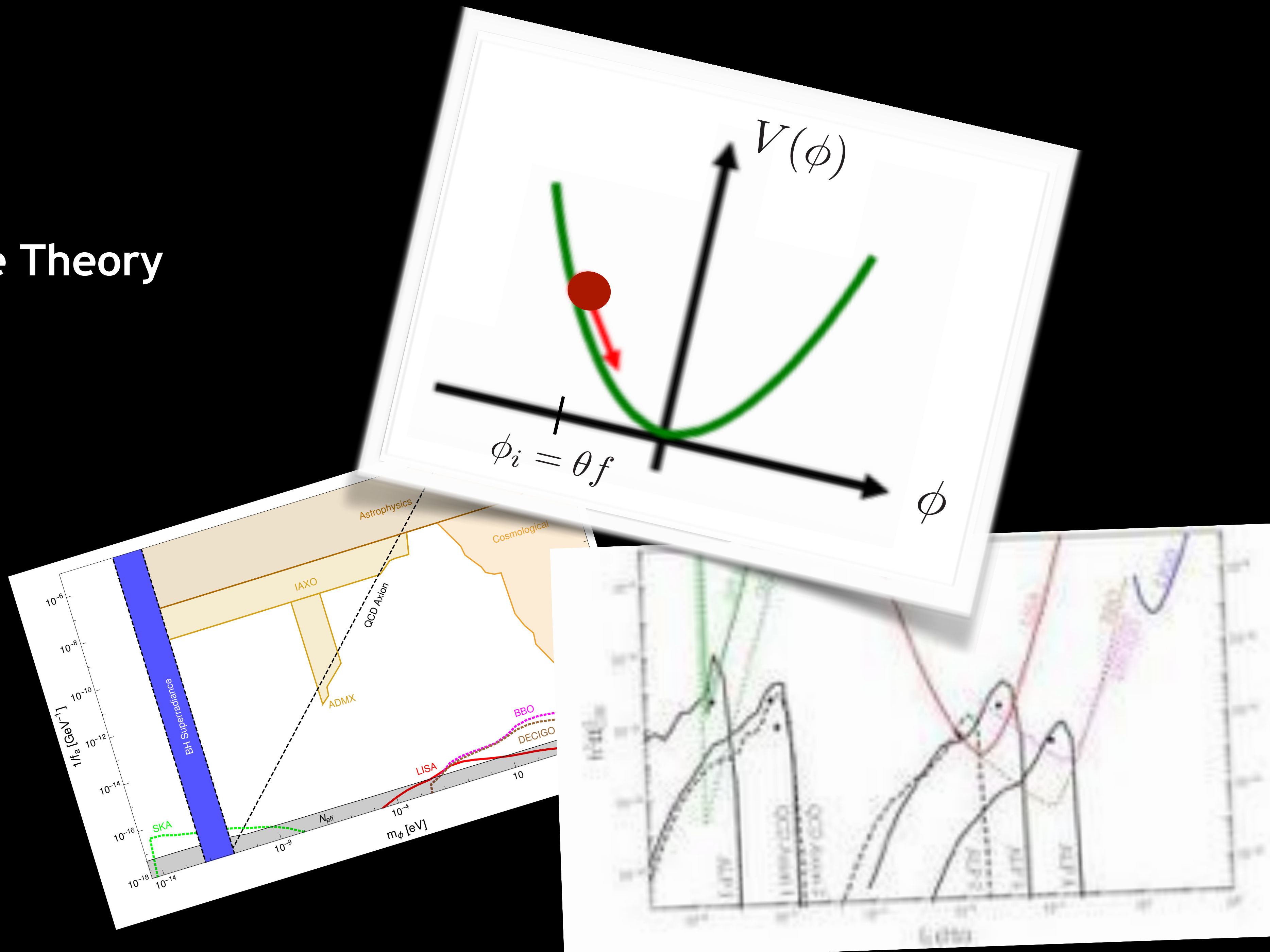
Audible Axions

Particle & Astroparticle Theory Seminar

MPIK Heidelberg
November 25, 2019

Pedro Schwaller
(JGU Mainz)



JG|U PRiSMA+

Overview

- The early Universe and new physics
- Gravitational waves as windows into the early Universe
- Axions, strong CP problem, and dark matter
- Probing axions with GWs

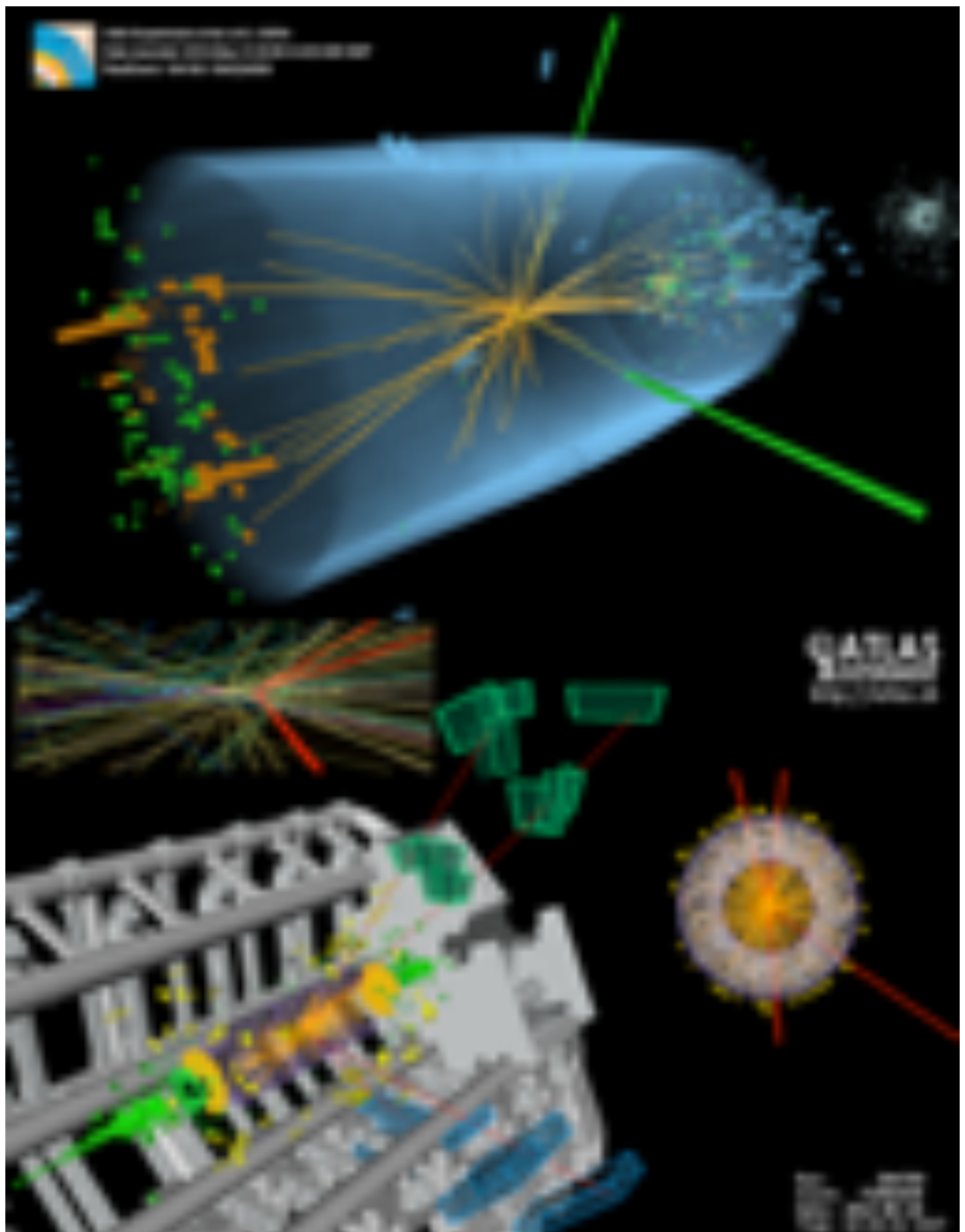
The Standard Model (of particle physics)

Matter

Forces

The Higgs (& nothing else)

Discovery 2012 by ATLAS & CMS



The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

"for the **theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles**, and which recently was **confirmed through the discovery** of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Reasons to go beyond

JG|U

- Curiosity!
  - Is there something else?

