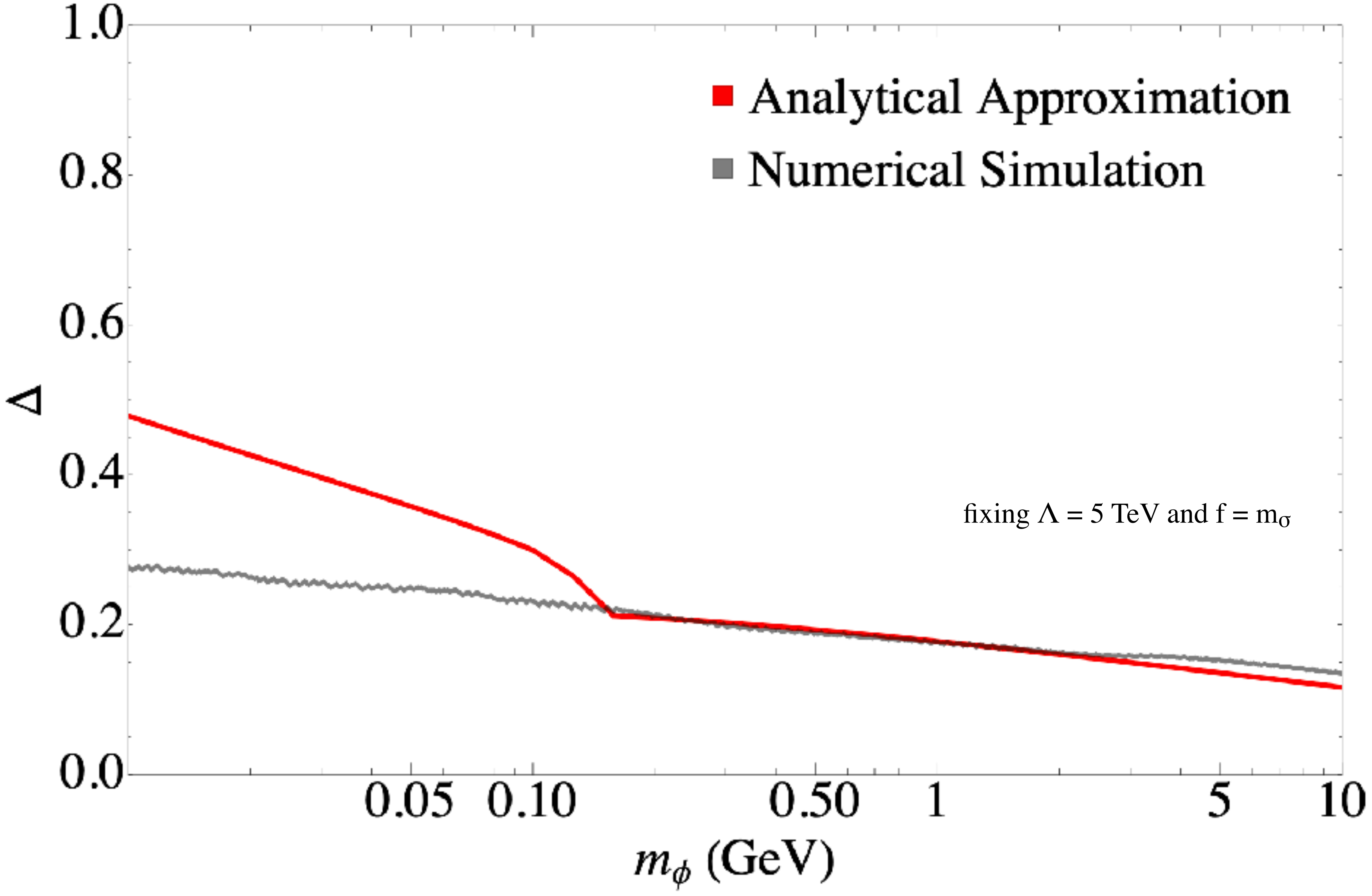

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$$x = m_\phi / T$$

Conformal Phase Transition

High T

T_c: nucleation of bubbles of the IR brane

Low T

Usual 5D picture here

- Important things to check:

Conformal Phase Transition

High T

conformal sector is in its hot, deconfined phase with unbroken conformal symmetry

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CFT undergoes a phase transition to the cold, confined phase

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"Freeze out"

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♦ **Important things to check:**

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◆ Important things to check:

- Does the phase transition complete? (otherwise the conformal sector remains in the hot phase and there is no DM candidate)

- Do the bubble collisions during the phase transition source stochastic gravitational waves consistent with NANOGrav?

Conformal Phase Transition

♦ Phase transition completion $\Gamma > H^4$

Check: the probability of bubble nucleation per unit volume per unit time Γ is greater than the Hubble parameter H^4

$$\Gamma \sim T_n^4 e^{-S_b}$$

$$S_b = S_3/T_n$$

Thick wall limit:

$$S_3 \approx \frac{\sqrt{3}}{\pi^2} \frac{N^3 \chi_r^3}{\sqrt{V(\langle\chi\rangle)(T_n/T_c)^4 - V(\chi_r)}},$$

χ_r = "release point"

$$H \sim \sqrt{\rho}/M_{\rm Pl} \sim T_c^2/M_{\rm Pl}$$

the vacuum energy of the CFT dominates over the energy of the radiation bath before the phase transition:

$$\rho \approx \pi^2 N^2 T_c^4/8.$$

$$\underset{= V(\chi)}{F_{\rm confined}(\langle\chi\rangle)} = \underset{= V_0 - \rho}{F_{\rm deconfined}(T_c)} \implies T_c = \sqrt{\frac{m_\sigma f}{\pi N}} \left(\frac{2}{4+\alpha}\right)^{1/4}$$

$$\alpha = 2(\sqrt{4 + m_\eta^2} - 2)$$

$$S_b \lesssim 4\left(\log \frac{M_{\rm Pl}}{T_c} + \log \frac{T_n}{T_c}\right)$$

von Harling and Servant , 17'

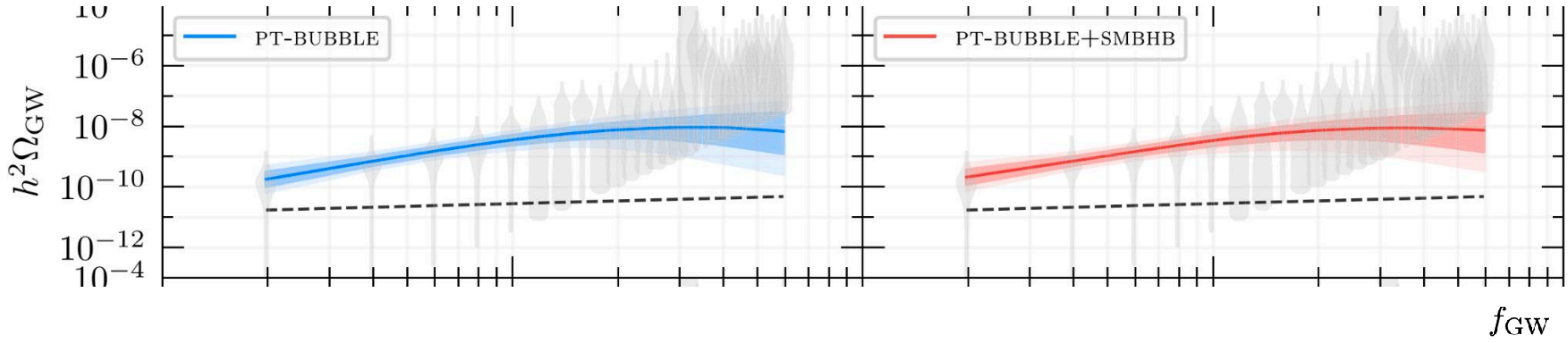
Agashe, Du, Ekhterachian, Kumar and Sundrum, 19'

Conformal Phase Transition

♦ Gravitational wave signal

Pulsars: cosmic clocks scattered across the Milky Way

PTA: Array of pulsars across the Milky Way → (nHz) GW detector of galactic dimensions!



