FCC-COSMOLOGY CONNECTION: PROBING PRIMORDIAL GW SOURCES AT COLLIDERS

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Cluster of Excellence PRISMA+

FCC phenomenology workshop

CERN, Geneva **July 6, 2023**

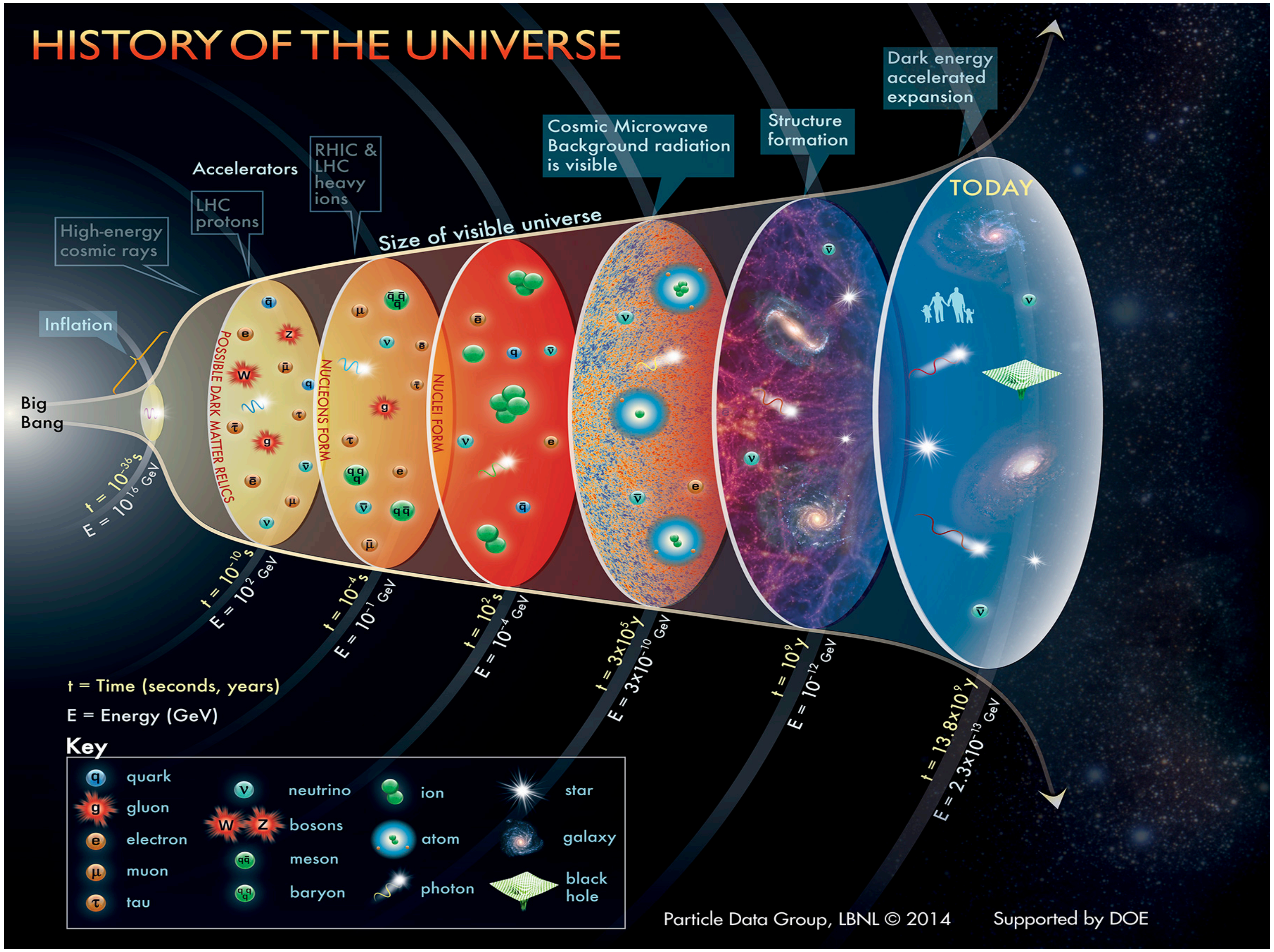
Gravitational waves as windows into the early Universe

New physics sources of primordial GWs

Collider probes of GW sources

See also talks by
Germano, Michael and Chiara!

Thermal history and particle physics



Thermal history and particle physics

Early universe holds the key to many fundamental open questions in particle physics

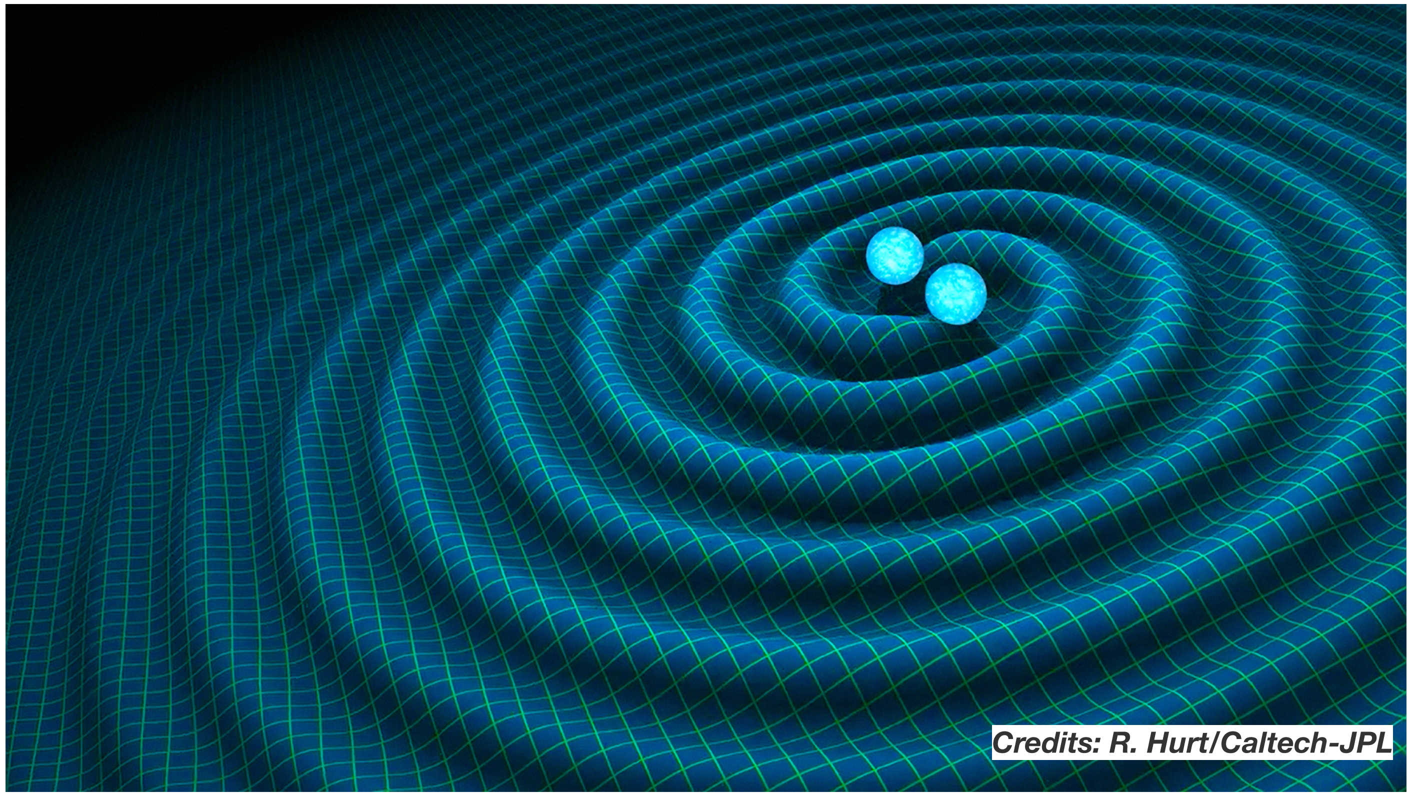
- What is dark matter, and how is it made
- What is the origin of matter
- What is the dynamics of inflation and reheating
- How is electroweak symmetry broken

Gravitational waves as messengers from the early Universe

Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

- Stochastic GW background



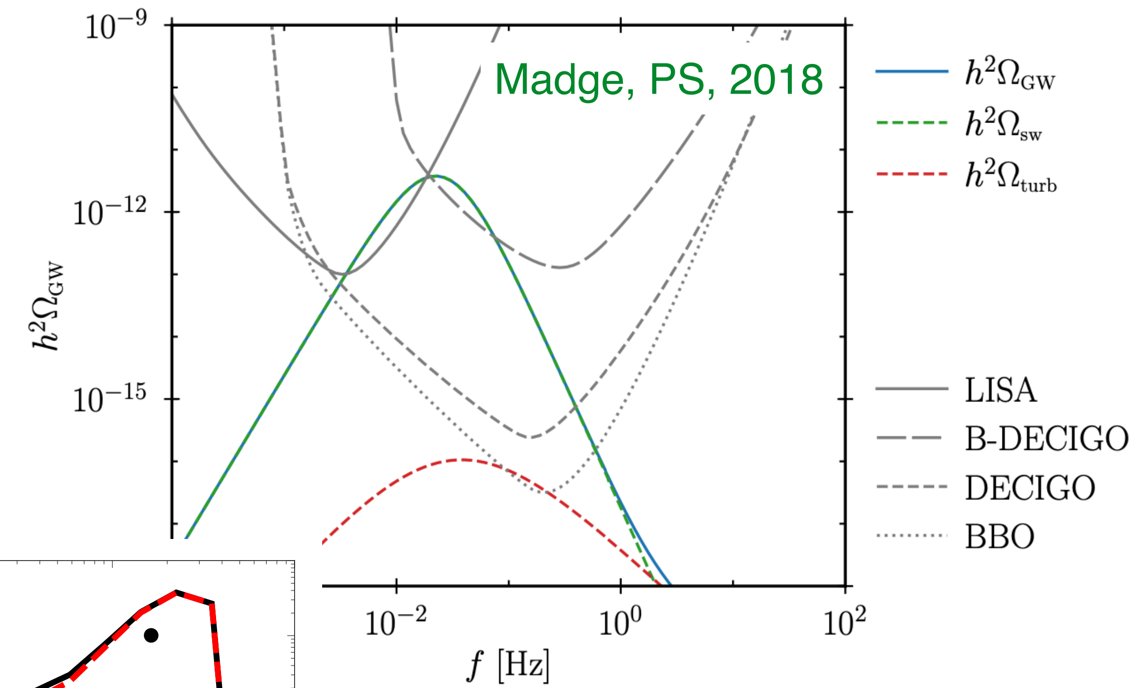
Relevant scale: Hubble radius ↔ GW wavelength

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

Signal shape and frequency is characteristic for the source. Examples:

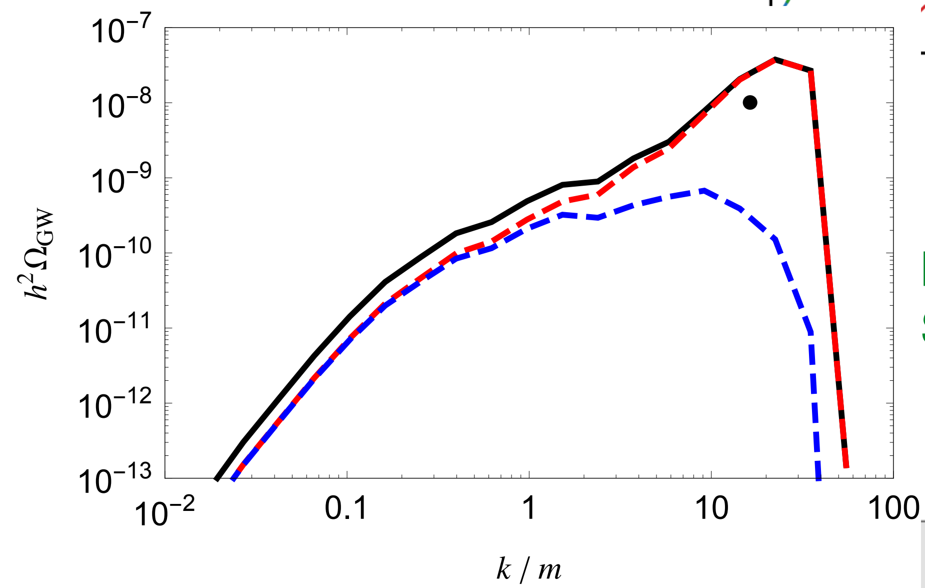
Phase transition

- Peak position depends on critical temperature



Audible axions:

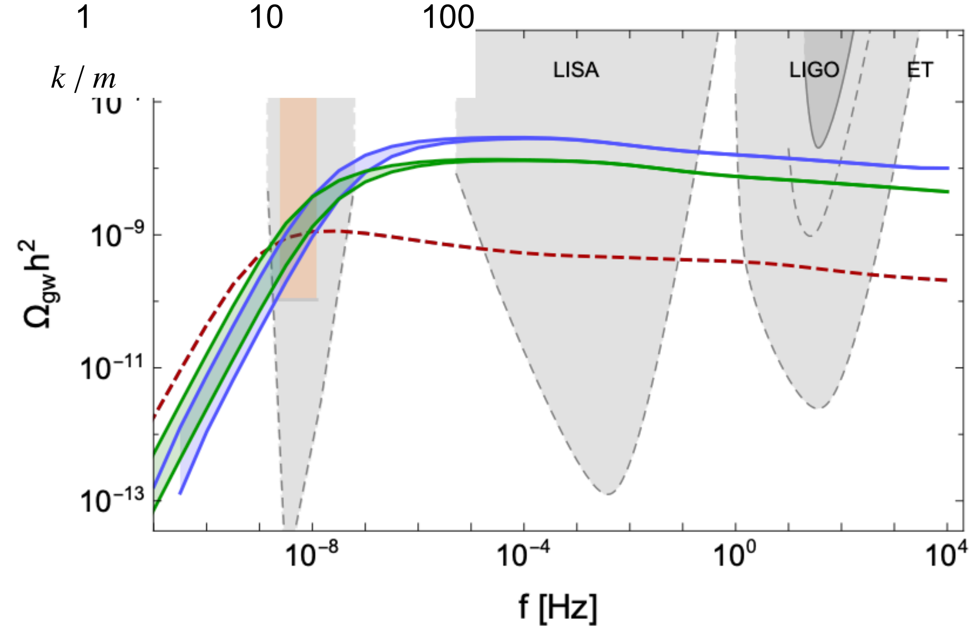
- Peaked but chiral



Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings

- Flatter spectrum

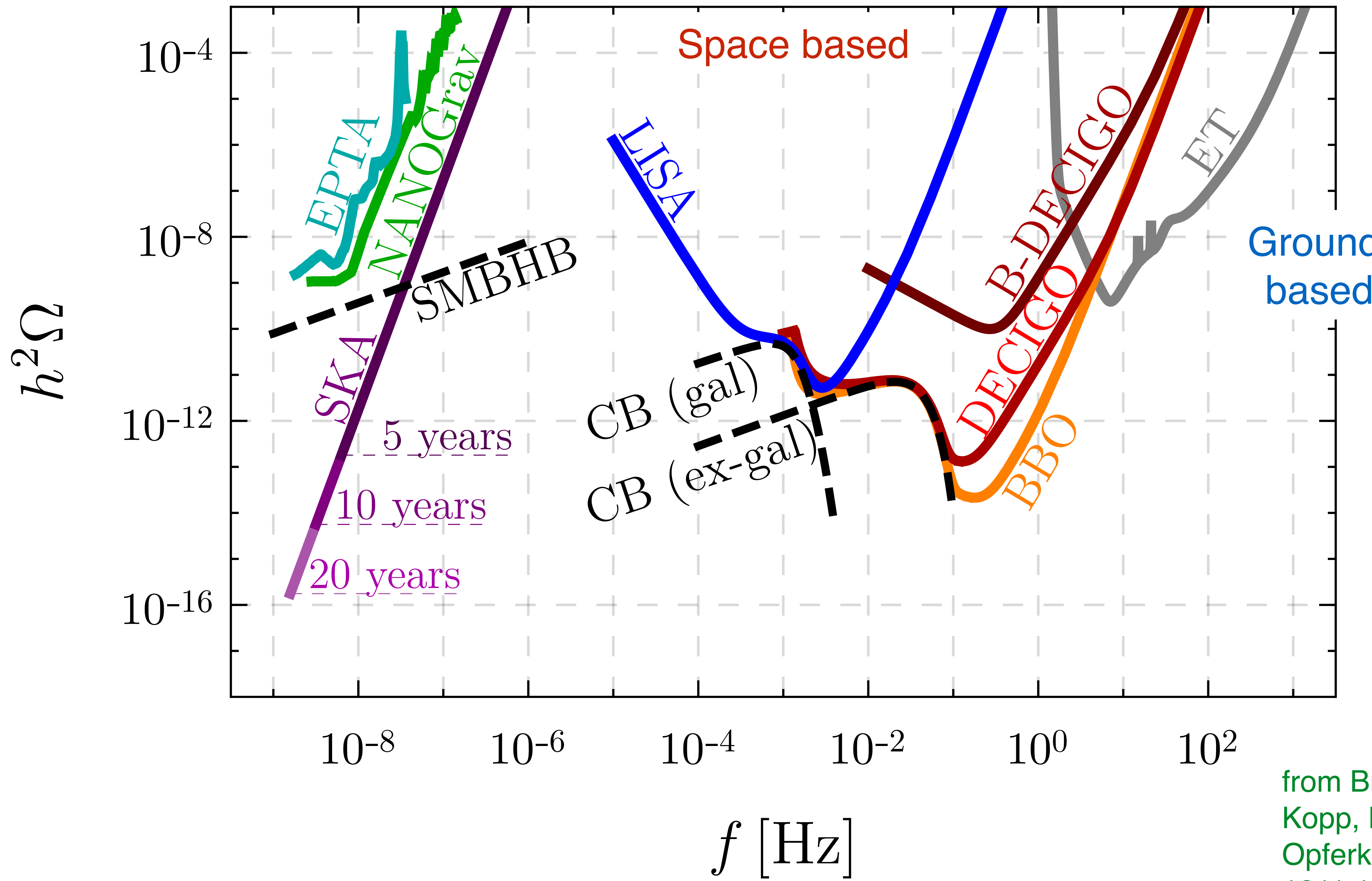


Buchmuller, Domcke, Schmitz, 2021

Frequency ranges

New physics scale

MeV GeV TeV PeV

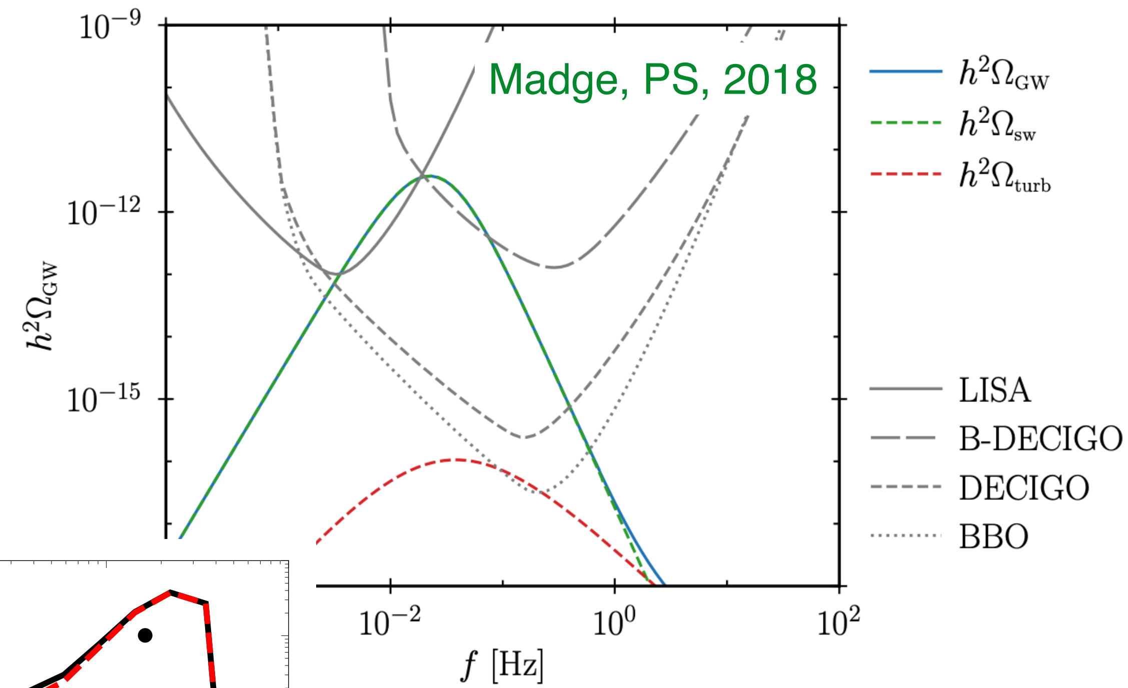


from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

New physics mass scales for PTA

Phase transition

- $T_* = M_{NP} \sim \text{MeV} - \text{GeV}$

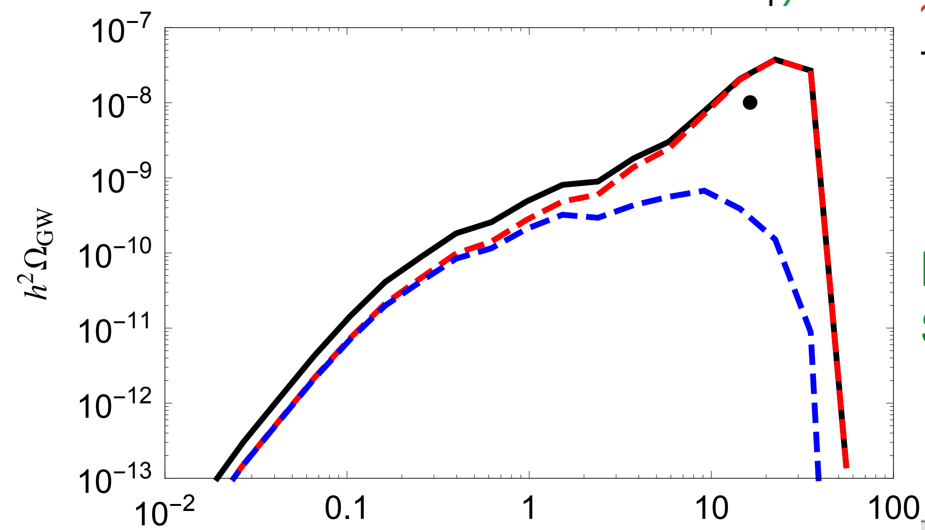


Madge, PS, 2018

Audible axions:

- $T_*^2/M_{Pl} = M_{NP}$

$\rightarrow M_{NP} \sim 10^{-14}$ eV

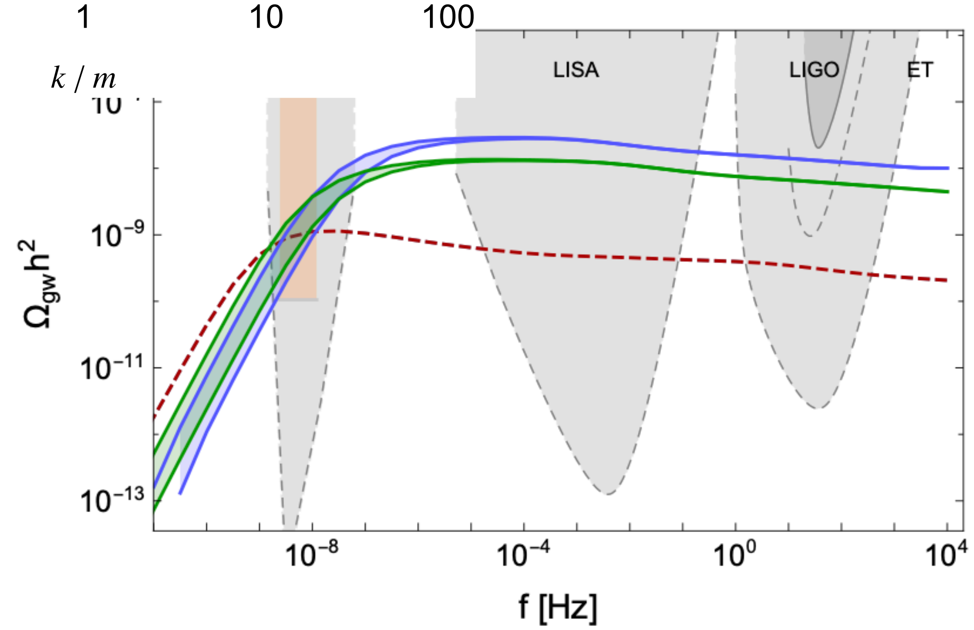


Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings/domain walls

- $T_* \sim \Gamma_{decay}$

  $M_{NP} \gg \text{MeV}$



Buchmuller, Domcke, Schmitz, 2021

Some general thoughts

Thermal history and particle physics

Early universe holds the key to many fundamental open questions in particle physics

- What is dark matter, and how is it made
- What is the origin of matter
- What is the dynamics of inflation and reheating
- How is electroweak symmetry broken

GWs themselves are not an open question (yet)

- Very interesting to think what we can learn from them about the open questions

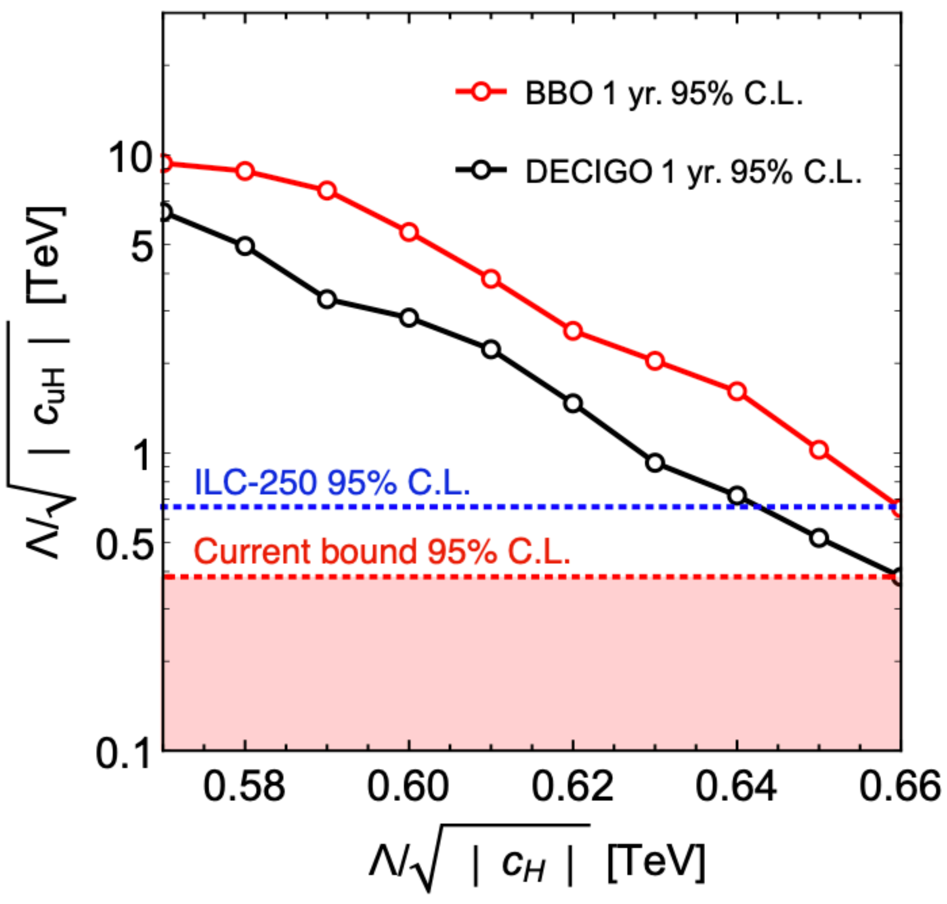
“Motivated” GW sources: EWSB

Electroweak symmetry breaking

- Modified/extended Higgs potential
- First order electroweak phase transition -> GWs!