- Origin of Matter
- Nature of Dark Matter

Can not be explained within SM

Requires new Physics!!!

- Quark and Lepton Flavour puzzles
- Strong CP problem

Parameterised but not explained in SM

Hints for new Physics

- Inflation, Dark Energy, Reheating…

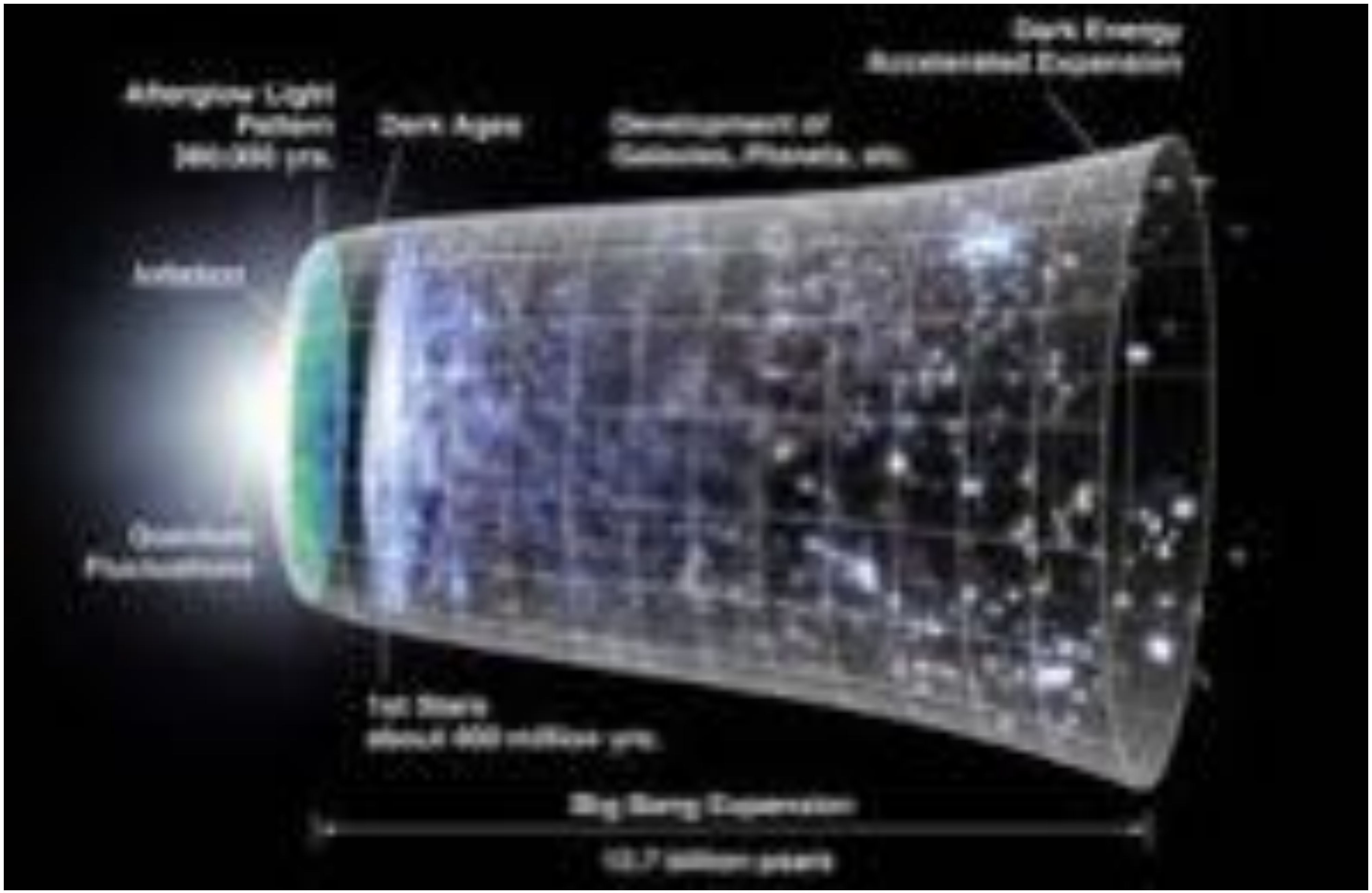
Reasons to go beyond

- Curiosity!
  - Is there something else?
- Origin of Matter
- Nature of Dark Matter
- Quark and Lepton Flavour puzzles ?
- Strong CP problem
- Inflation, Dark Energy, Reheating…

Connected with Cosmology/early Universe

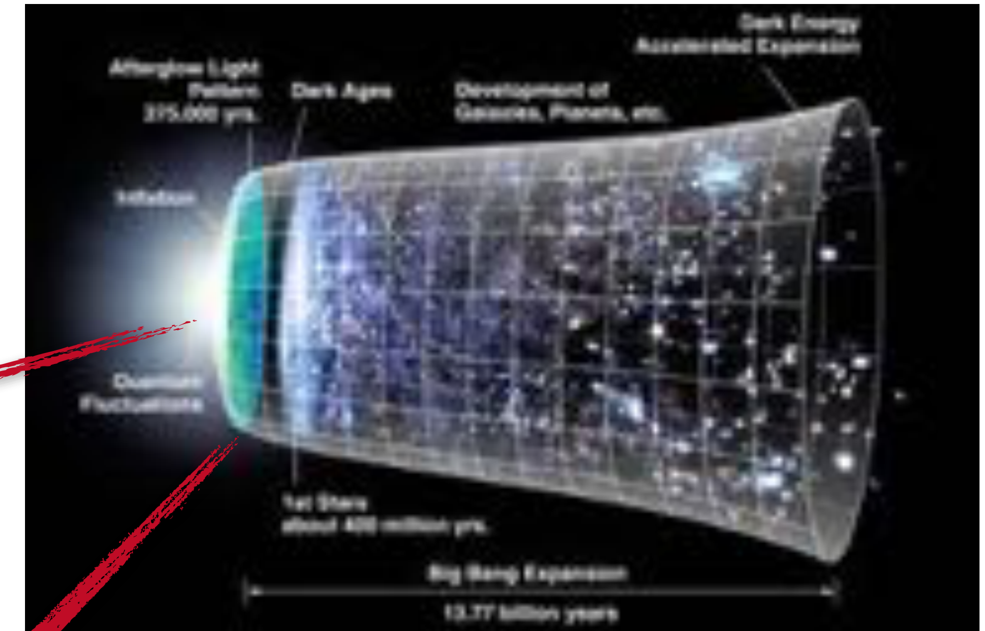
What do we know about the early Universe?