Conformal Phase Transition

♦ Gravitational wave signal

NANOGrav data favor:

$T_R \in (0.017, 3.3)$ GeV and $\beta_{\rm GW}/H < 27$ at the 95% CL

Assuming the signal is dominated by bubble wall collisions: Caprini et al, 15', 20'

peak fractional abundance:

$$\Omega_{\rm GW} h^2 \approx 1.3 \times 10^{-6} \left(\frac{H}{\beta_{\rm GW}}\right)^2 \left(\frac{100}{g_*}\right)^{1/3}$$

peak frequency of the GW:

$$f_{\rm GW} \approx 0.04 \text{ mHz} \left(\frac{\beta_{\rm GW}}{H}\right) \frac{T_R}{\rm TeV} \left(\frac{g_*}{100}\right)^{1/6};$$

phase transition duration:
(can be extracted from bounce action)

$$\frac{\beta_{GW}}{H} = T \frac{dS_b}{dT}\bigg|_{T_n}$$

$$T_R^4 = \frac{15}{4} \frac{N^2}{g_*(T_R)} T_c^4 = \frac{15}{2\pi^2(4+\alpha)} \frac{f^2 m_\sigma^2}{g_*(T_R)}$$

$$T_R \approx 0.2\sqrt{m_\sigma f}$$

ratio of energy released
to energy of radiation bath

$$\alpha_{\rm GW} = \frac{15 N^2}{4 g_*(T_n)} \left(\frac{T_c^4}{T_n^4} - 1\right)$$

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for supercooled phase transition $T_c^4 \gg T_n^4$

$$\alpha_{\rm GW} \gg 1$$

Conformal Phase Transition

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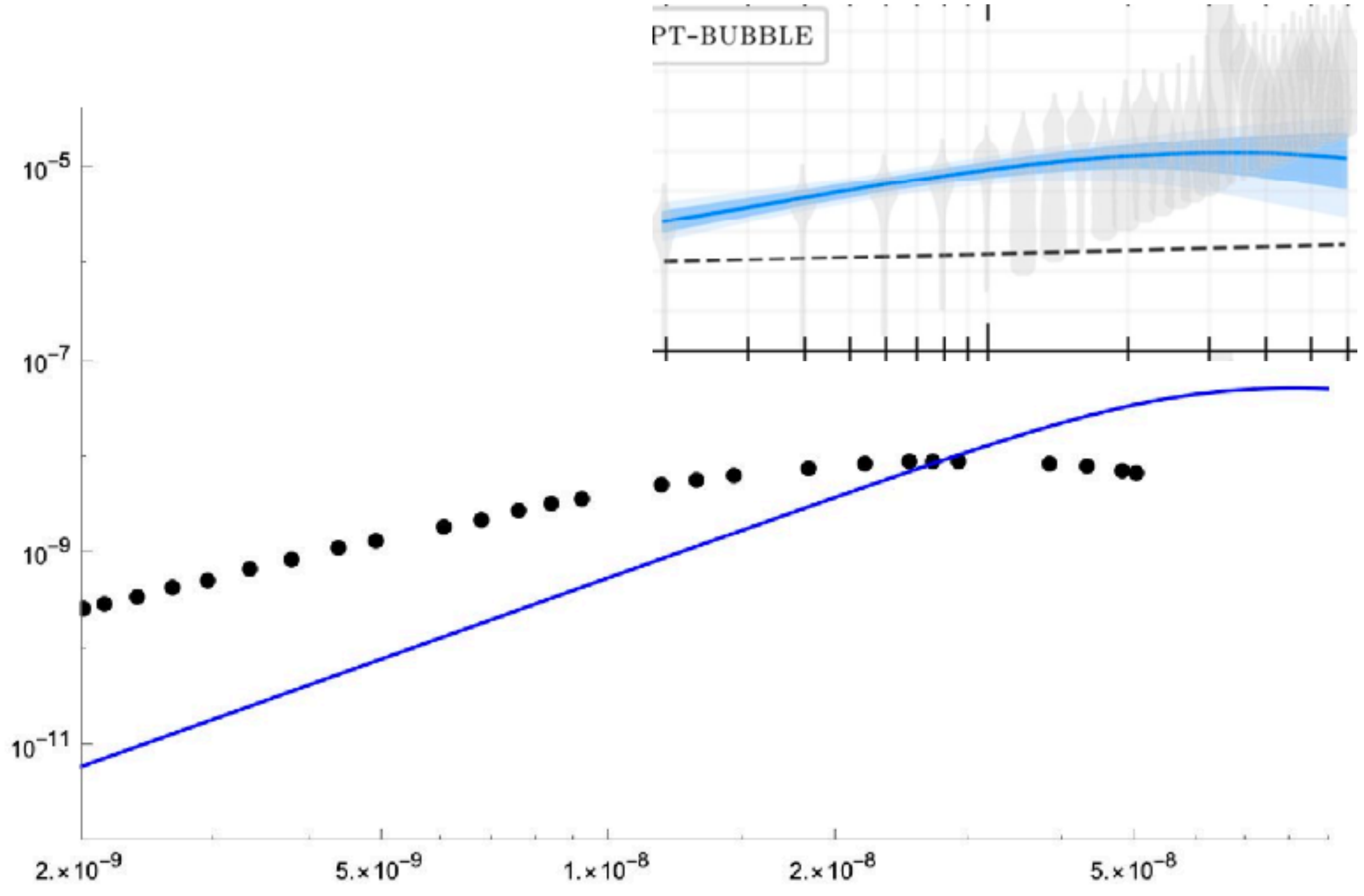
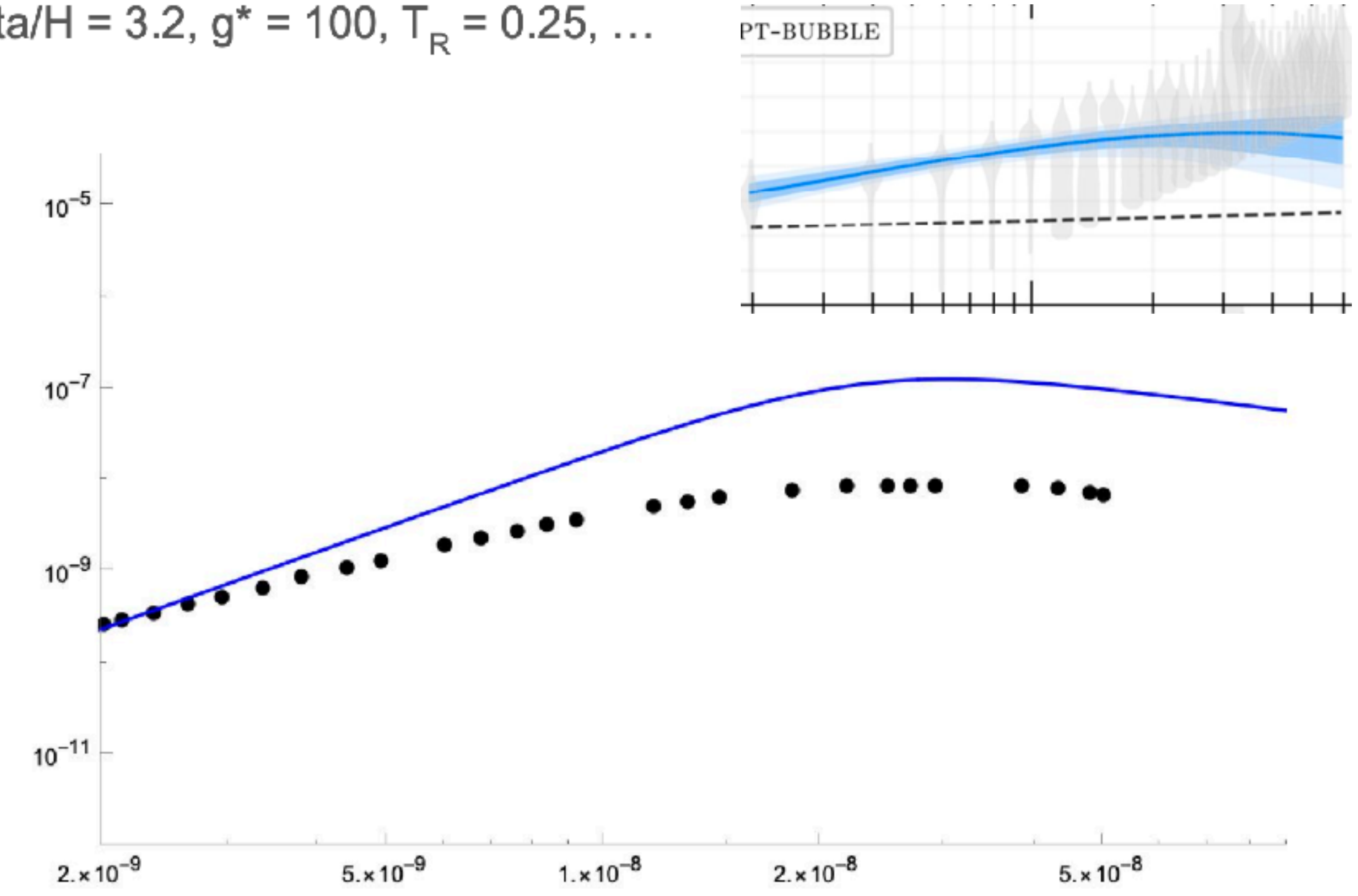
Assuming the signal is dominated by bubble wall collisions: Caprini et al, 15', 20'

Beta/H = 5, g* = 100, T_R = 0.43, Nc = 8.49; mχ = 1; ε = 0.15; λ = 1;