FCC

- Probe Higgs potential via double Higgs production
- In general probe SMEFT operators, search for new states coupled to Higgs



Hashino, Ueda, 2210.11241

Baryogenesis

Electroweak baryogengesis requires departure from equilibrium

- First order phase transition -> GWs :)
- “strong” connection, though not necessarily strong GWs

FCC (and laboratory tests)

- EDMs for CPV source
- Some new physics that extends the Higgs sector or modifies its couplings
- PT could also be in dark sector (plus asymmetric DM…)

Vanilla EWBG prefers slow bubbles (=small GWs)

- Some models with successful baryogengesis from fast bubbles

Azatov et al, 2106.14913

Dark matter

Generic (but weak) connection

- DM implies some kind of dark sector
- Could have a first order PT
- Example: New confining force, or any kind of new symmetry that requires breaking
  PS, 1504.07263, and many others

Also specific scenarios with strong GW connection

- DM produced from PT dynamics
  Breitbach et al, 1712.03962

FCC

- Dark sector searches
- Missing energy, also LLPs for richer dark sectors, new mediators
- Benchmark scenarios might be useful -> discussion

Strong CP problem

Axions/ALPs

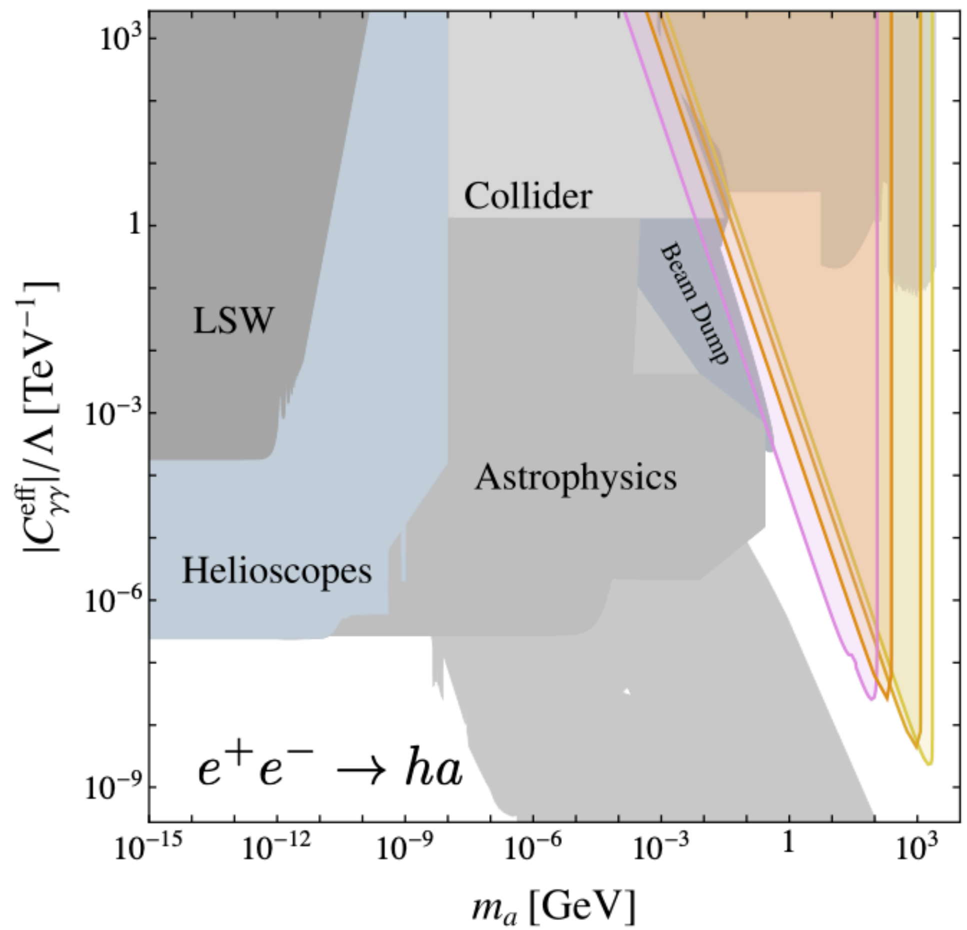
Rich GW phenomenology

- Axion dynamics (misalignment)
- Axion strings and domain walls
- Peccei Quinn breaking PT

FCC

- Searches for heavy (GeV-ish) ALPs
- Possible ALP-flavour connection

Later: NANOGrav GWs at FCC



Bauer et al, 1808.10323

Impossible to list everything

Inflation/Reheating

- Often unaccessible at colliders
- Non-trivial probes possible in freeze-in DM scenarios, e.g. constraints on reheating temp from collider data

Becker et al, 2306.17238

Flavour

- GWs from breaking of flavour symmetries, generation of mass scales

Greljo et al, 1910.02014

Neutrinos

- Leptogenesis… GWs

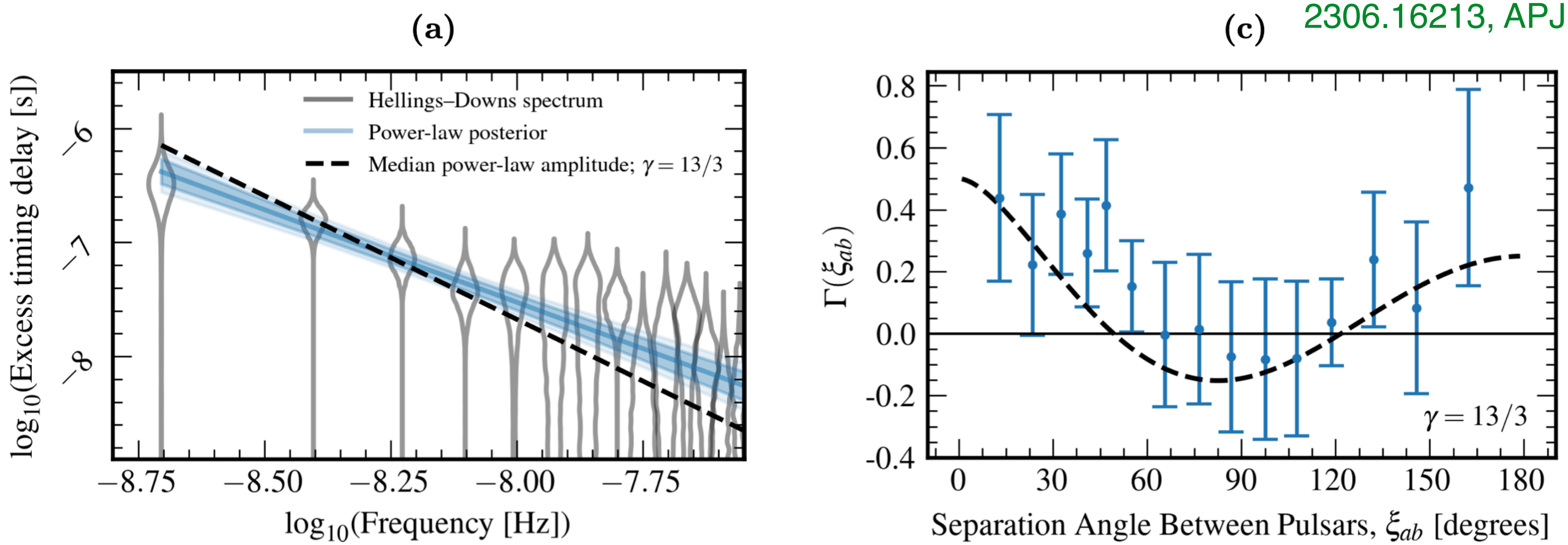
Dror et al, 1908.03227

Sources in PTA frequency range and FCC

Pulsar timing arrays

NANOGrav has observed evidence for a stochastic GW background at nano-Hz frequencies:

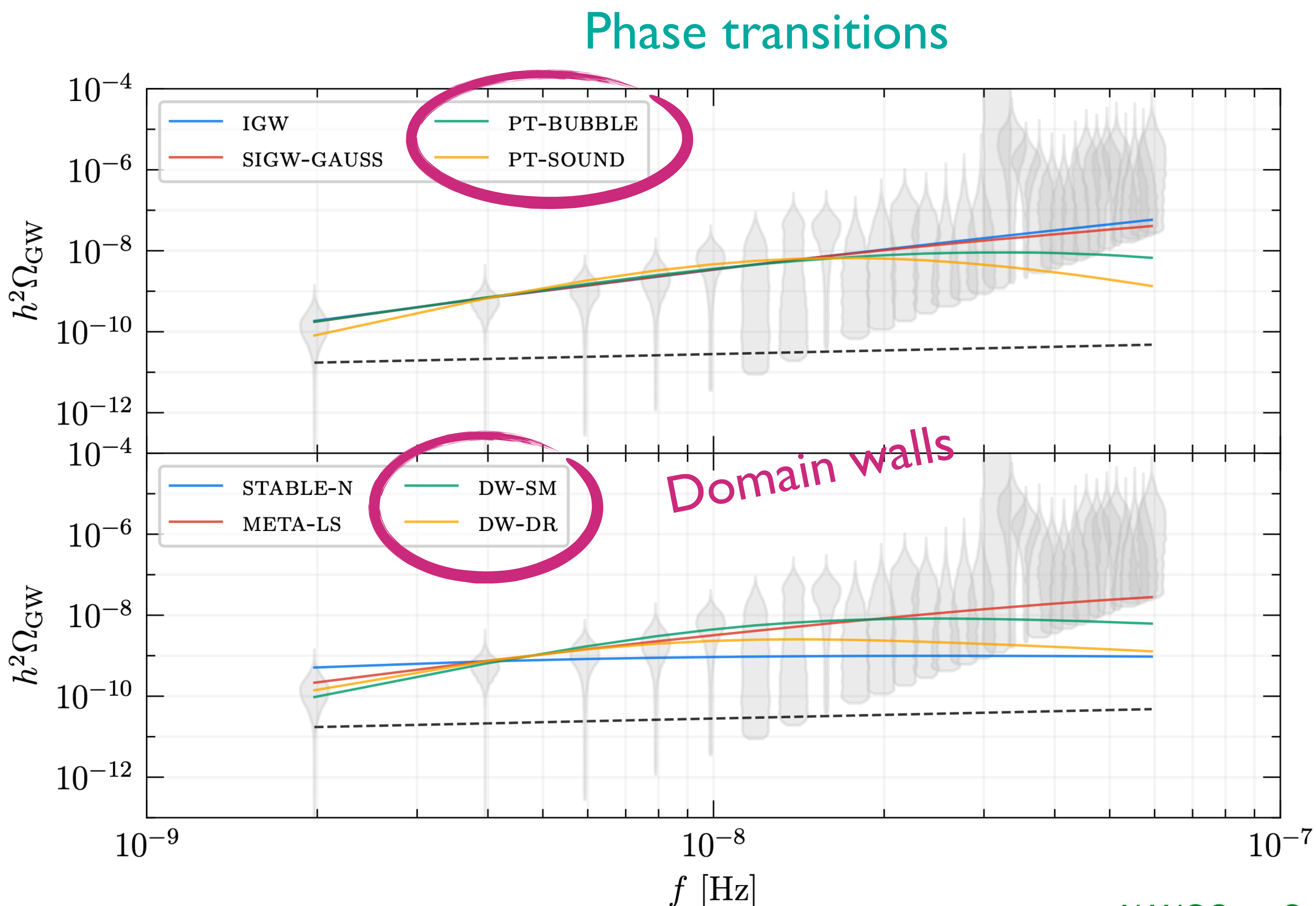
NANOGrav Collaboration, 2306.16213, APJL 951



Strong evidence for Hellings-Downs correlation

Also supported by new EPTA+InPTA, CPTA data (PPTA less)

Compatible with primordial GWs from new physics



NANOGrav Collaboration,
2306.16219, APJL 951

Thoughts:

This is a very strong signal!

$$\Omega_{\mathrm{GW,\,today}} \sim 10^{-9}$$

Comparison: The photon density today is $\Omega_\gamma \sim 10^{-5}$, but photons were in thermal equilibrium in early Universe

Any source that can explain this must:

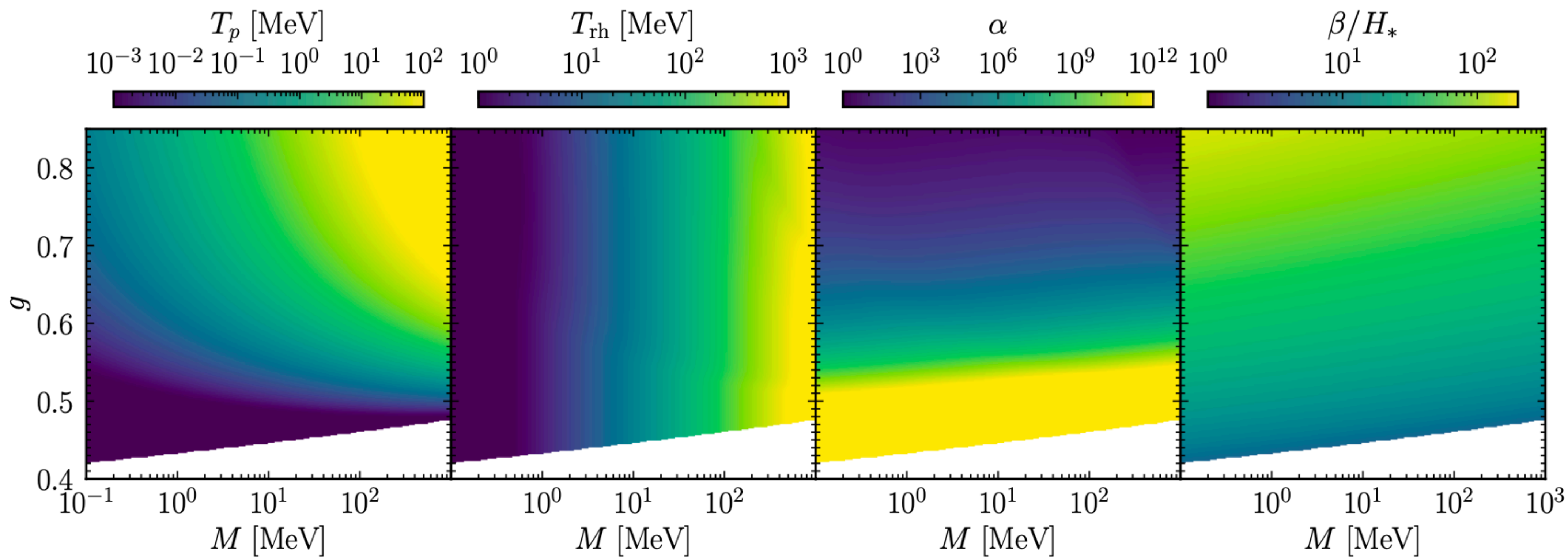
- Represent a significant fraction of the total energy density at the time of production, $T_* \sim (10 - 1000)\,\mathrm{MeV}$
- Be very efficient at converting that energy to GW radiation
- Then disappear before onset of BBN, $T \sim 1\,\mathrm{MeV}$

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

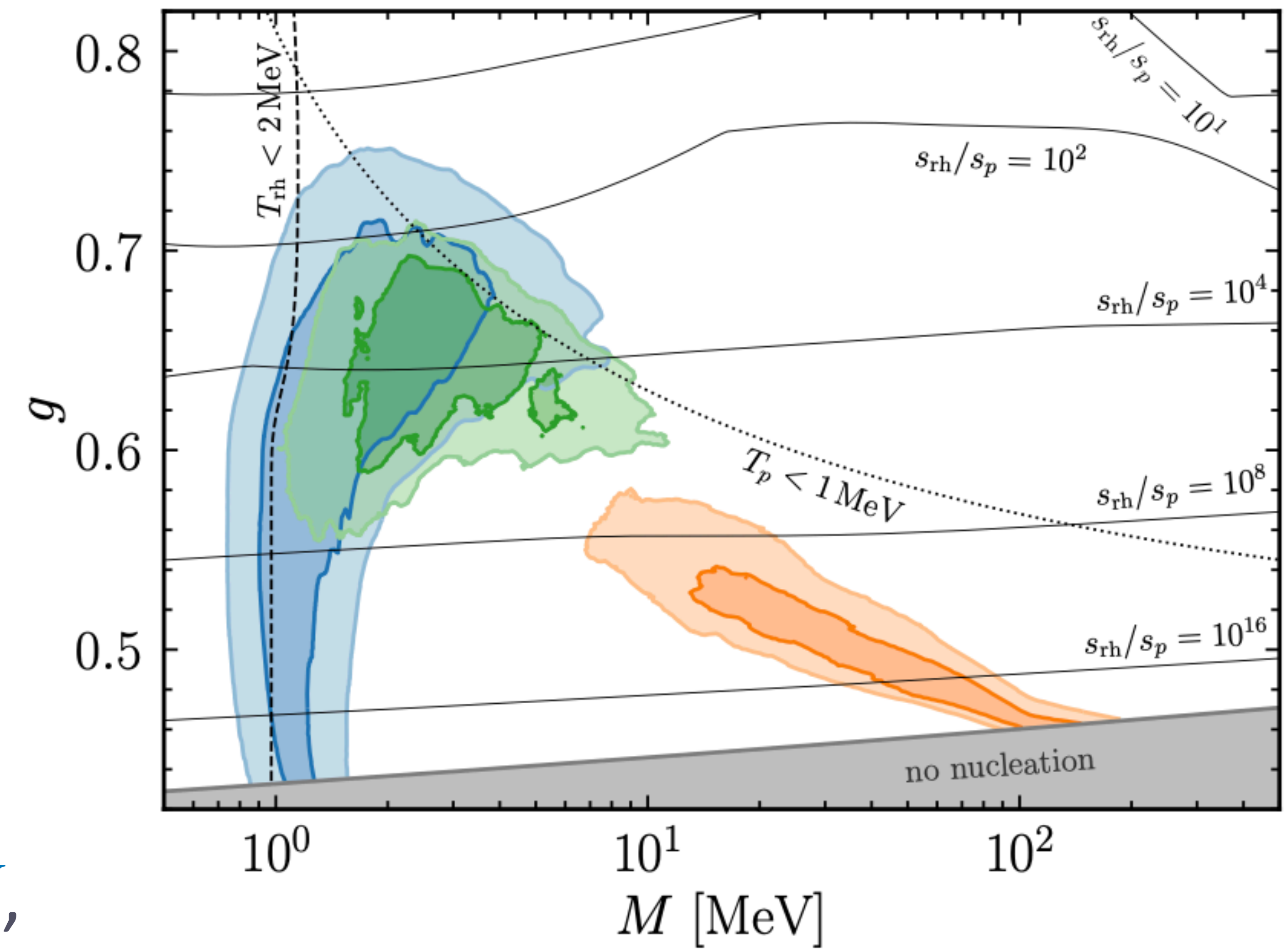
Supercooled phase transitions

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

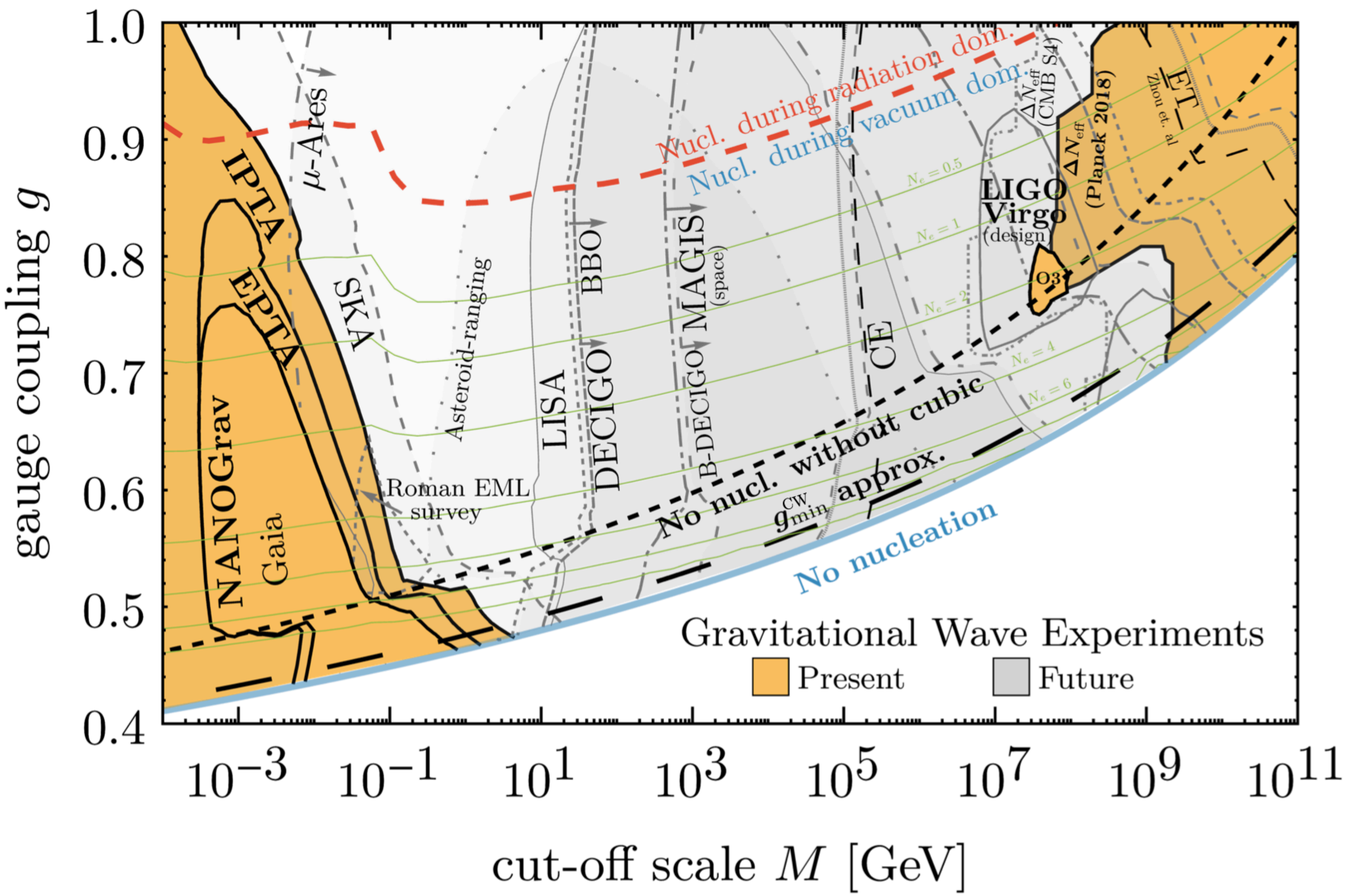
Higgs portal not viable, instead

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

FCC? Or low energy e+e- machine (e.g. MESA in Mainz)

At higher frequencies

Levi, Opferkuch, Redigolo, 2212.08085



LISA will probe above 10 GeV, colliders could fill gap

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: $U(1)_{\rm PQ} \to Z_N$

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

Annihilation triggered by QCD instantons

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

Madge et al, 2306.14856

Axion/ALP domain walls

Madge et al, 2306.14856

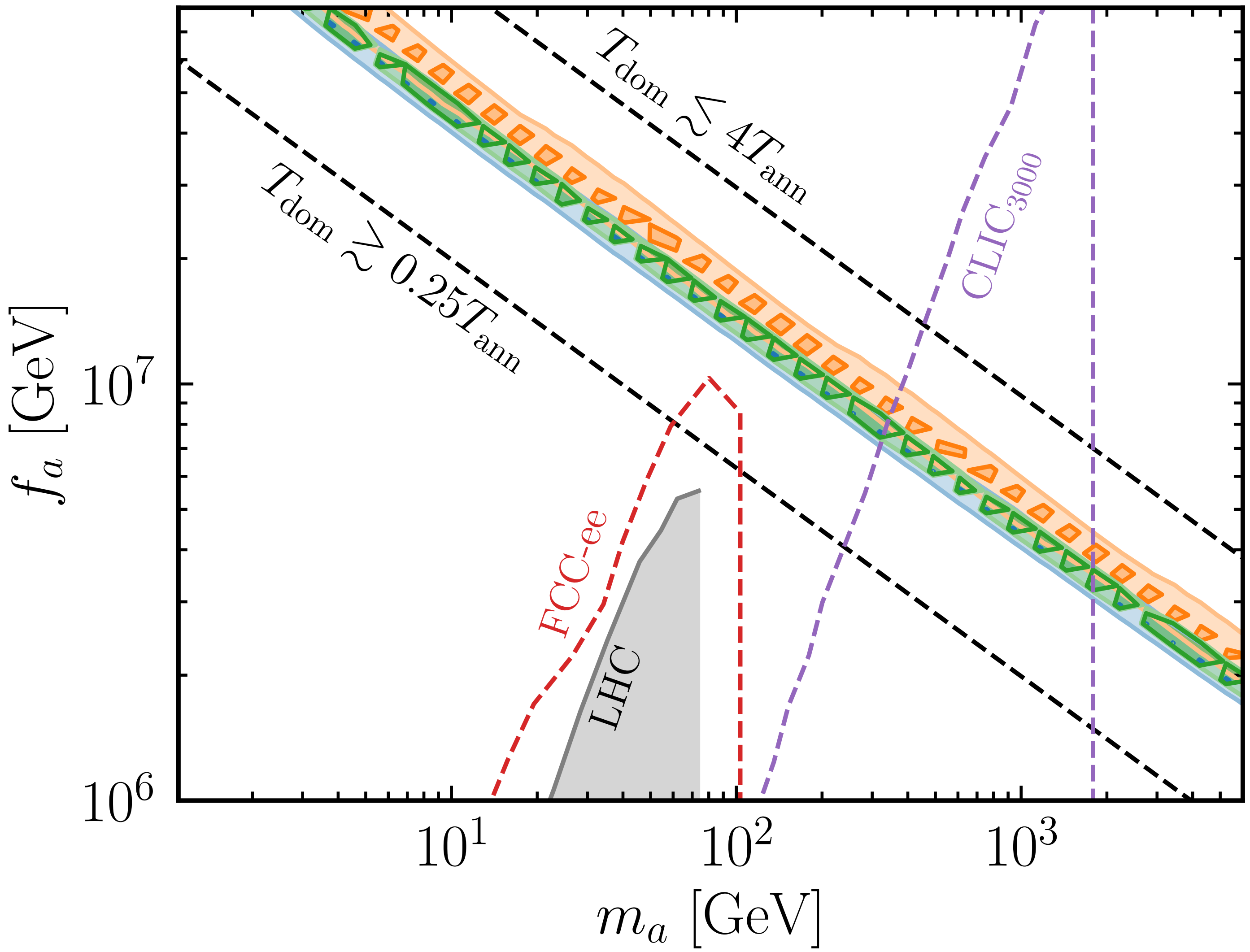
Concrete model: Aligned/clockwork Axions Higaki et al, 1606.05552

Heavy axion “partners” at weak scale

In reach of future colliders Bauer et al, 1808.10323

- Maybe room for improvement (FCC-hh?)