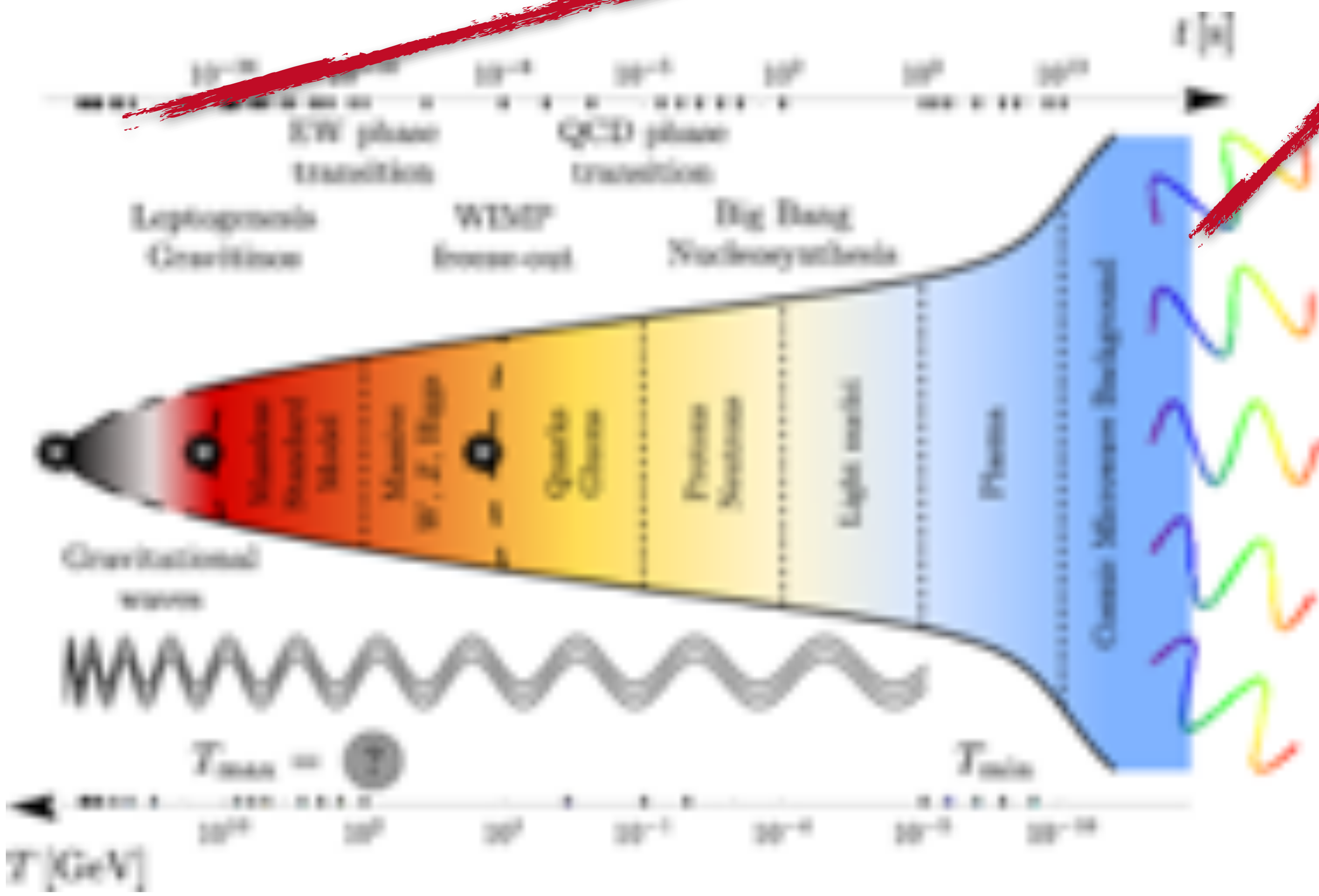
Thermal History



Gravitational Waves?