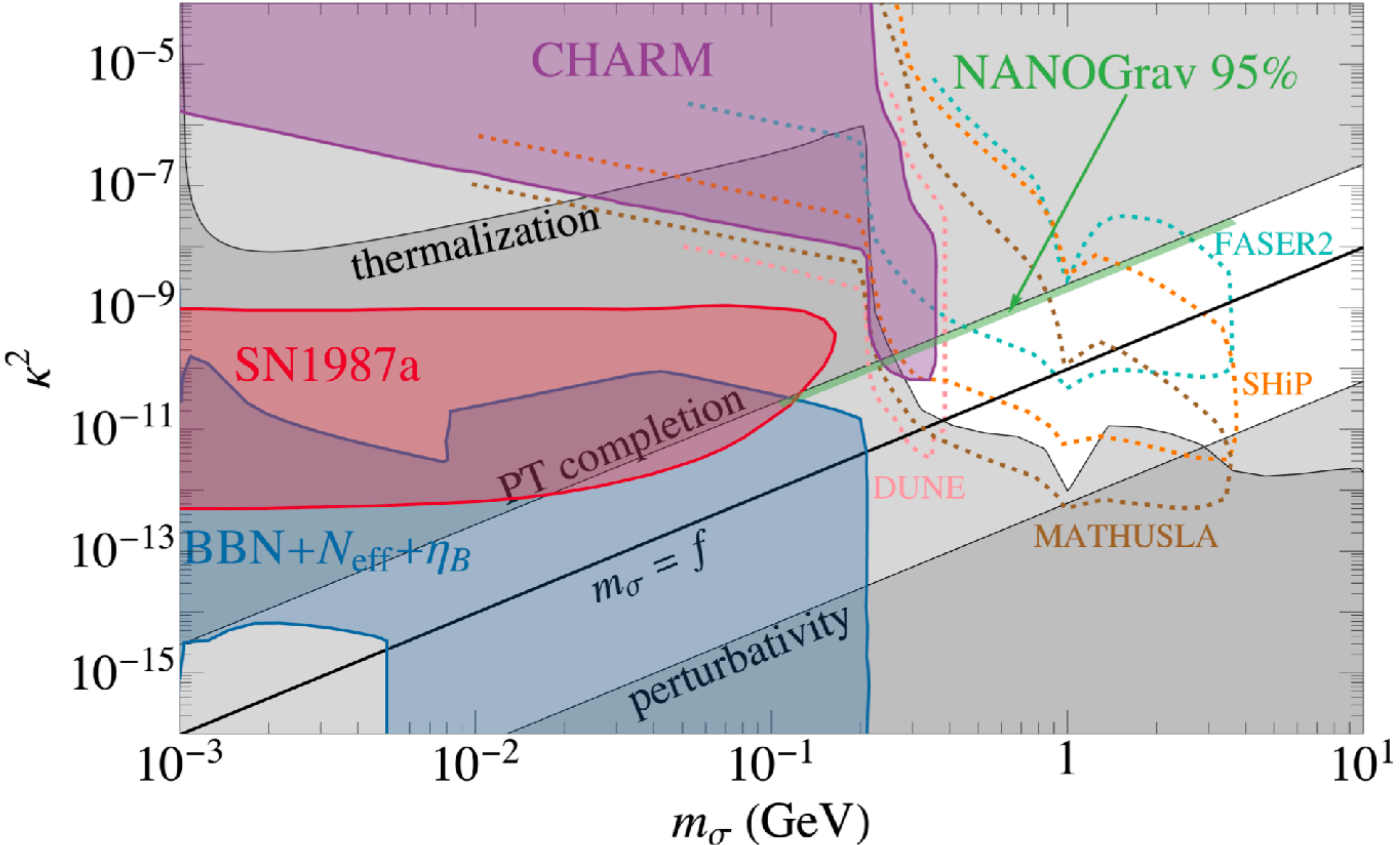
Beta/H = 3.2, g* = 100, T_R = 0.25, …



Forbidden Conformal DM at a GeV

Dilaton-porta Model

dilaton has the same couplings to the SM fermions and gauge bosons as the Higgs, but rescaled by a factor $\kappa = \frac{vf}{\Lambda^2}$



Λ=5TeV

λ=1

Thermalization bound:
$\Gamma > H$ at $T = m_\sigma$

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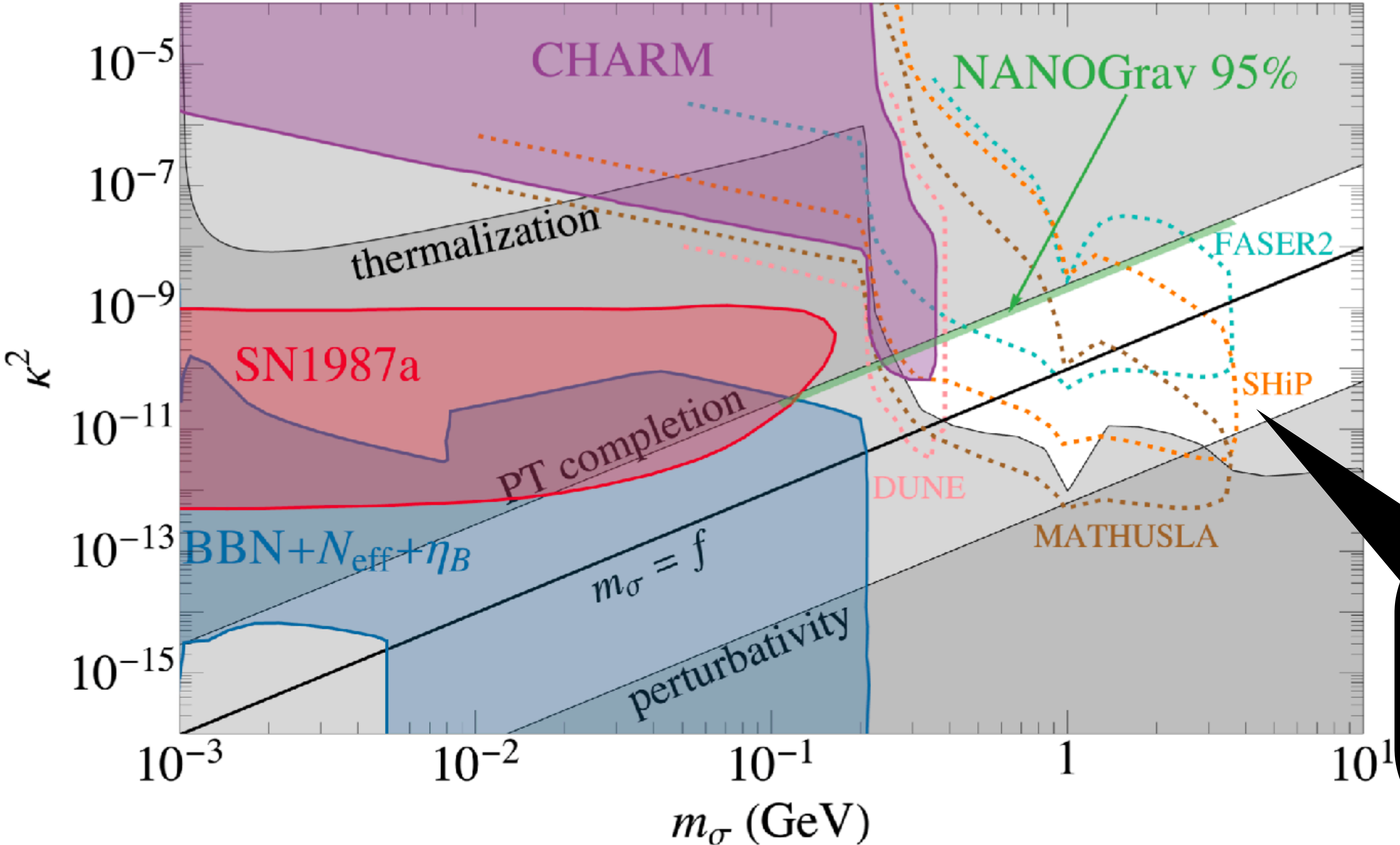

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The salient feature: Not just NANOGrav signal: the model will be tested in the future facilities searching for LLP