However…



Axion/ALP domain walls

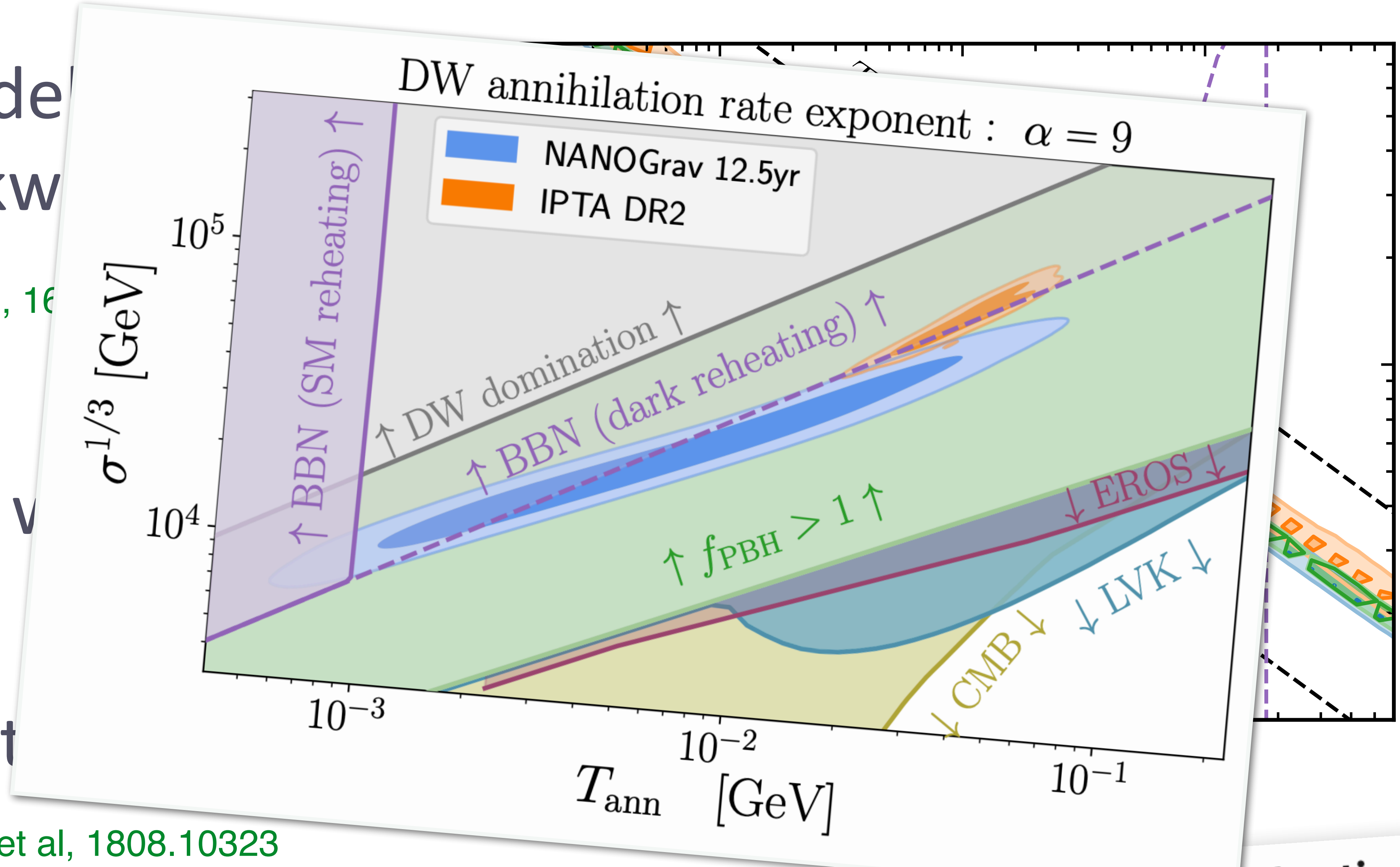
Madge et al, [2306.14856]

Concrete mode…
Aligned/clockw…
Axions Higaki et al, 16…

Heavy axion "partners" at v… scale

In reach of fut… colliders Bauer et al, 1808.10323

▶ Maybe …



Domain wall interpretation of the PTA signal confronting black hole overproduction

Yann Gouttenoire (Tel Aviv U.), Edoardo Vitagliano (Hebrew U.)

Jun 30, 2023

Summary

FCC-ee/hh should have sensitivity to GW sources in the LISA frequency band

BSM-Higgs/SMEFT important benchmark scenario

Dark matter, baryogenesis, strong CP also motivate new physics that connect GWs & FCC

- Do we have enough benchmark models

Low frequency stochastic GWBG has been observed, could be (partially) due to new physics

- Possible collider connection should be further explored, it is not impossible (but might be difficult)!

If we see GWs, how do we solve the inverse problem?

- Again, other probes (FCC) help. How to connect?
- Lesson from LHC: Simplified models with Lagrangians, EFTs, “super-models”

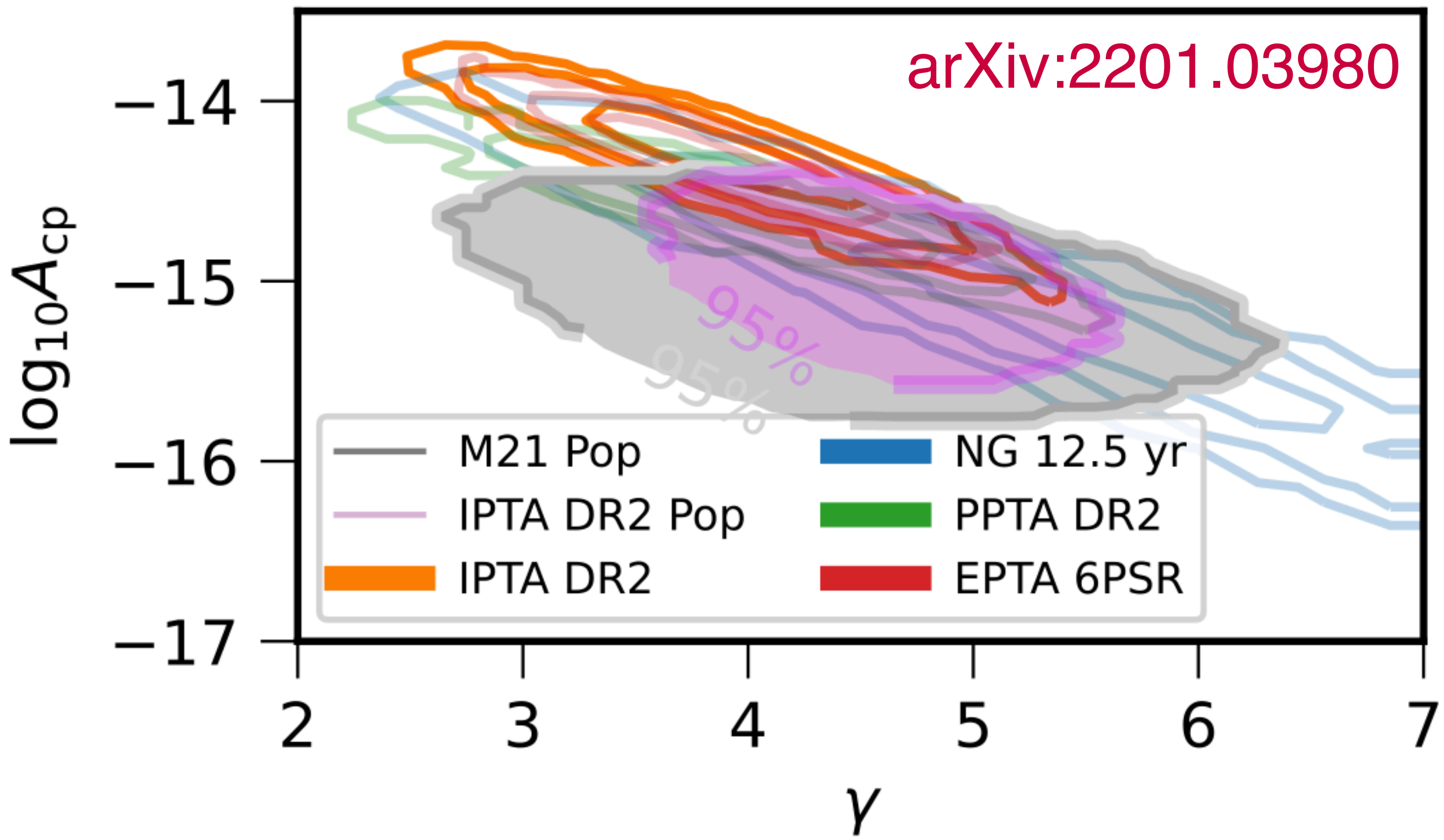
What is a Pulsar Timing Array?

Not an anomaly?

There is an expected background from supermassive black hole binaries (SMBHB)!

Expected slope of $\gamma = 13/3$, but can vary in practice

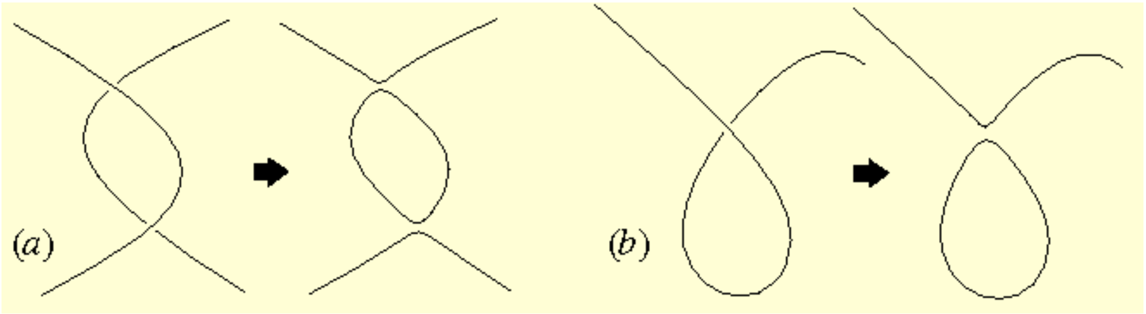
Amplitude a bit high for pure Astro signal

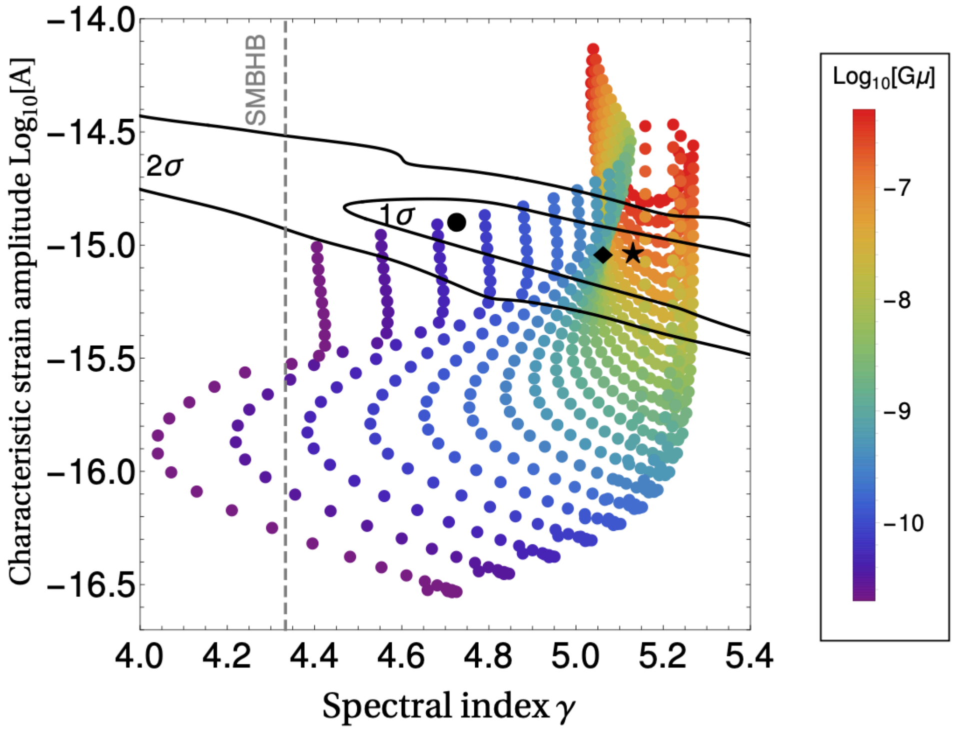


- Room for new physics contribution!

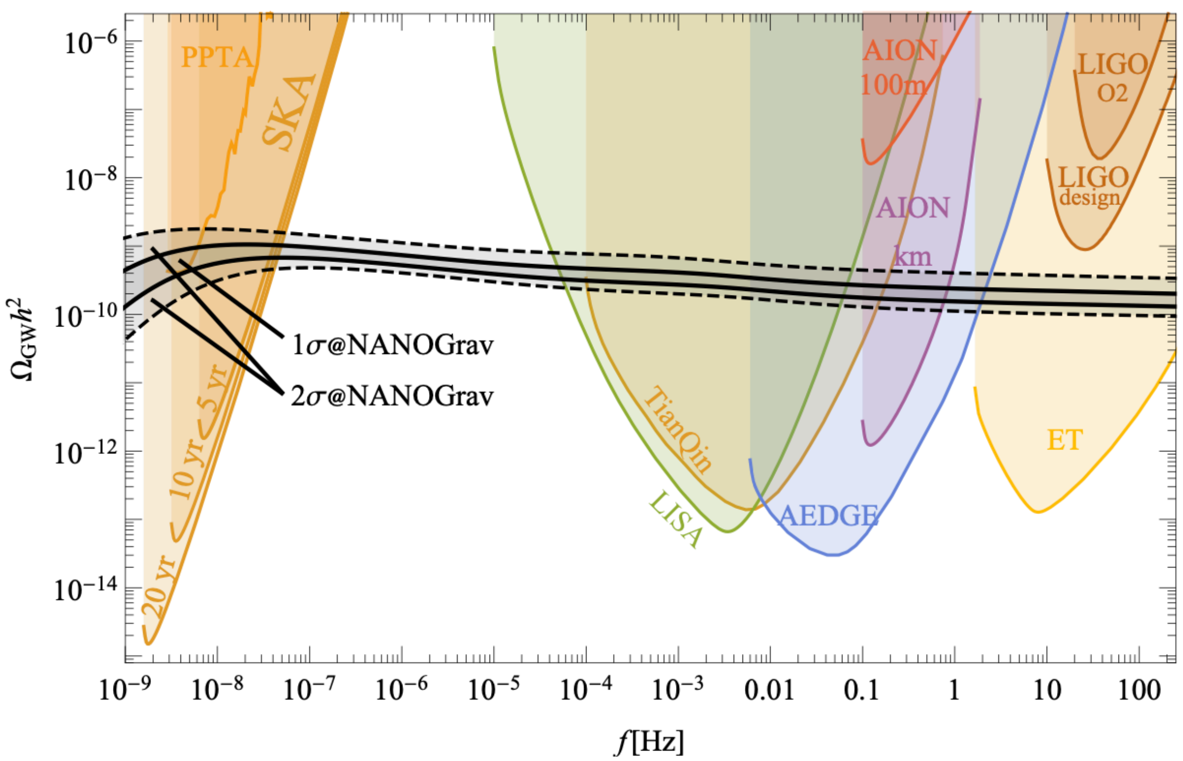
Simple power laws: Inflation or cosmic strings

Strings work better though!