- First direct observation in 2016
- New window into early universe



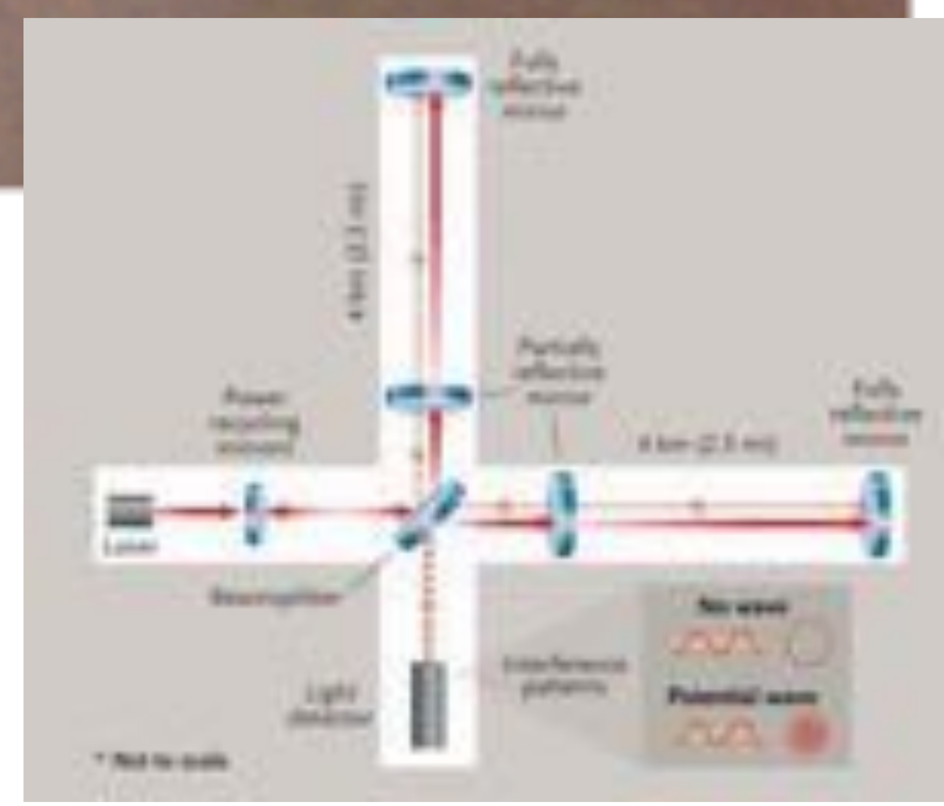


e.g.
- Electroweak symmetry breaking
- Baryogenesis
- Dark matter production

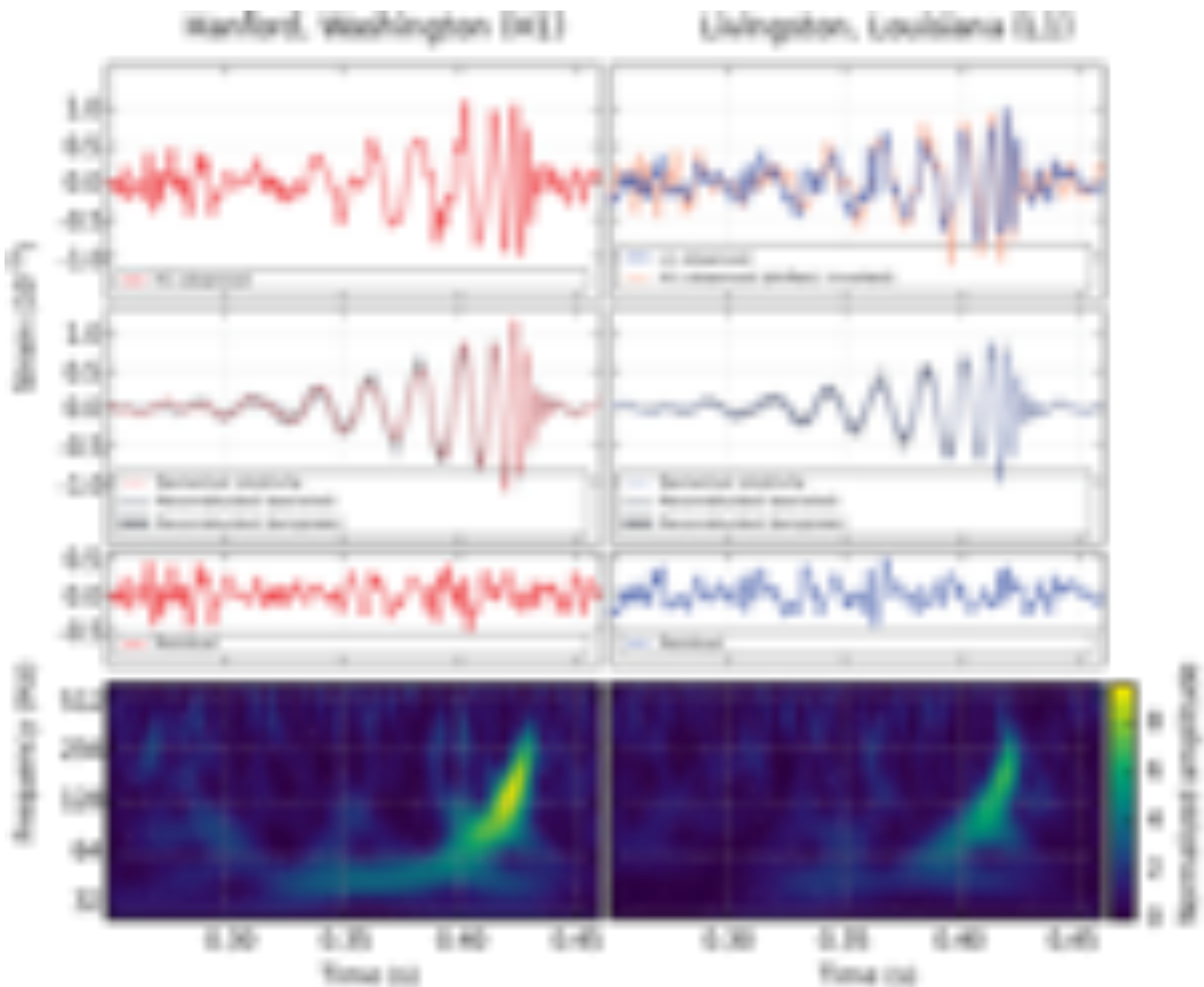
Physics Highlight 2016

LIGO

Hanford, Washington, USA



Signal

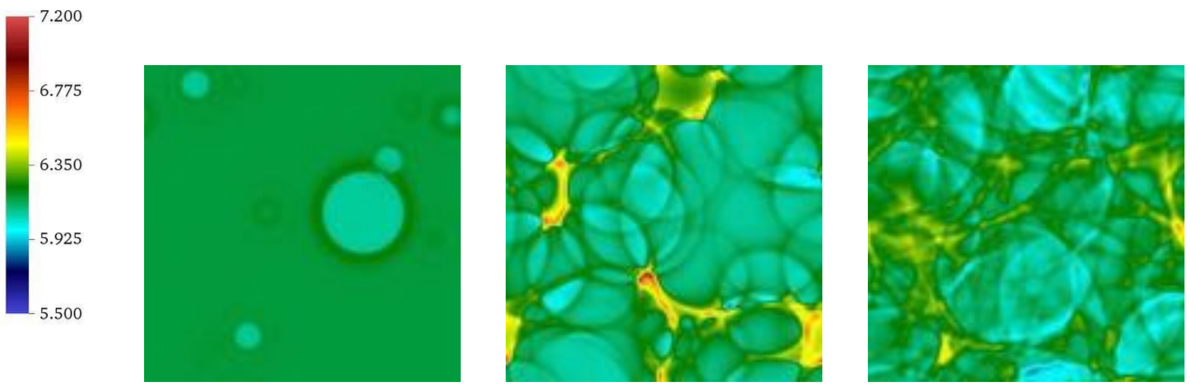


GWs & early Universe

- CMB encodes information about the state of the universe at the time of its emission
  - Densities of matter, radiation, dark matter
  - Fluctuations (seeds for galaxy formation)
  - Hubble rate (interesting discrepancy!)
- GWs could do the same
  - For earlier (and different) times
  - Need a strong source (CMB photons are just there!)

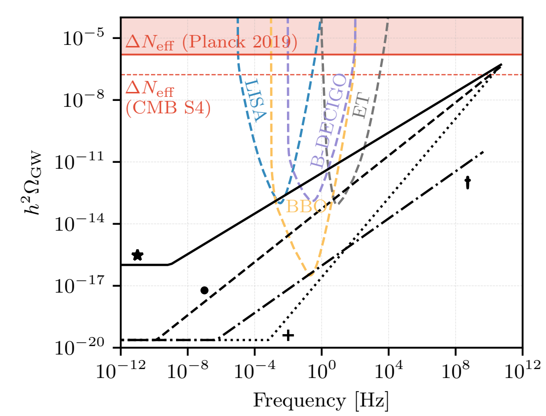
Primordial sources of GWs

- First order phase transitions (symmetry breaking)