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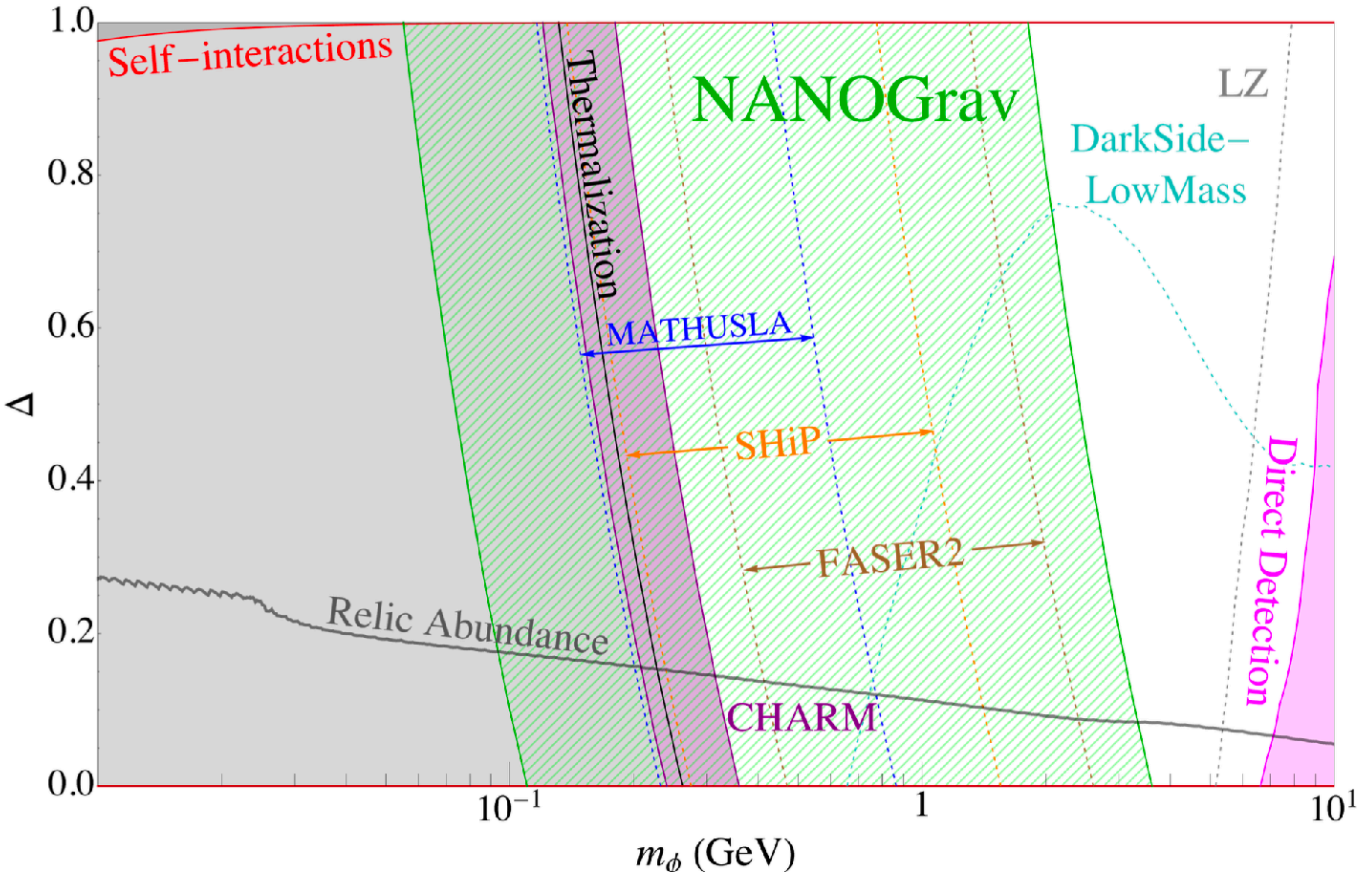


$$\Delta = (m_\sigma - m_\phi)/m_\phi$$

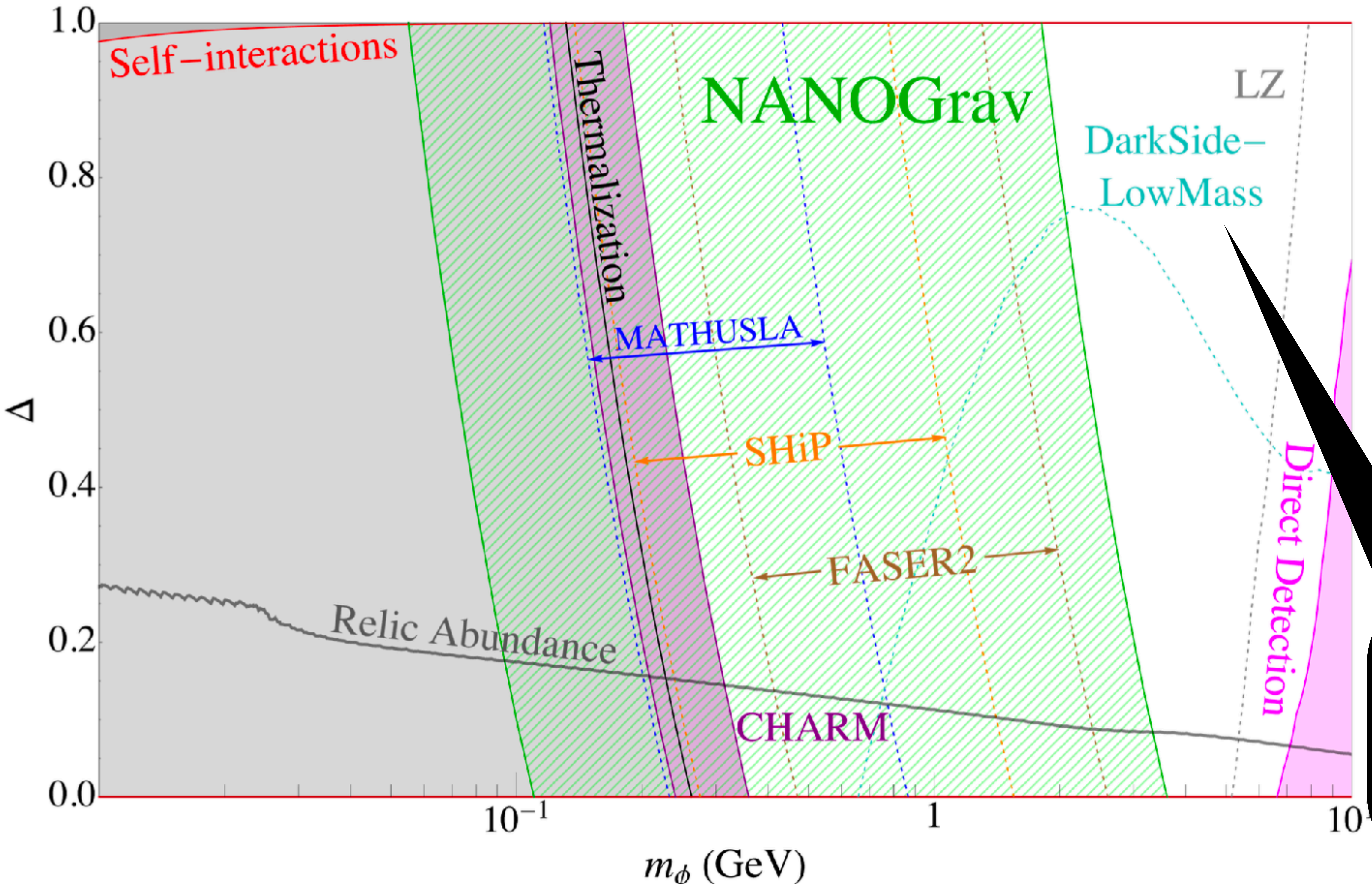
$$\sigma_{\phi N} = \frac{m_n^4}{\pi(1+\Delta)^4\Lambda^4(m_\phi+m_n)^2}$$

$f/m_\sigma = 4.5$

$\Lambda = 5$ TeV

$\lambda = 1$

Forbidden Conformal DM at a GeV



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$f/m_\sigma = 4.5$

$\Lambda = 5$ TeV

$\lambda = 1$

The salient feature: Not just NANOGrav signal: the model will be tested in the future facilities searching for LLP, and also by future direct detection

Other Constraints

♦ Higgs can decay to KK modes of the dilaton through a brane-localized interaction with the Goldberger–Wise scalar

$$\Gamma(h \to \mathrm{KK} + \mathrm{KK}) \sim \frac{\Lambda^2}{8\pi m_h} \left(\frac{f}{\Lambda}\right)^6$$

number of KK modes lighter than the Higgs is of order m_h/f

$$\Gamma(h \to \text{invisible}) \sim \frac{m_h}{8\pi} \left(\frac{f}{\Lambda}\right)^4 < \mathbf{0.11}$$ ATLAS, 23'

$$\Lambda/f \gtrsim 10.$$

✔ $f \sim \mathrm{GeV}$ and $\Lambda \sim \mathrm{TeV}.$

Other Constraints

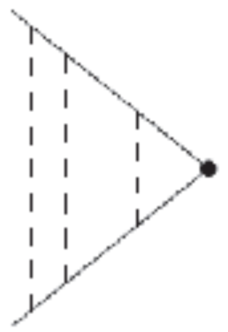
♦ DM annihilation into SM fermions (via the dilaton portal)

Safe: Cross section is samll

$$\langle \sigma v(\phi\phi \to f\bar{f})\rangle \sim 10^{-36}\ \mathrm{cm}^3/\mathrm{s}\,((1-\Delta)(3+\Delta))^{-2}\left(\frac{m_f}{0.5\ \mathrm{MeV}}\right)^2\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4$$

- How about Sommerfeld Enhancement (via dilaton)?

$$SE \approx \frac{\pi}{\epsilon_v}\frac{\sinh\left(\frac{12\epsilon_v}{\pi\epsilon_\phi}\right)}{\cosh\left(\frac{12\epsilon_v}{\pi\epsilon_\phi}\right)-\cos\left[2\pi\sqrt{\frac{6}{\pi^2\epsilon_\phi}-\left(\frac{12\epsilon_v}{\pi\epsilon_\phi}\right)^2}\right]},$$



$$\alpha_{\mathrm{eff}} = m_\phi^2/(4\pi f^2)$$

$$\epsilon = \frac{m_\sigma}{\alpha_{\mathrm{eff}} m_\phi} = 4\pi(1+\Delta)^3\frac{f^2}{m_\sigma^2}$$

Sommerfeld enhancement is only a large effect when $\epsilon \ll 1$

for $f = m_\sigma$ and a DM velocity of 0.5×10^{-3}, we find only a small enhancement of 2% to 17%

Summary

1. We present the first extensive study of light thermal relic DM which is a composite of a CFT. We have focused on forbidden DM
2. for a range of dilaton masses around 0.1–2 GeV, the conformal phase transition can source a nHz-scale stochastic GW background consistent with that observed at NANOGrav
3. Theoretical and experimental bounds pointed to dark sector masses in the range 0.1– 10 GeV. Imposing the requirements that the dark sector thermalizes with the SM, that the conformal phase transition completes, and that the dilaton effective theory is valid led to a lower bound on the dilaton mass of about 0.1 GeV; meanwhile, direct detection bounds constrained the DM mass to be less than 10 GeV.
4. The viable parameter space below a few GeV will be probed by experiments searching for light, weakly-coupled particles like FASER2, MATHUSLA, and SHiP. Future direct detection experiments specialized for low mass WIMPs, in particular DarkSide-LowMass, will be sensitive to the remaining parameter space up to 10 GeV.