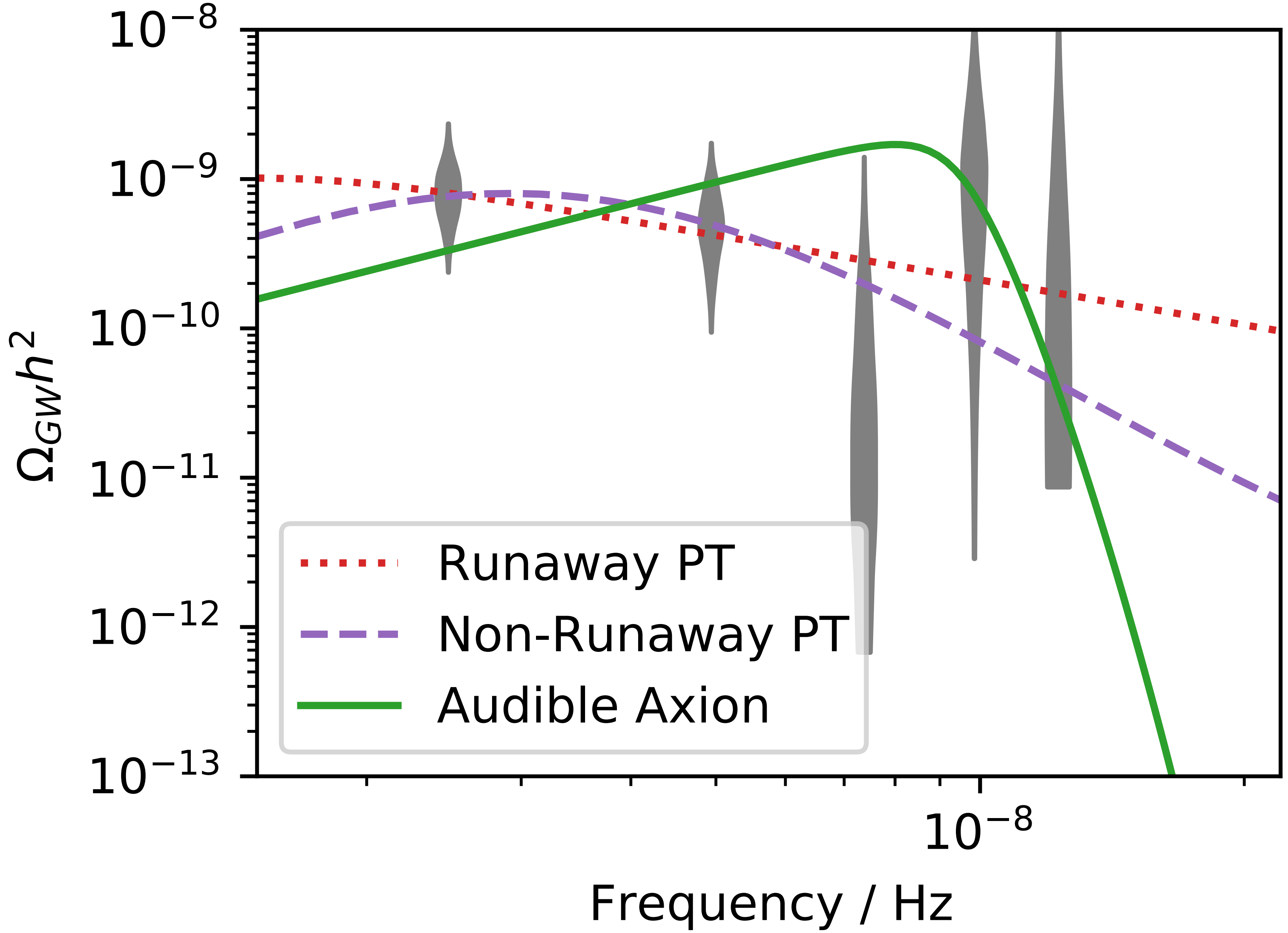


Blasi, Brdar, Schmitz, 2009.06607



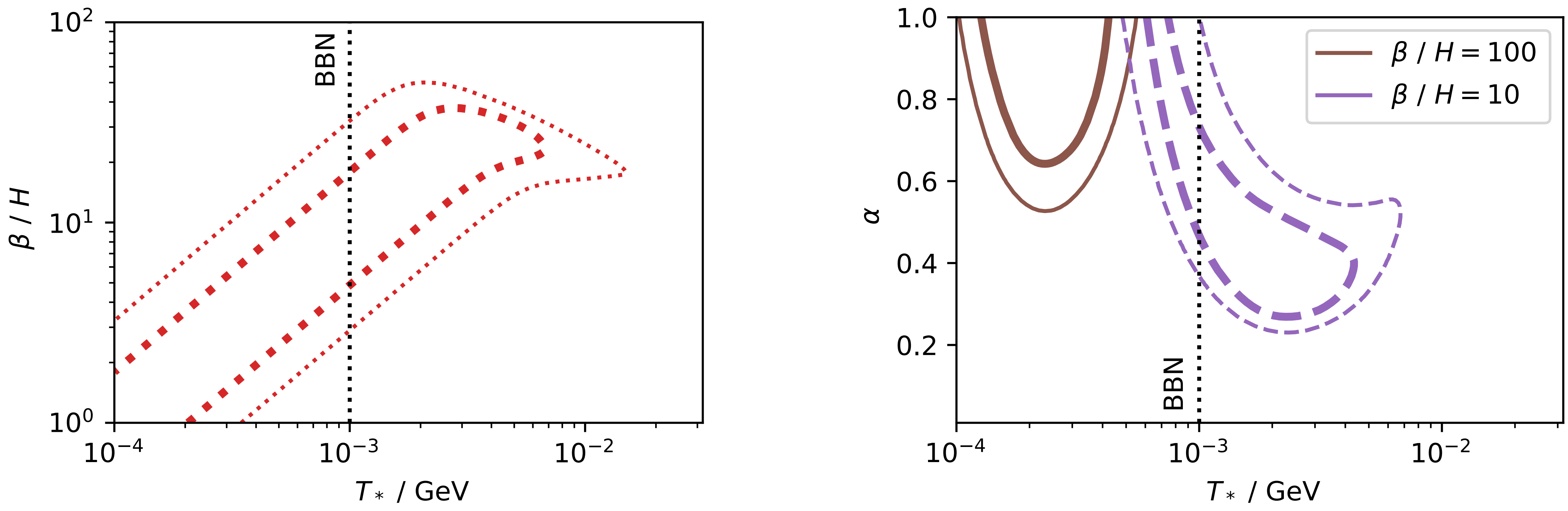
Ellis, Lewicki, 2009.06555

Broken power laws: PTs and axions



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



Generic PT parameterisation, best fit with PT at temperatures in few MeV range

A dark sector at the few MeV scale? X17?!? Neutrino masses?

Wolfram Ratzinger & PS, 2009.11875

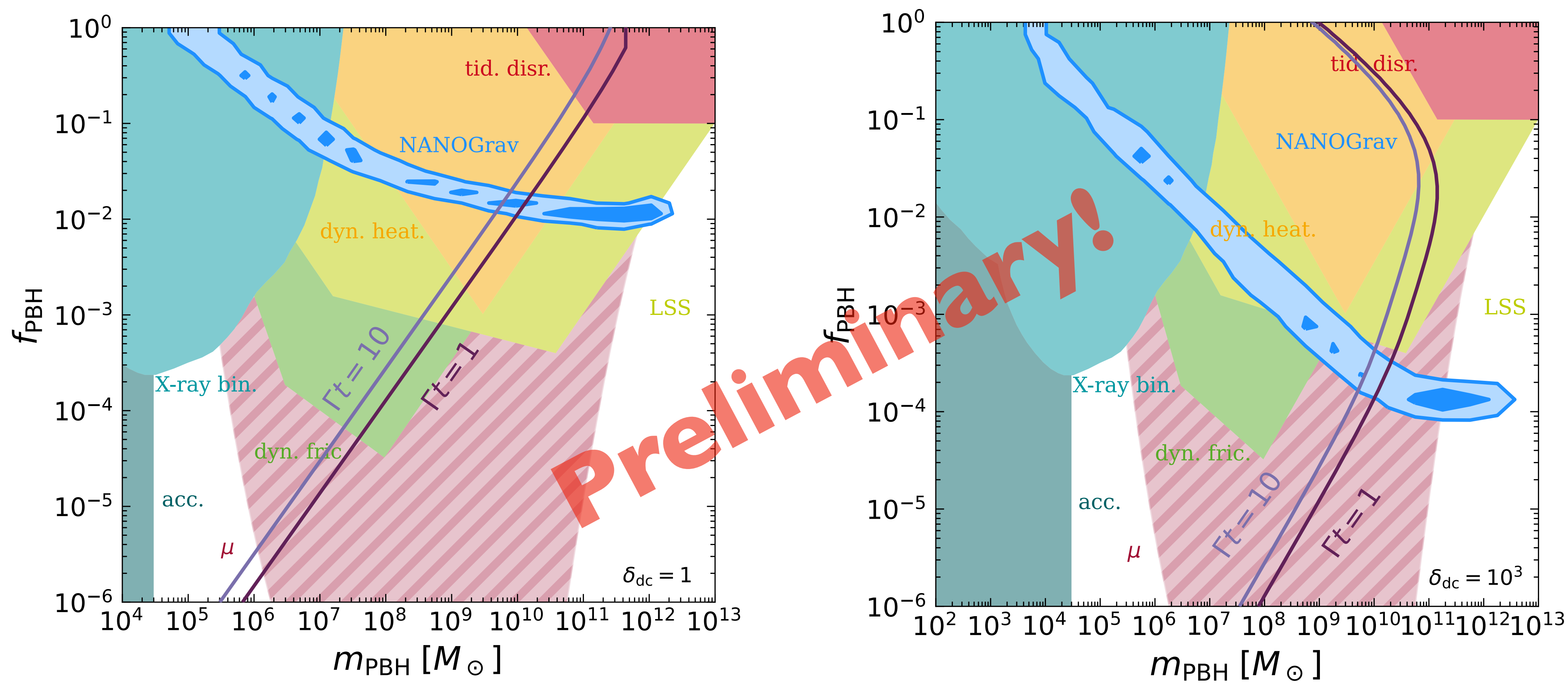
More BHs?

Signal from mergers “stupendously” large primordial BH?

Atal, Sanglas, Triantafyllou, 2012.14721

Only possible with large clustering!

Depta, Schmidt-Hoberg, PS, Tasillo, in preparation



Model discrimination

GW spectra, chirality

- With more PTA data (+ other GW detectors)

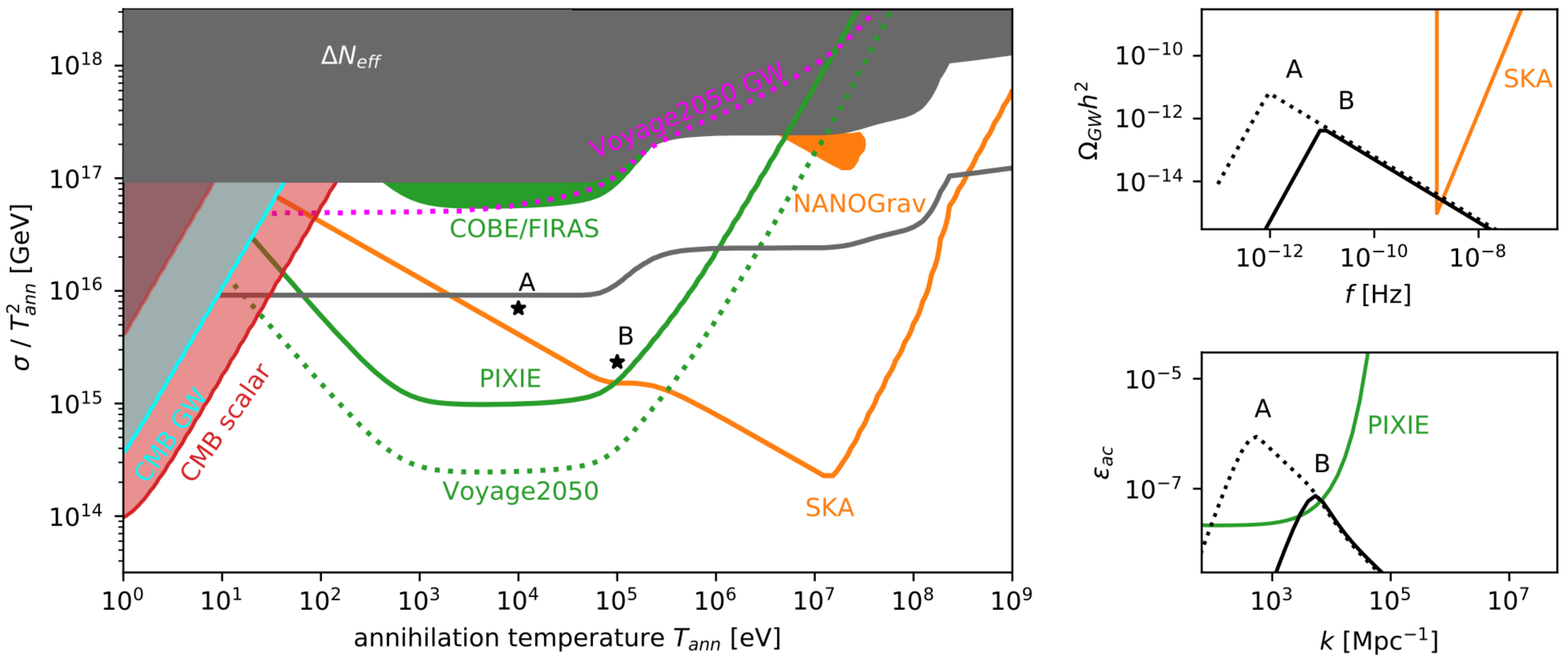
Cosmology

- Many sources contribute to N_{eff}, should not upset BBN
- Requires concrete models