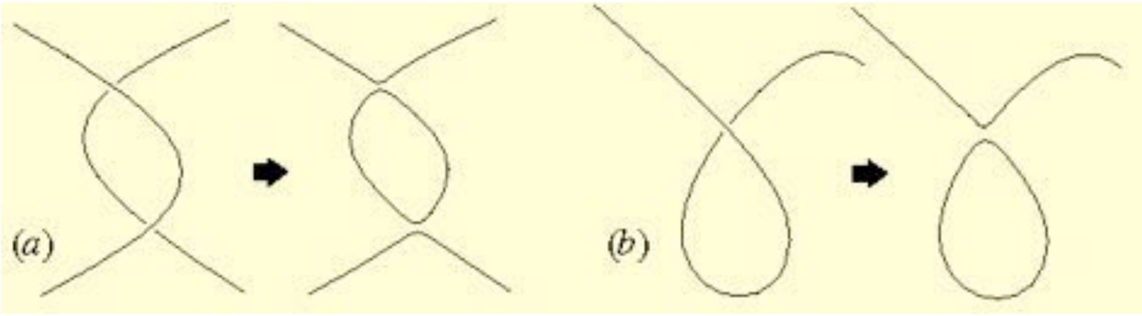


from Hindmarsh et al

- Inflation/Reheating



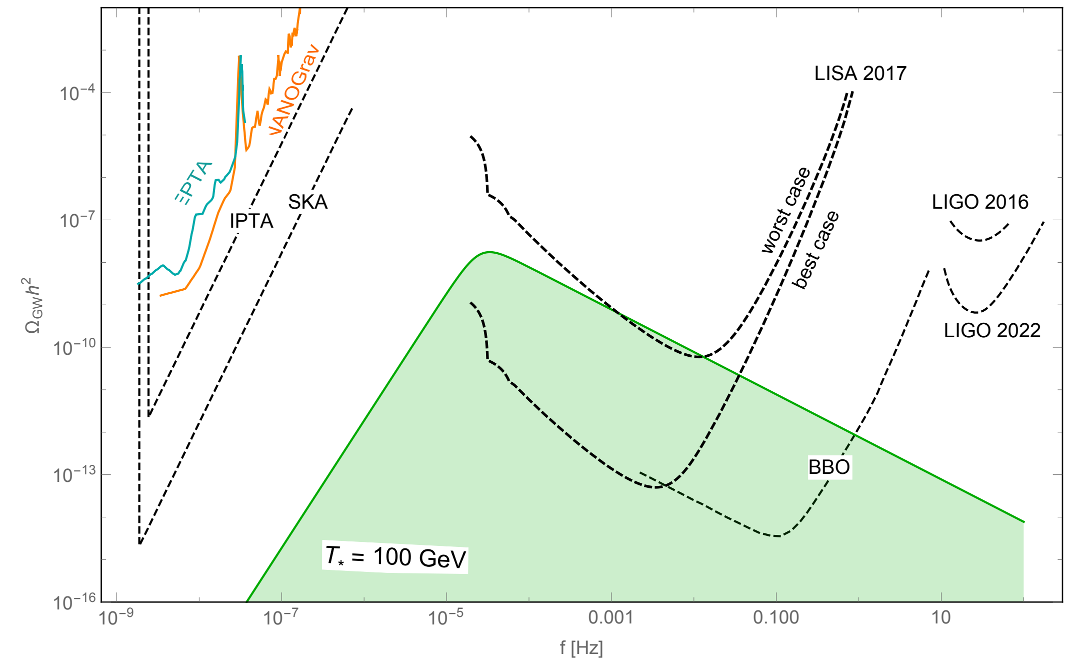
- Cosmic strings



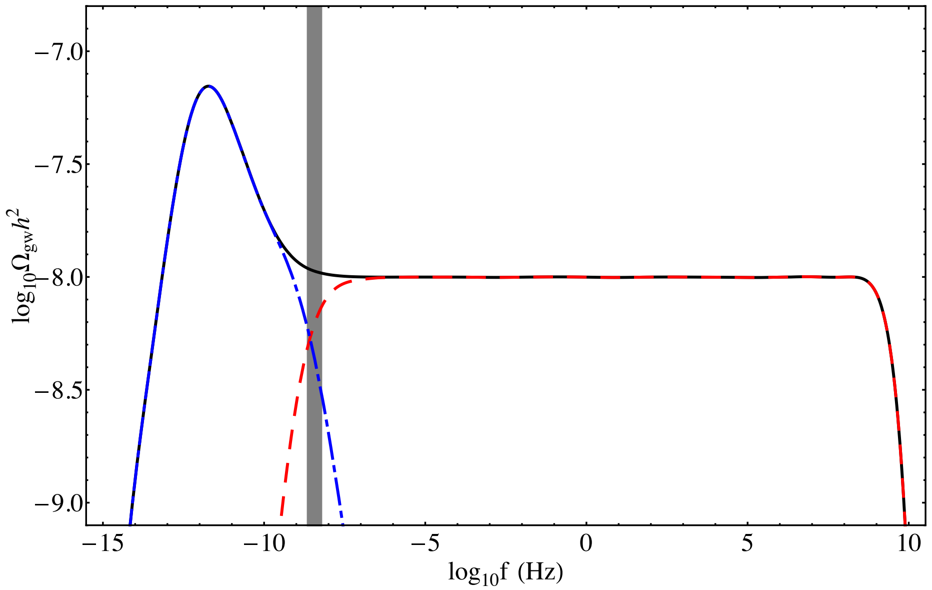
- and now… Axions!

Signal shape and frequency

- Characteristic for source, e.g.
- Phase transition, peak location depends on T_{nuc}

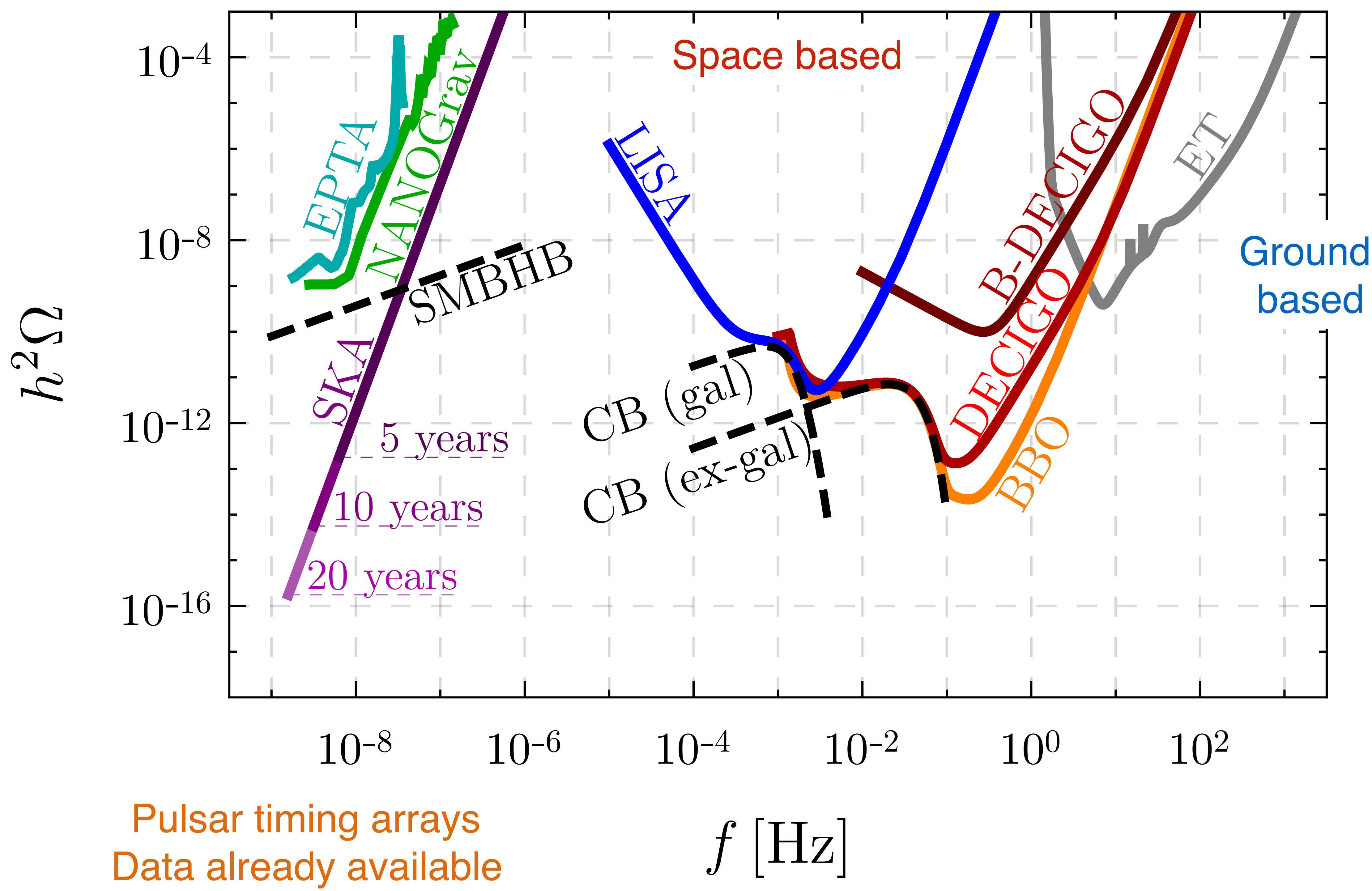


- Cosmic strings



Sanidas, Battye, Stappers, 2012

Frequency ranges



Pulsar timing arrays
Data already available

Axions?