Cảm ơn

Back-up

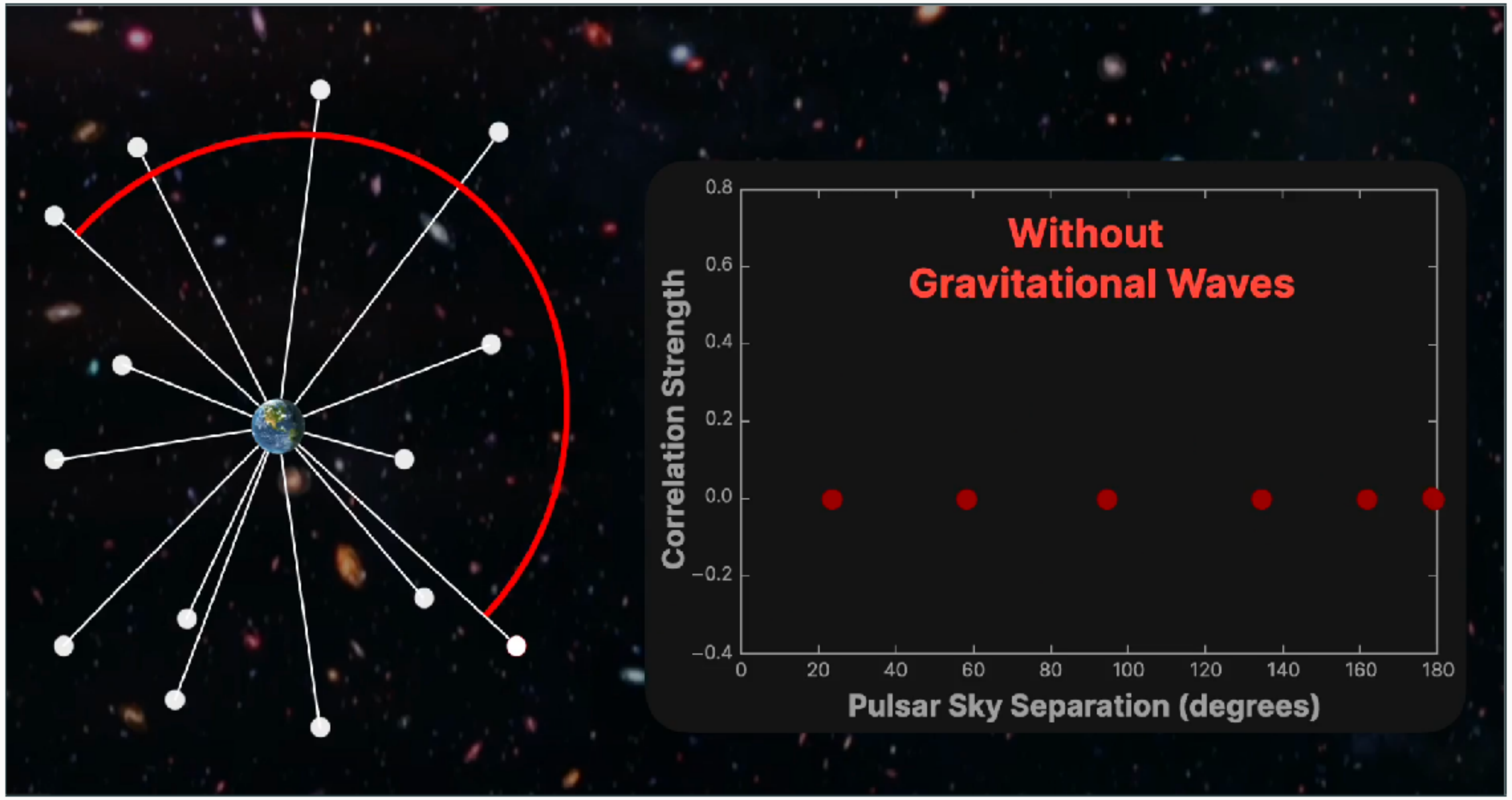
PTAs are galaxy-sized GW detectors that allow us to search for nHz GWs

Array of pulsars across the Milky Way → GW detector of galactic dimensions!

- Look for tiny distortions in pulse travel times caused by nanohertz GWs.
- Signal builds up over time; monitor PTA over years and decades.