CMB spectral distortions

- Strong GW sources imply large anisotropies “somewhere”
- Anisotropies couple at least gravitationally to SM plasma
- We are close to CMB decoupling → spectral distortions

Example GW source: Annihilating domain walls



Spectral distortions already probe parameter space

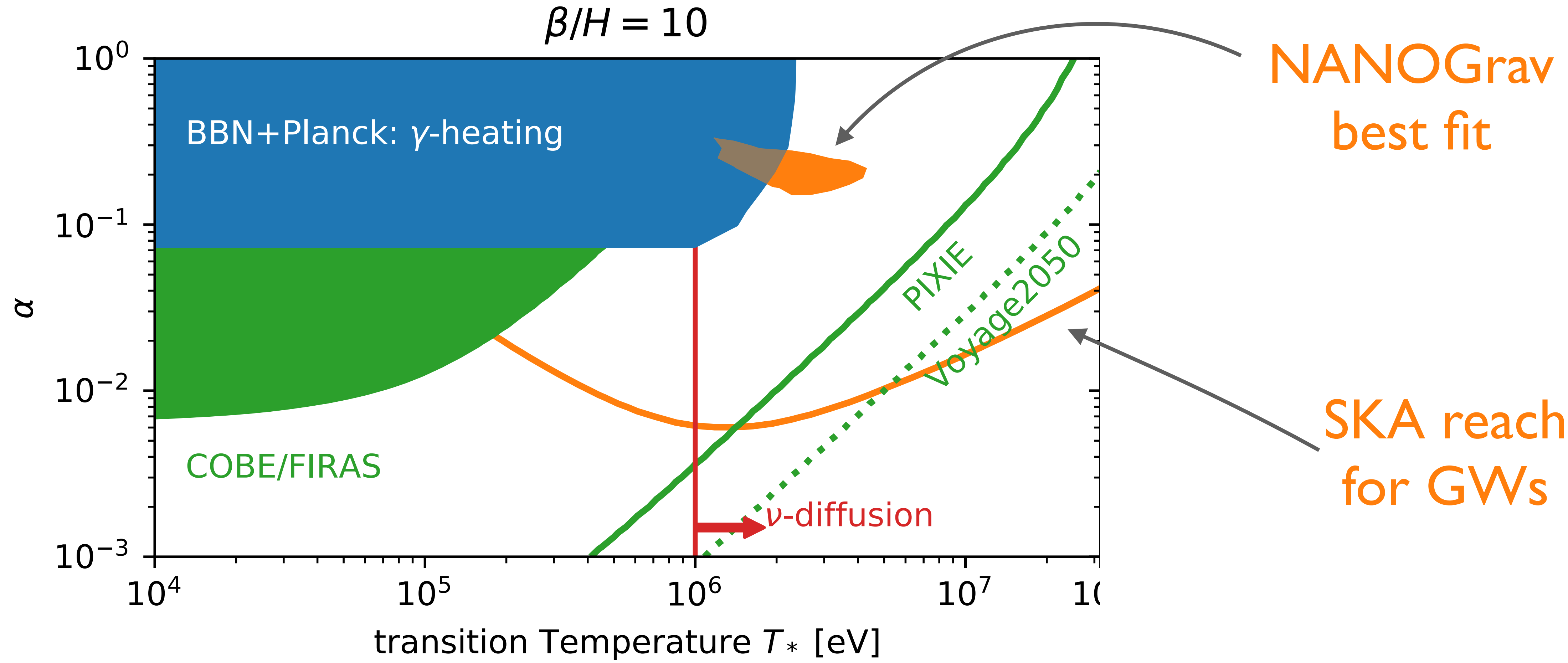
Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

Probing sub-MeV phase transitions

Can also directly probe the scalar (density) fluctuations induced by PTs in a dark or visible sector



More sensitive! Multi-messenger cosmology!

Ramberg, Ratzinger & PS, 2209.14313

Summary

GWs offer new window into the early Universe

- A stochastic GW background could tell us about unknown dynamics in the early Universe, pre-CMB

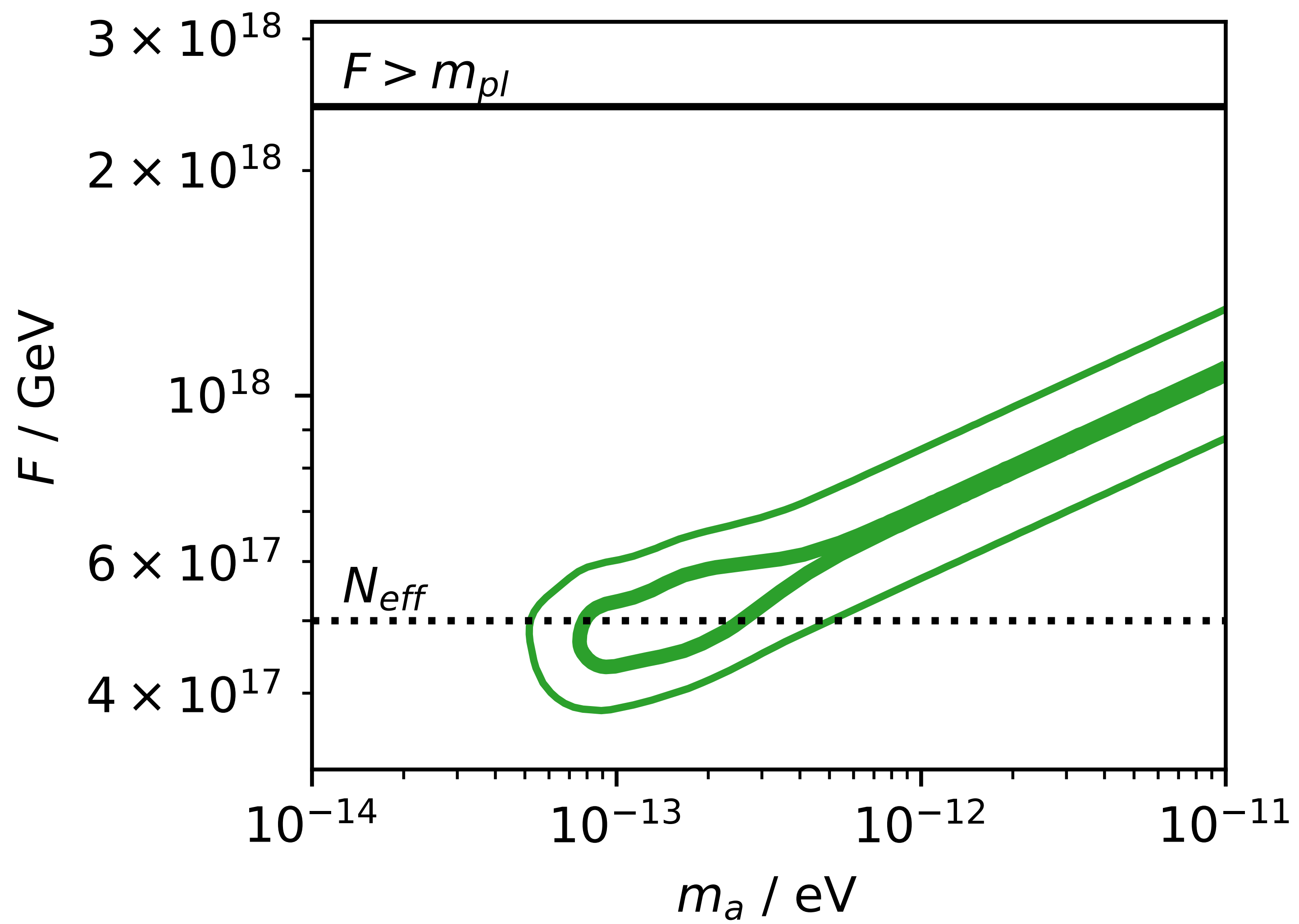
PTA data shows first evidence of such a GW background

- Lot more data expected in the coming years
- Should eventually see SMBHB signal, plus maybe a new physics contribution :)

Model discrimination will require additional astro/cosmo data, e.g. spectral distortions, $N_{\rm eff}$, …

Lot of fun to work on this right now!

Example: Audible Axion



Parameter reconstruction already possible

Non-trivial constraints from cosmology (N_{eff})