Axions & ALPs

- Strong CP problem

$$\mathcal{L}_{\rm QCD} \supset \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$

with *Θ~1*

- Neutron EDM: $|d_n| \lesssim 10^{-26} \text{e cm} \quad \Longrightarrow \quad \theta < 10^{-10}$

- Axion is dynamical solution

$$\mathcal{L}_{\rm QCD} \supset \left(\theta + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi^2} G\tilde{G}$$

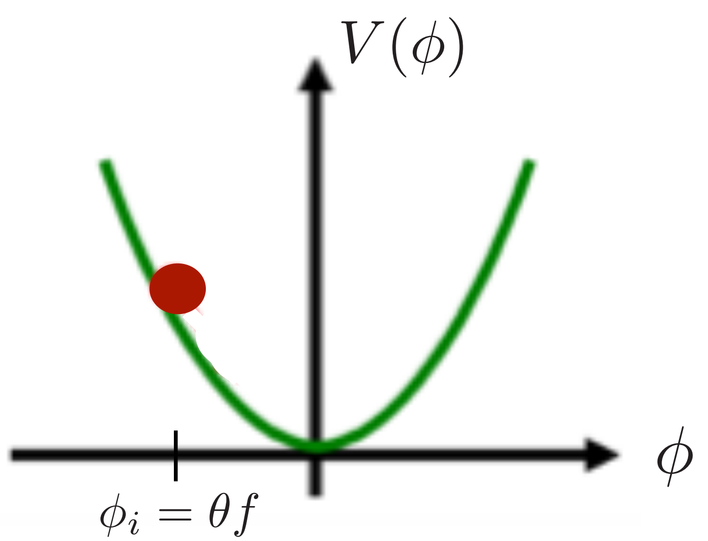
symmetry breaking scale, suppresses couplings to SM

- Ground state has *Θ~0*

Axion misalignment and DM

- Axion EOM

$$\phi'' + 2aH\phi' + a^2 m_\phi^2 \phi = 0$$



- Starts rolling when $H \sim m_\phi$

- Redshifts with a^{-3} , i.e. like non-relativistic matter

- Candidate for non-particle dark matter

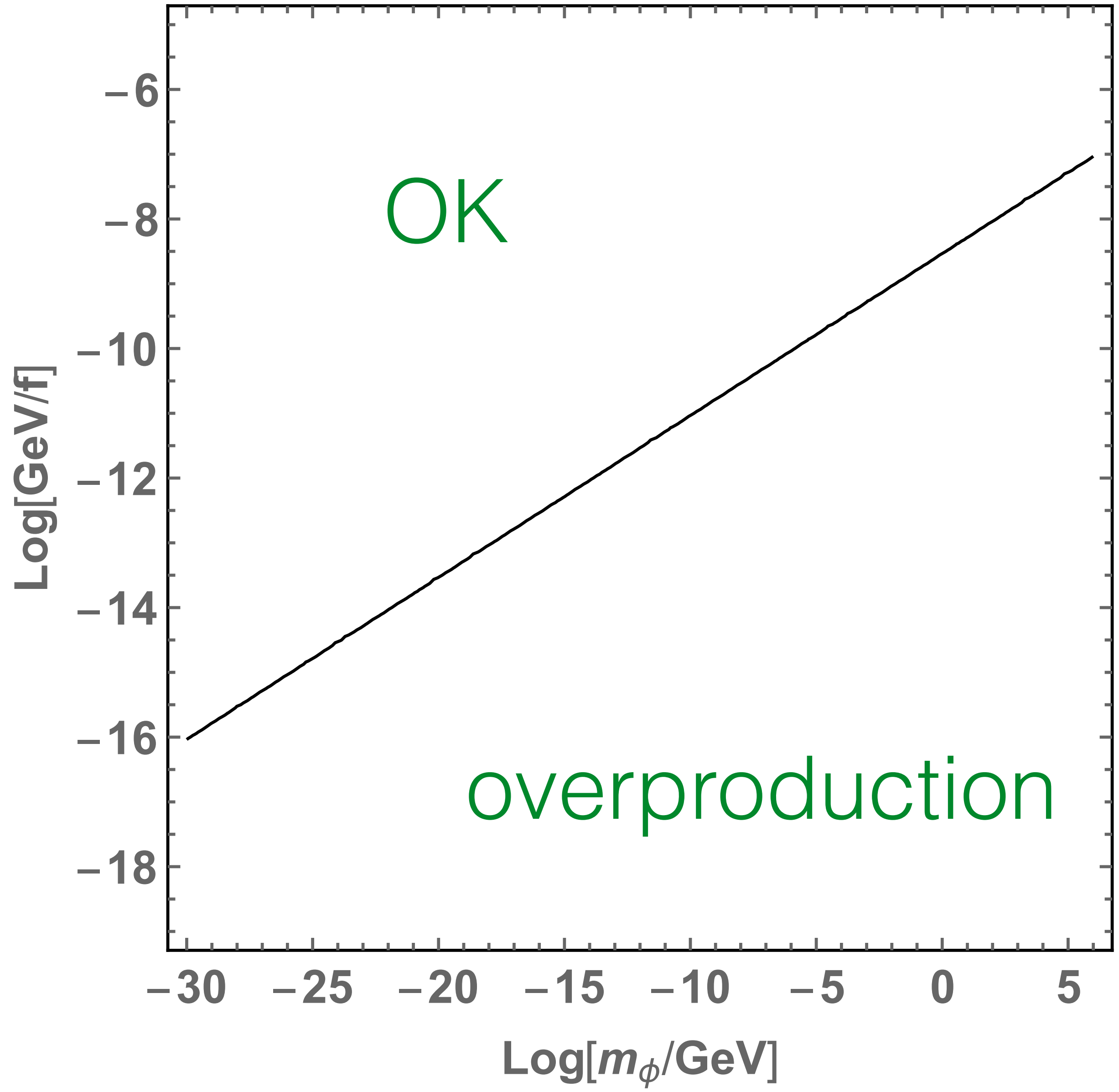
Relic abundance

- Energy density $$\rho_\phi = \frac{1}{2} m_\phi^2 \theta^2 f^2$$
- Hubble $$m_\phi \sim H_{\rm osc} \sim \frac{T_{\rm osc}^2}{M_P}$$
- Energy fraction $$\frac{\rho_\phi}{\rho_{\rm rad}} \sim \frac{m_\phi^2 \theta^2 f^2}{T_{\rm osc}^4} \sim \frac{\theta^2 f^2}{M_P^2}$$
- Increases due to redshift

$$\frac{a_{\rm osc}}{a_{\rm eq}} \sim \frac{\sqrt{m_\phi M_P}}{\rm eV}$$

Relic abundance II

$$\Omega_{\rm today} \sim \theta^2 f^2 \frac{m_\phi^{1/2}}{M_P^{3/2}\,{\rm eV}} \qquad\qquad \Omega_{\rm observed} \approx 0.12$$



The Audible Axion

JG|U

- We consider the following effective field theory consisting of an axion-like particle (ALP) ϕ and a massless dark photon X_μ

$$\mathcal{S} = \int d^4x \sqrt{-g}\left[\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}\right]$$

- We assume some explicit breaking of the global symmetry at the scale $\Lambda = \sqrt{mf}$, which generates a mass for the ALP