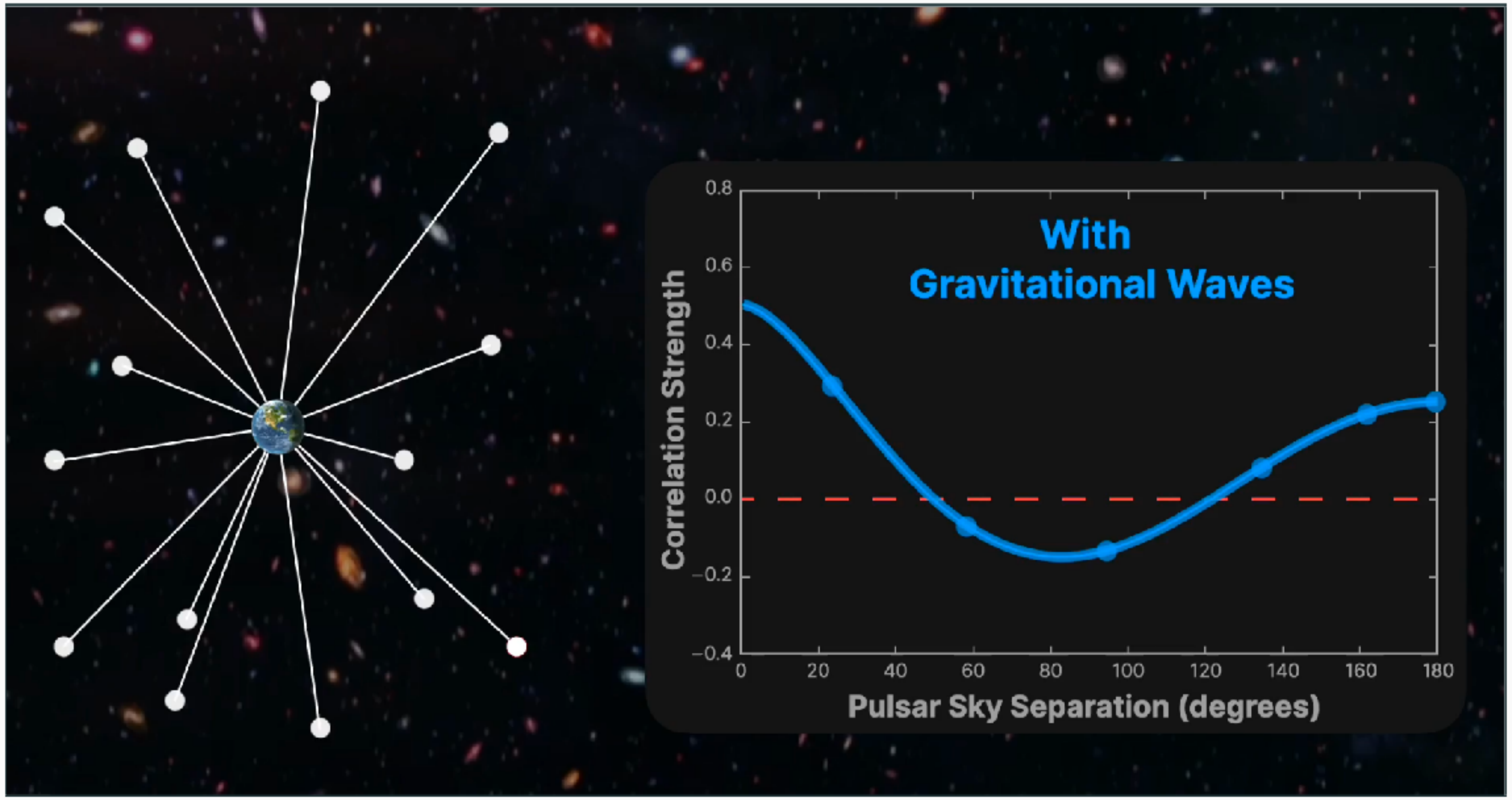
Kai Schmitz

Hallmark signature in cross-correlation of timing residuals of pulsar pairs



Kai Schmitz

… signature in cross-correlation of timing residuals of pulsar pairs

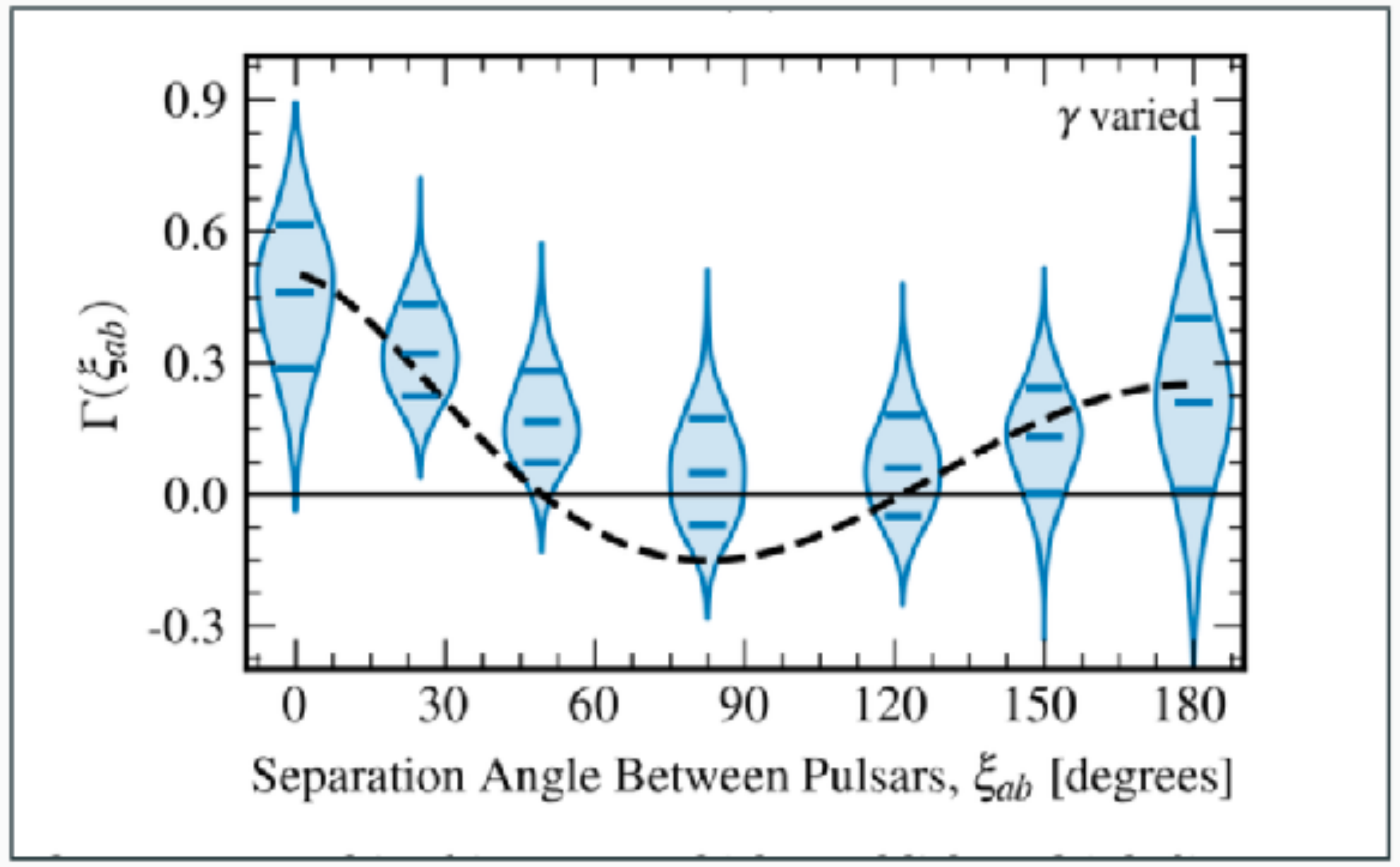


Quadrupolar correlations described by Hellings–Downs (HD) curve

[Hellings, Downs: Astrophys. J. 265 (1983) L39]

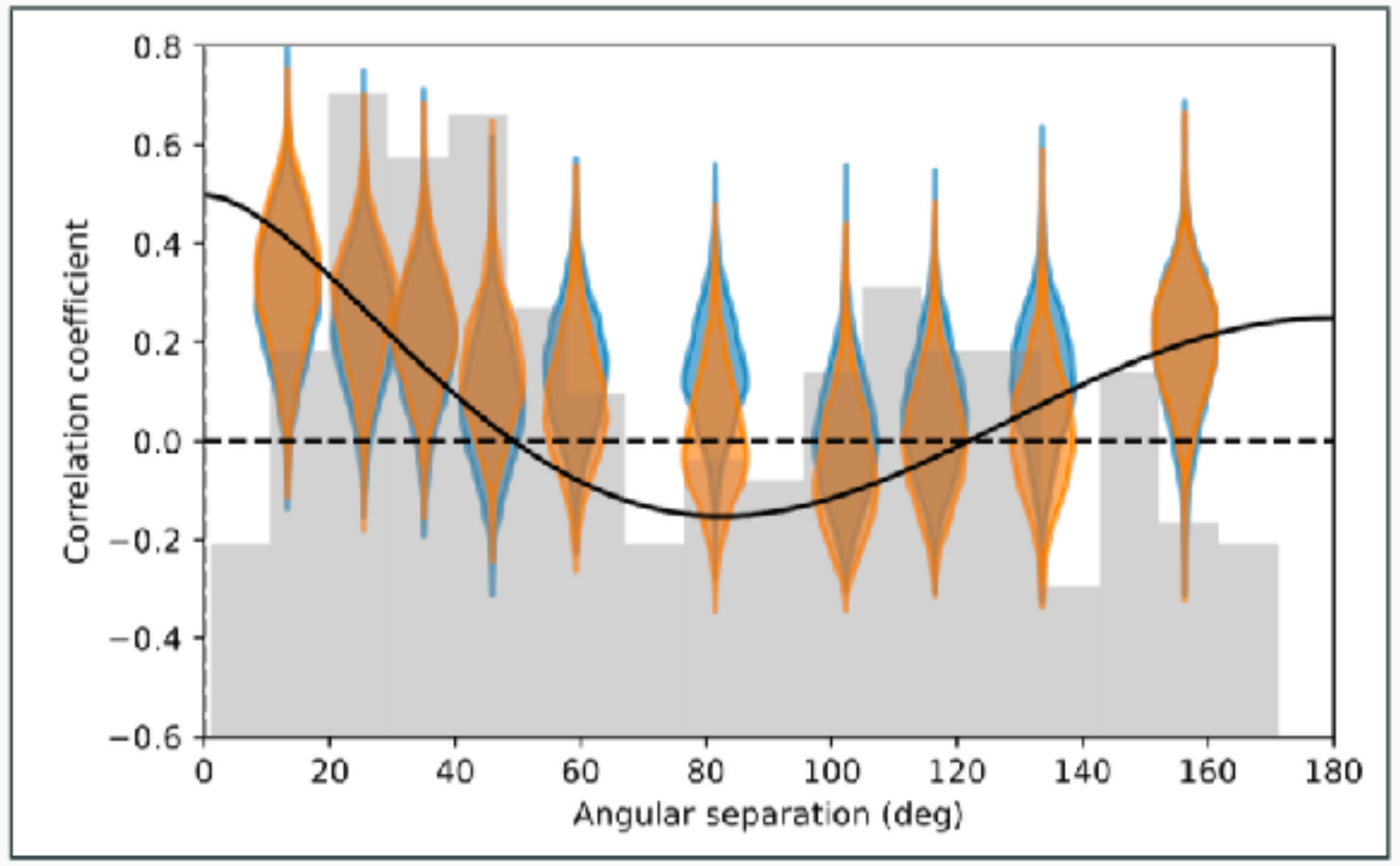
Major announcment on June 29: compelling evidence for HD correlations