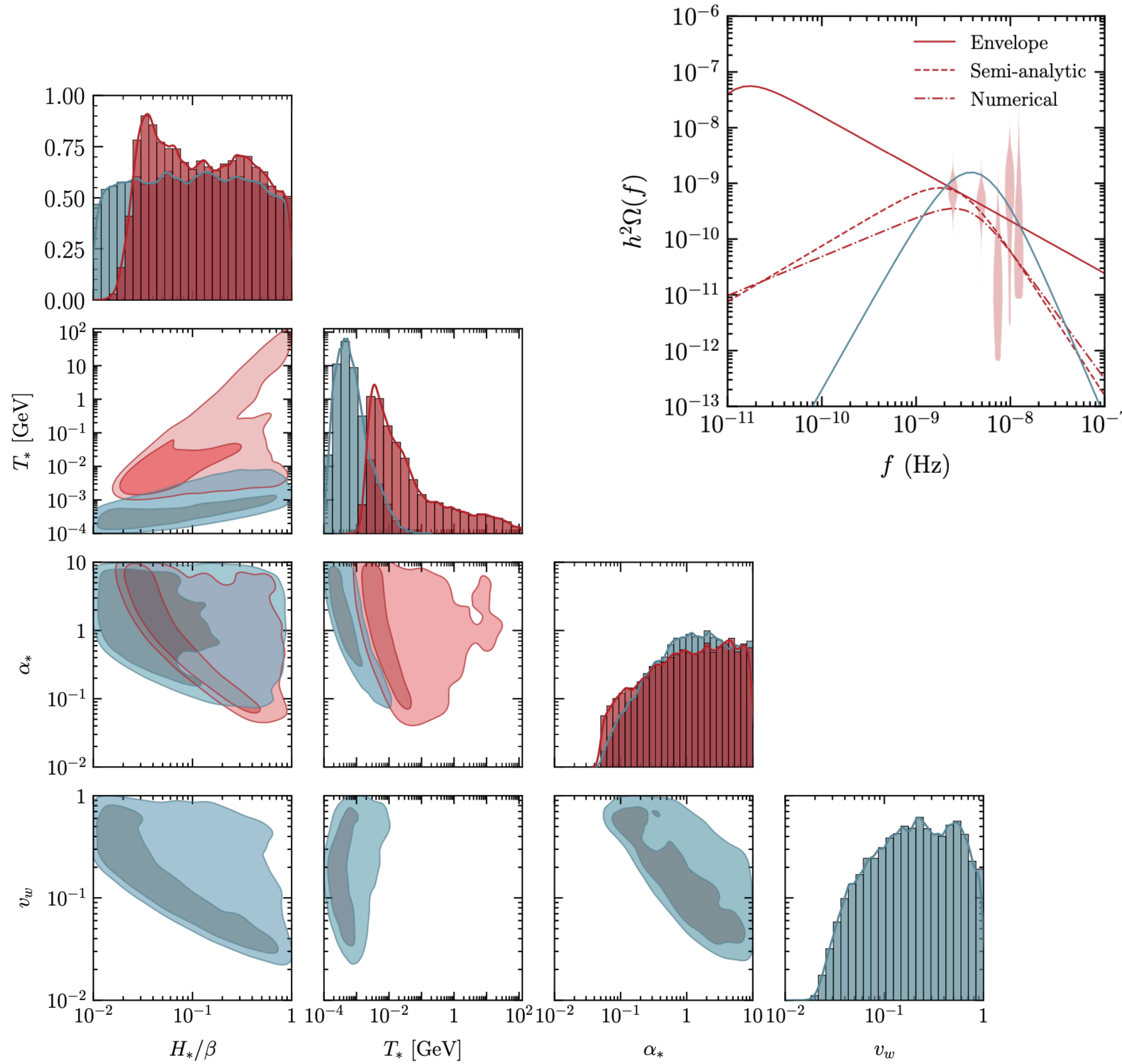
Wolfram Ratzinger & PS, 2009.11875

NANOGrav search for GWs from PTs

Fit to full timing data, including all PT parameters

Assuming either sound wave (blue) or bubble collision(red) source

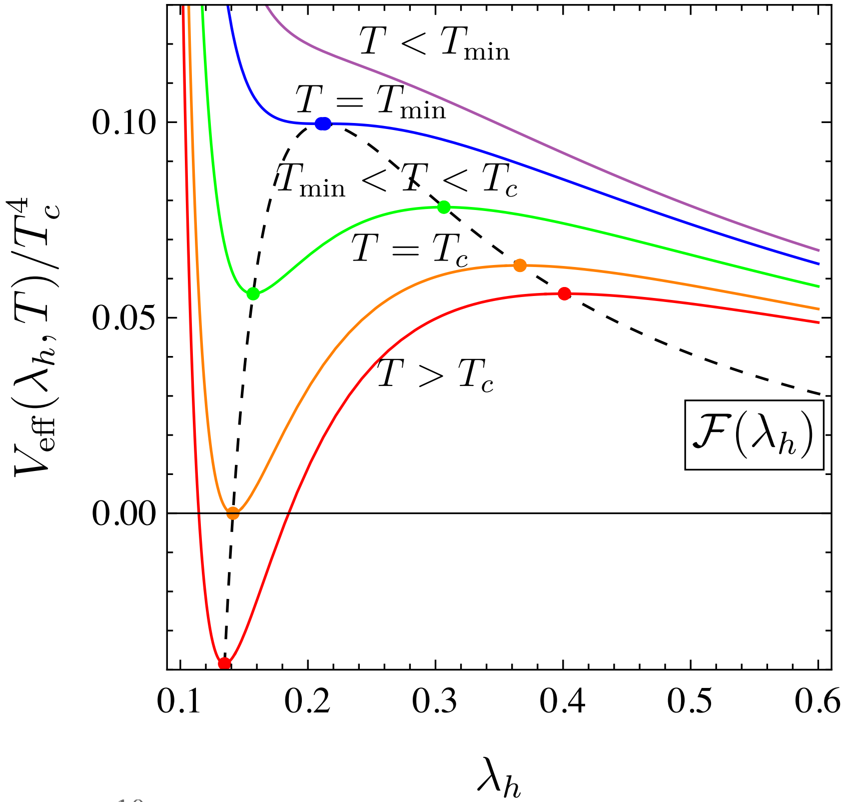
NANOGrav collaboration, 2104.13930



Strongly coupled PTs are also difficult

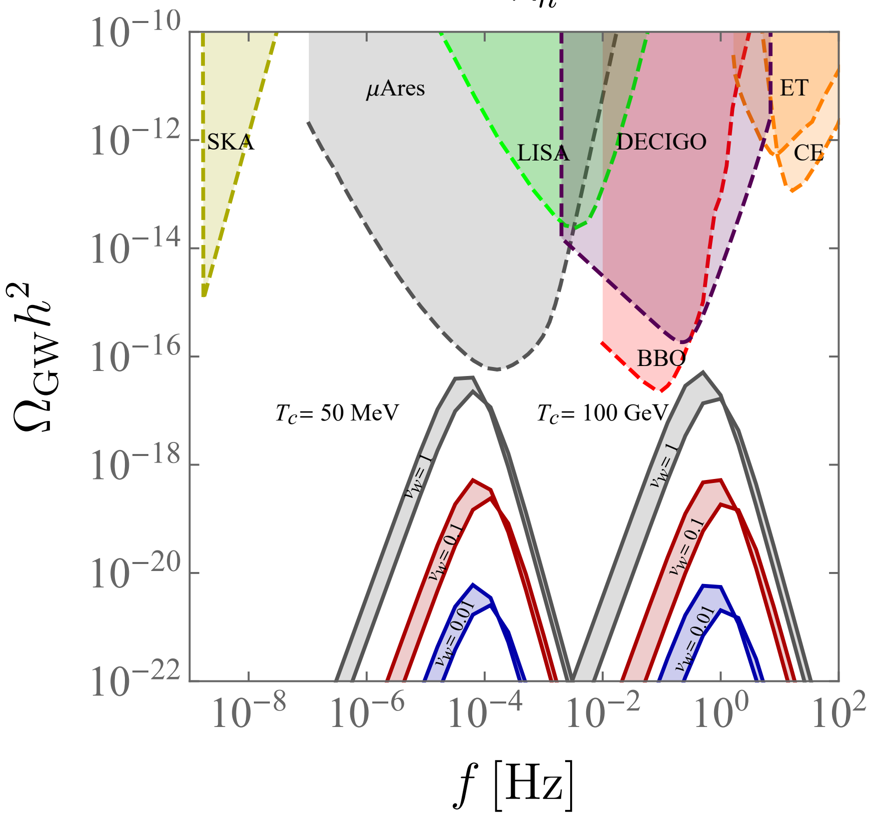
Computed thermal effective potential in improved holographic QCD

- Fit to reproduce finite T lattice data



First prediction for GW spectra of QCD-like dark sectors from holography

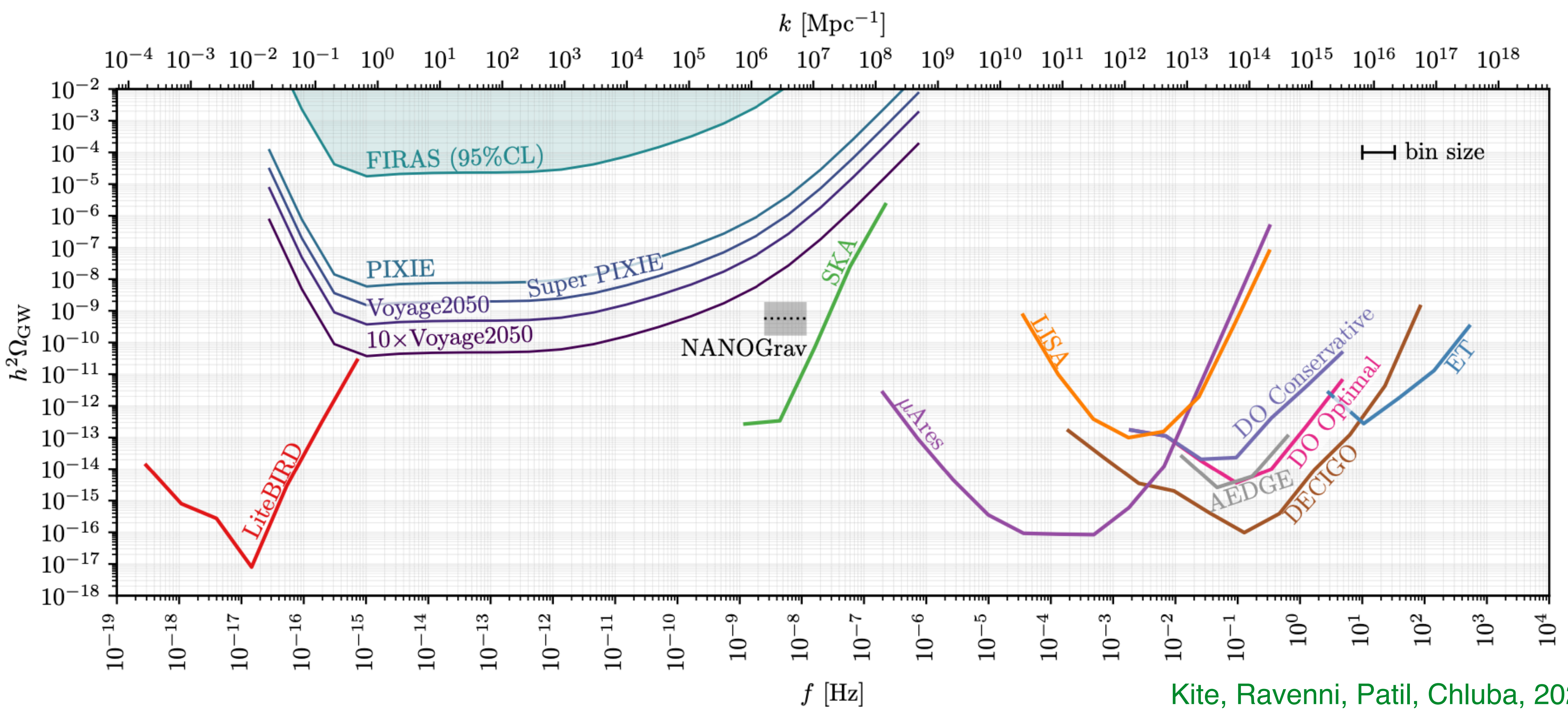
Enrico Morgante, Nicklas Ramberg, PS, in preparation



except for the wall velocity…

Probing sub-MeV phase transitions

Very low frequency GWs induce CMB spectral distortions



Kite, Ravenni, Patil, Chluba, 2021

Probe sources that give peaked GW spectra (like PTs)

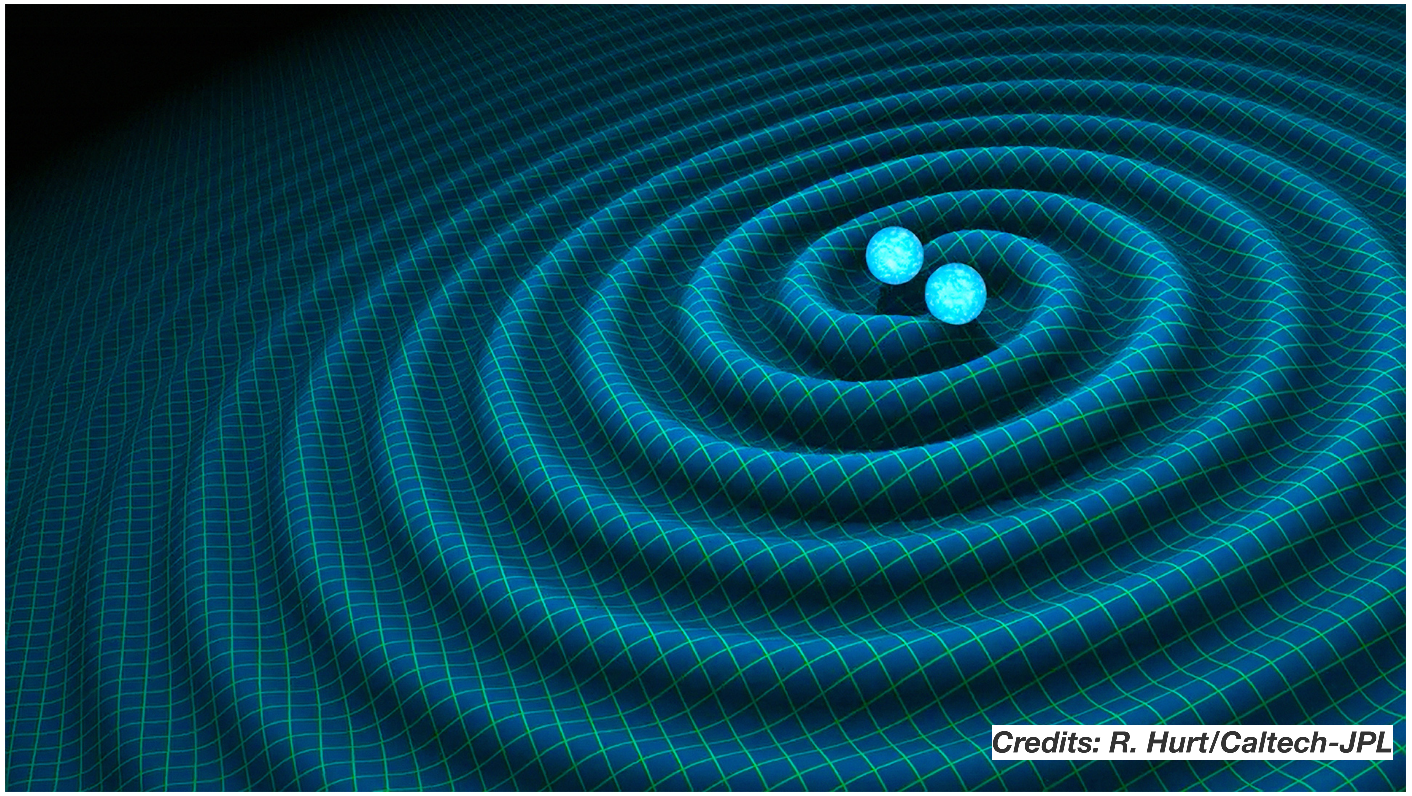
Gravitational waves as messengers from the early Universe

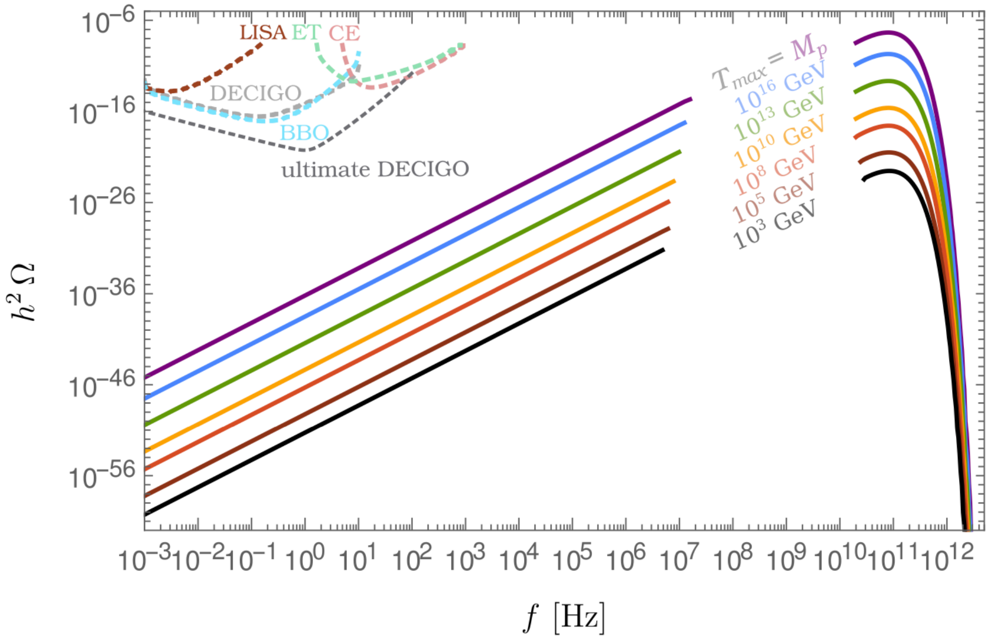
Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

- Stochastic GW background

Or with very very (very!) high temperatures





From Ringwald, Schütte-Engel, Tamarit, 2020

original computation: Ghilieri & Laine 2015

Thermal History