2306.16213: NANOGrav



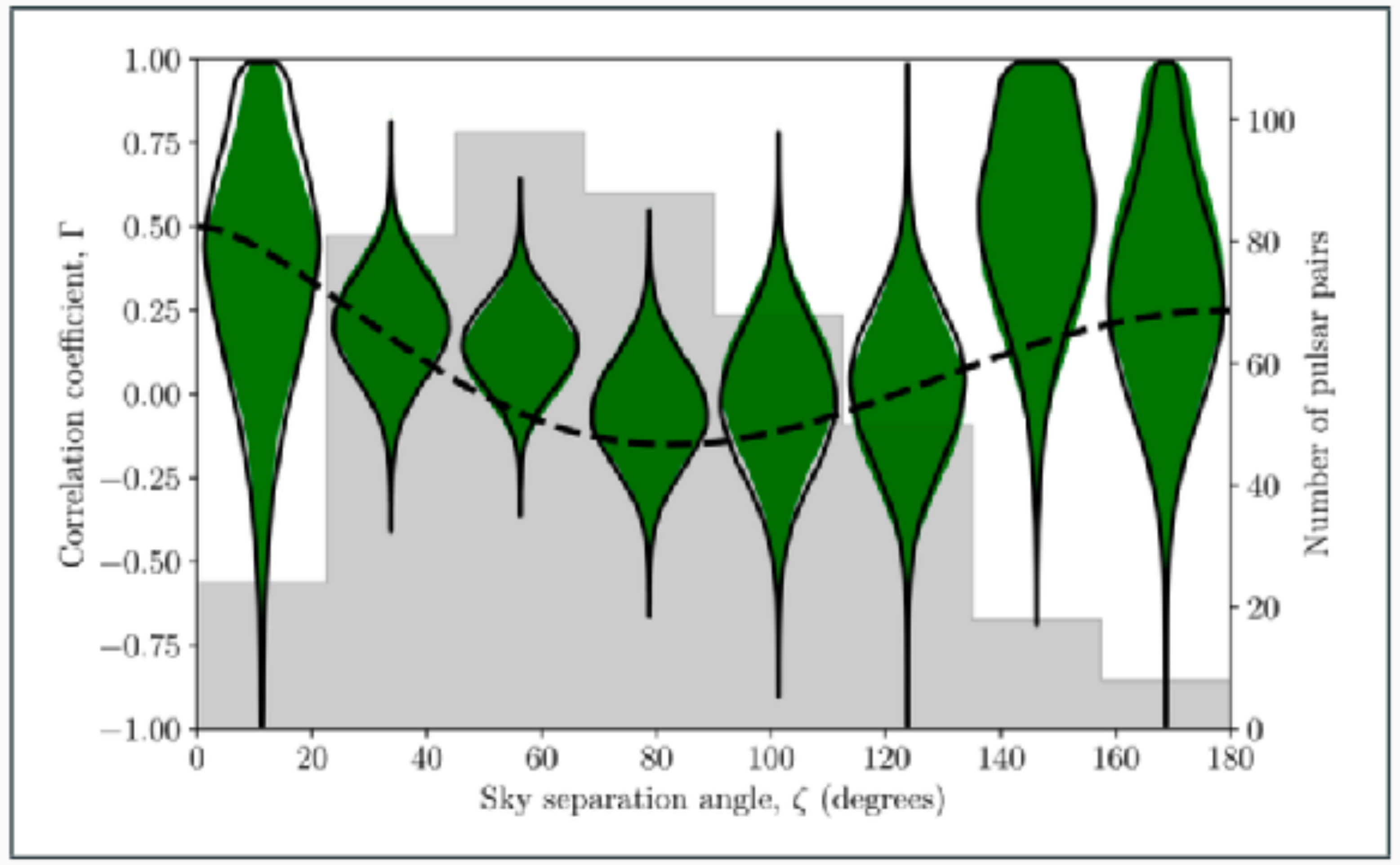
68 pulsars, 16 yr of data, HD at $\sim 3\cdots4\,\sigma$

2306.16214: EPTA+InPTA



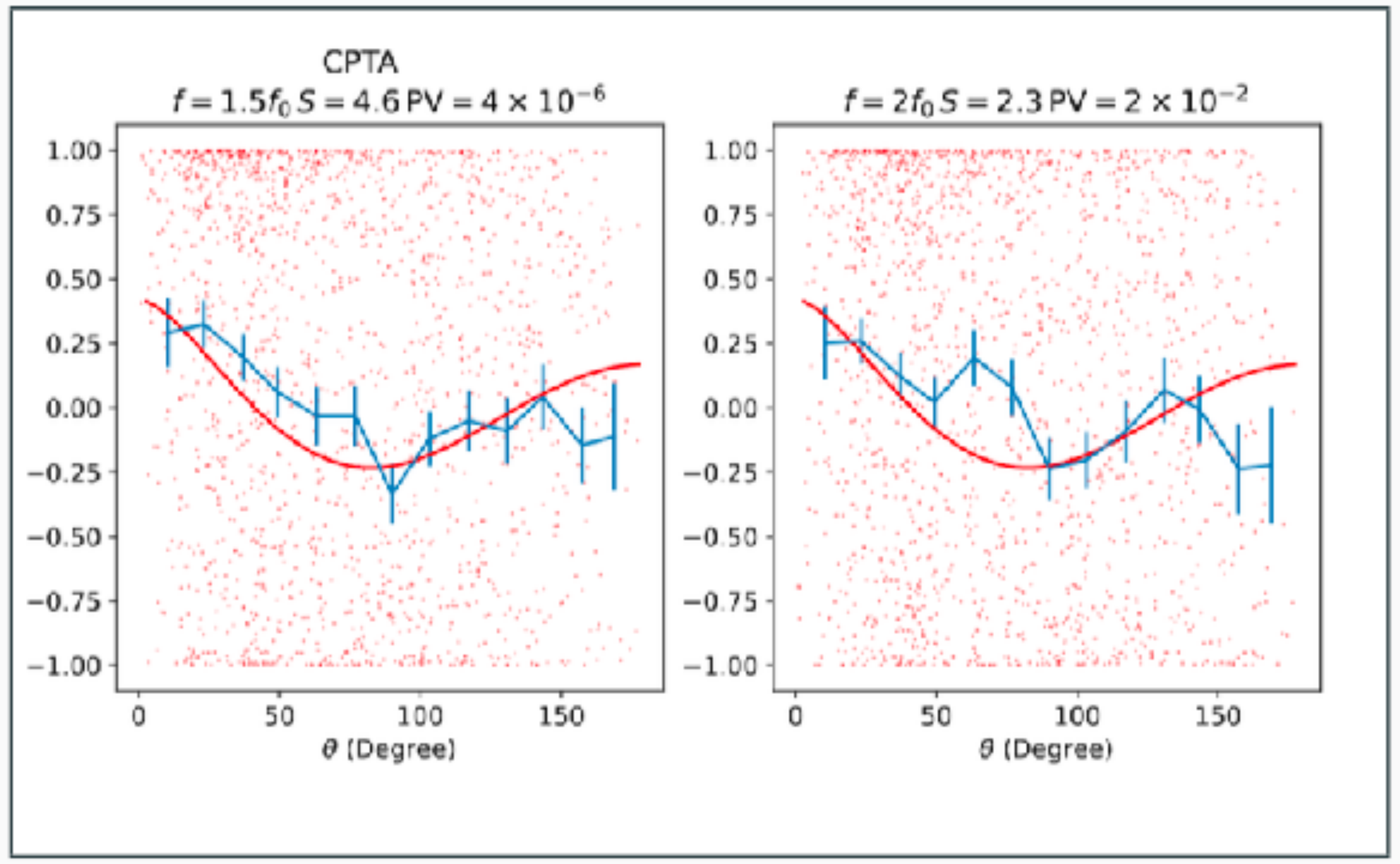
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

2306.16216: CPTA

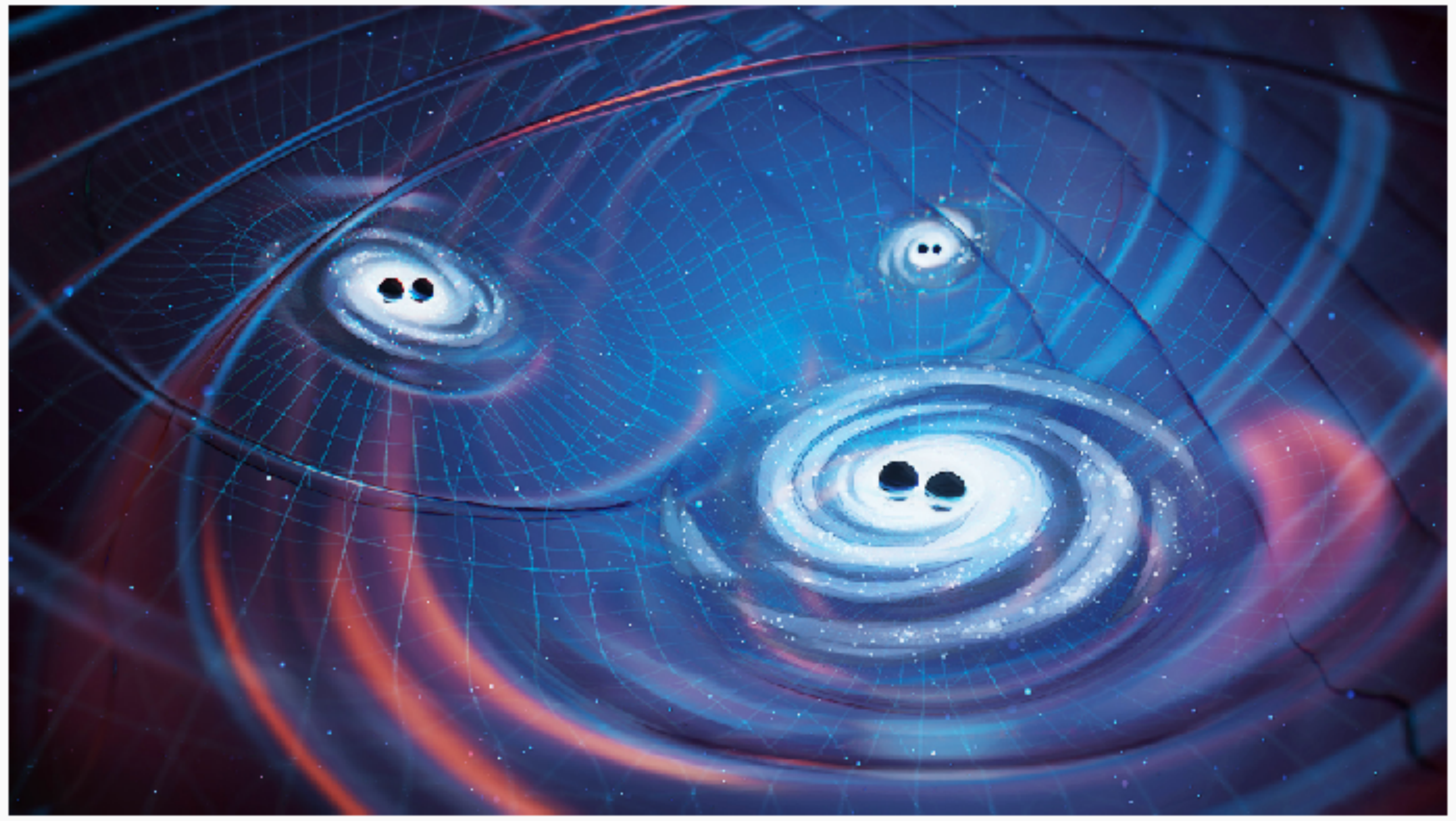


57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

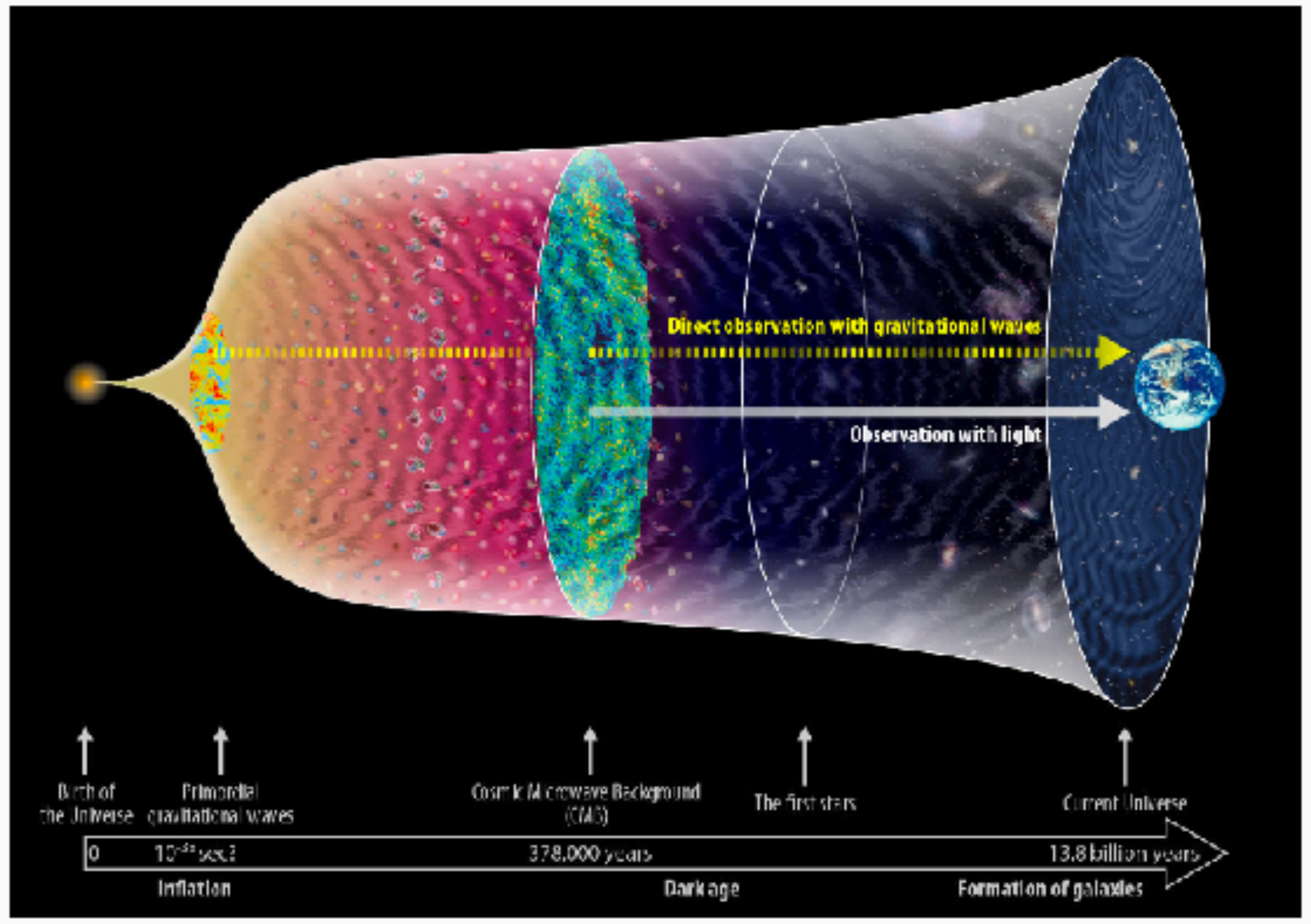
Kai Schmitz

Interpretation: SMBHBs (realistic) or new physics (speculative)

❶ Supermassive black-hole binaries



❷ GWs from the Big Bang



- SMBHBs: No SMBHB mergers observed → data-driven field thanks to PTAs
- New physics: Probe cosmology at early times, particle physics at high energies

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BSM scenarios: Inflationary gravitational waves, scalar-induced gravitational waves, cosmological phase transition, cosmic strings, domain walls, axions, and many more

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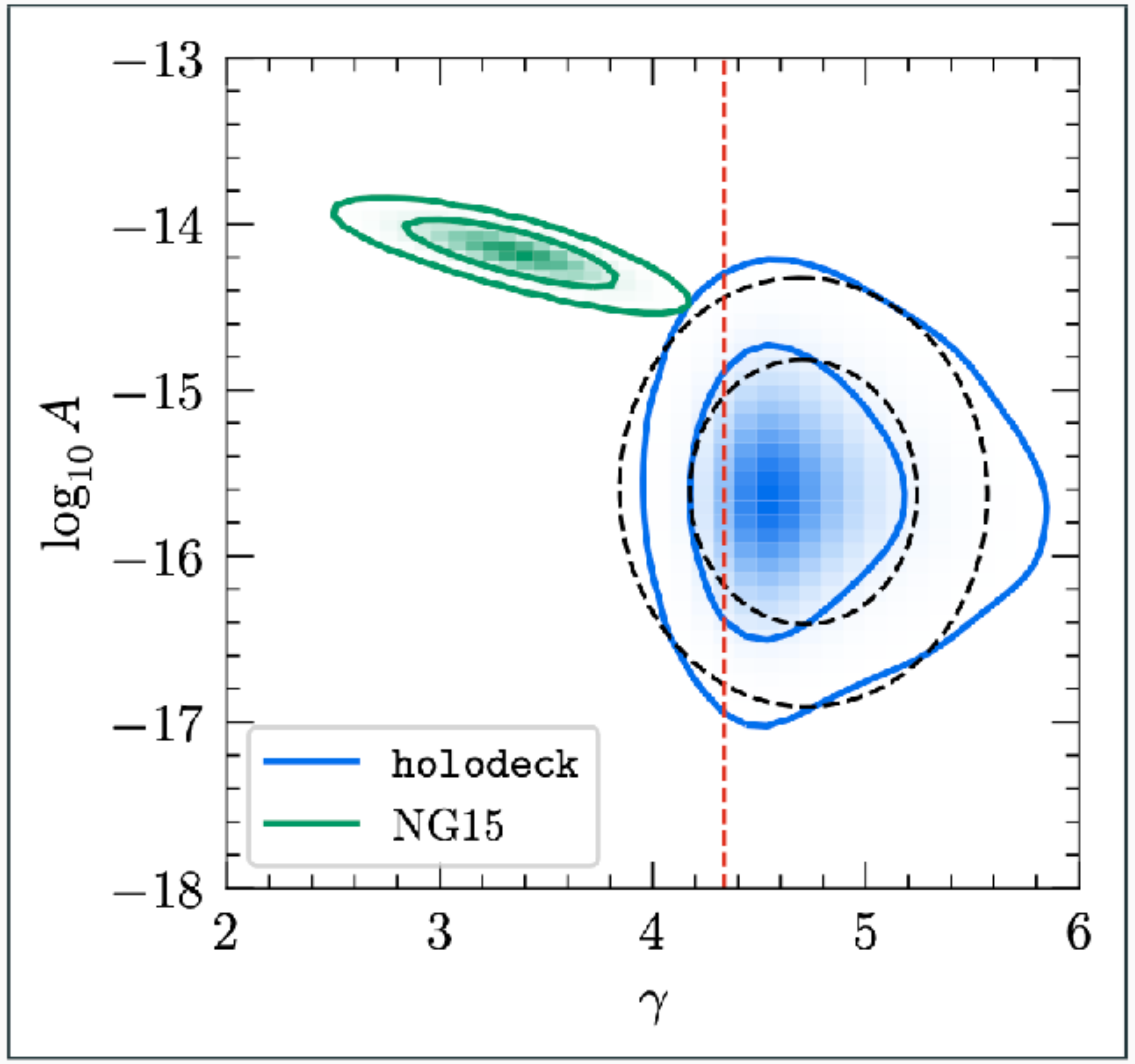
SMBHBs: simplest models of binary evolution struggle to explain the data

[NANOGrav 2306.16219]



Compare observed spectrum (NG15) to theoretical expectation (holodeck)

- Assume SMBHBs on circular orbits and purely GW-driven orbital evolution
- 95 % regions barely touch → 2σ tension between observations and theory
- GW-only evolution unable to bring binaries to the PTA band within a Hubble time

Kai Schmitz