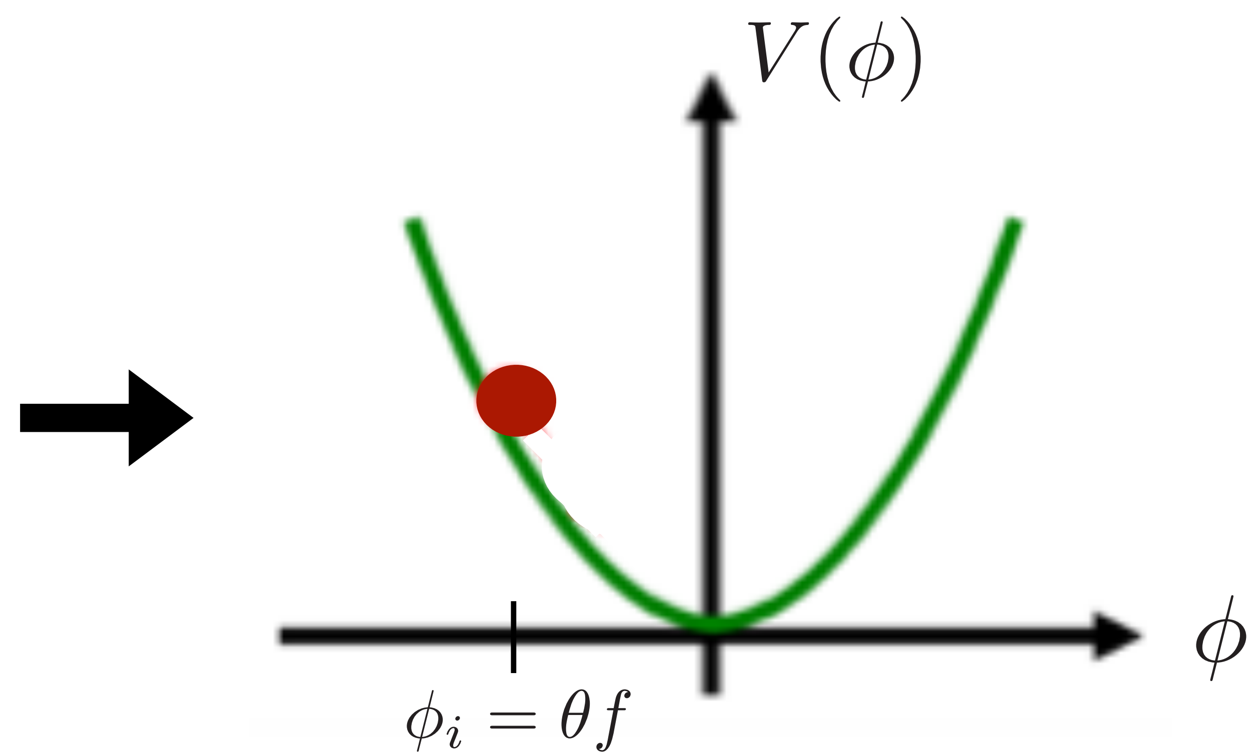
$$V(\phi) = m^2 f^2\left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

$$\phi_i = \theta f\,, \qquad \phi_i' \approx 0\,, \qquad \theta \sim \mathcal{O}(1)$$

Vacuum misalignment

- Since the ALP has no reason to be near the minimum of the potential when it tilts, we generically expect initial conditions of the form

$$\phi_i = \theta f \,, \qquad \phi_i' \approx 0 \,, \qquad \theta \sim \mathcal{O}(1)$$

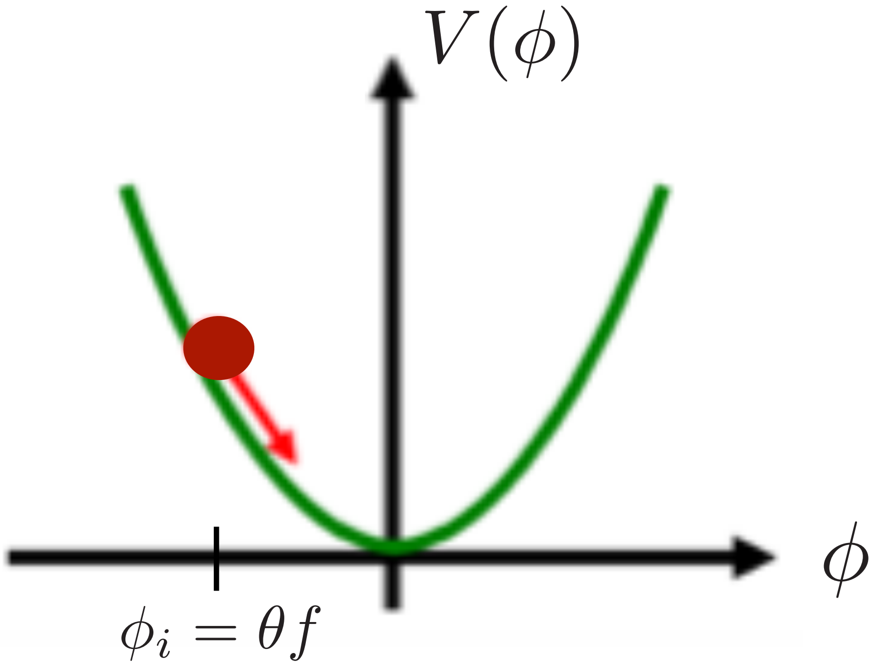


Rolling

- The ALP begins to oscillate when the Hubble rate drops below the ALP mass

$$H_{\rm osc} \sim m\,, \qquad \rho_\phi^{\rm osc} \sim \frac{1}{2} m^2 \phi_i^2$$

$$\Omega_\phi^{\rm osc} = \frac{\rho_\phi^{\rm osc}}{\rho_{\rm tot}^{\rm osc}} \approx \frac{m^2 \theta^2 f^2/2}{3 M_P^2 H_{\rm osc}^2} \approx \left(\frac{\theta f}{M_P}\right)^2$$



- Dark Photon EOM

$$\left(\frac{\partial^2}{\partial \tau^2} - \nabla^2\right) \vec{X} = \alpha \frac{\phi'}{f} \vec{\nabla} \times \vec{X}\,, \qquad \vec{\nabla} \cdot \vec{X} = 0\,.$$

Source for dark photons (while ALP rolls)

Quantum picture

JG|U

We quantize the dark photon field as

Circular pols. ($\mathbf{k} \times \boldsymbol{\varepsilon}_\pm = \mp i k \boldsymbol{\varepsilon}_\pm$)

$$\hat{X}^i(\mathbf{x}, \tau) = \sum_{\lambda=\pm} \int \frac{d^3k}{(2\pi)^3} v_\lambda(k,\tau)\, \varepsilon^i_\lambda(\mathbf{k})\, \hat{a}_\lambda(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}$$

which leads to the following equation for the mode functions

$$v''_\pm + \omega^2_\pm(\tau) v_\pm = 0\,, \qquad \omega^2_\pm(\tau) = k^2 \mp k \frac{\alpha}{f}\phi'$$

As the ALP rolls, there exist momenta for which $\omega^2_\pm$ is negative. The corresponding modes are tachyonic and grow exponentially:

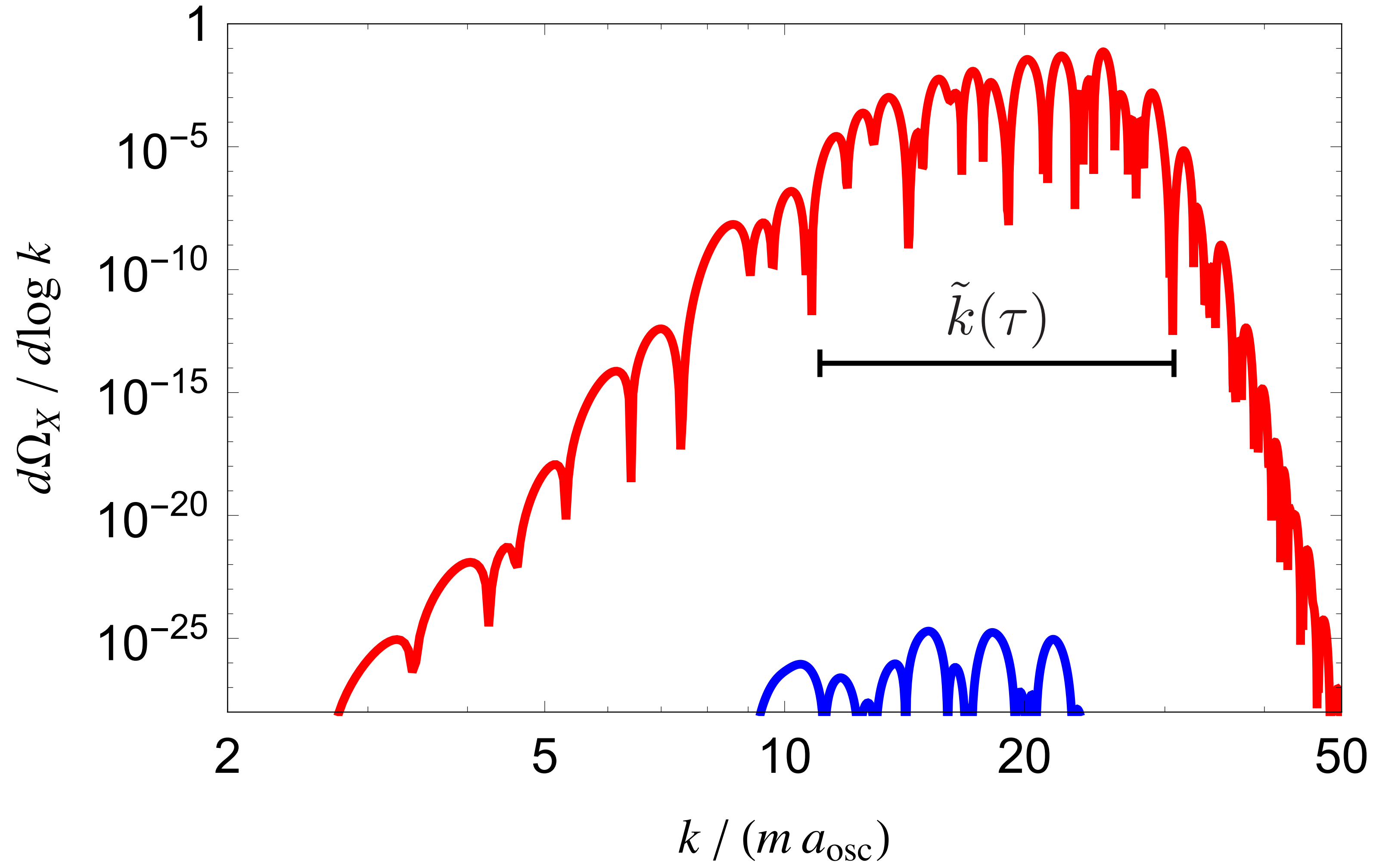
$$v_\pm(k,\tau) \sim e^{|\omega_\pm|\tau}$$

PRiSMA+

Dark photon spectrum

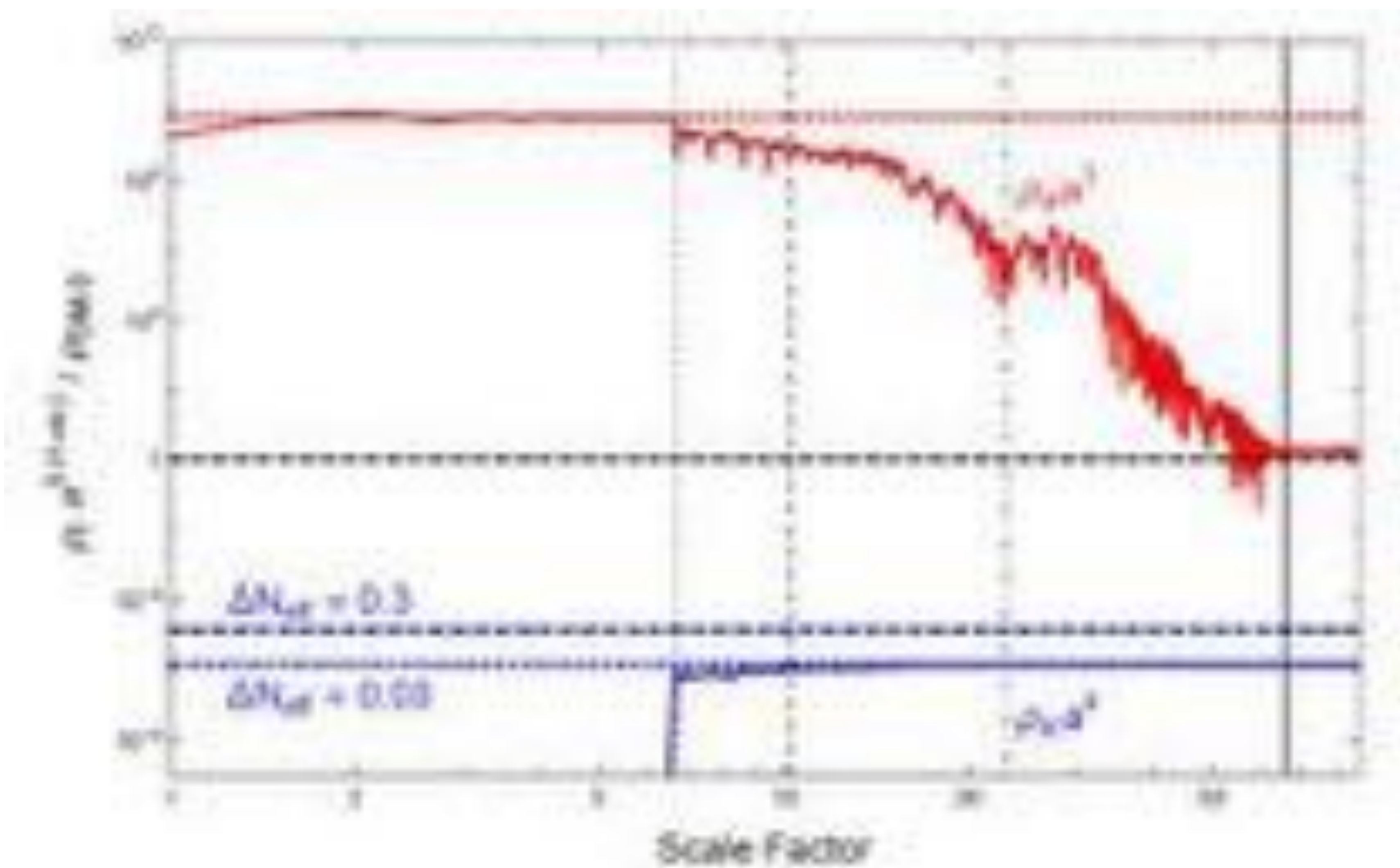
- Initial condition violates parity (field rolls to the left or to the right)
- One dark photon helicity dominates
- A certain range of modes undergoes tachyonic growth

$$0 < k < \frac{\alpha\phi'}{f}\,, \qquad \frac{k}{m} \lesssim \alpha\theta$$



Relic abundance

- Tachyonic dark photon production
- + parametric resonance
- efficient energy transfer away from axion
- N_{eff} constraint on dark photon abundance



GW production

JG|U

Dark photon modes in the range $0 < k < \theta \alpha m$ which were initially in vacuum grow exponentially when the axion begins to oscillate

$$v_\pm(k, \tau \ll \tau_{\rm osc}) = \frac{1}{\sqrt{2k}} e^{-ik\tau} \quad \xrightarrow[\omega_\pm^2 < 0]{} \quad v_\pm(k,\tau) \sim e^{|\omega_\pm|\tau}$$

These rapidly growing modes amplify quantum fluctuations of the dark photon into a time-varying, anisotropic classical energy distribution which sources gravitational waves

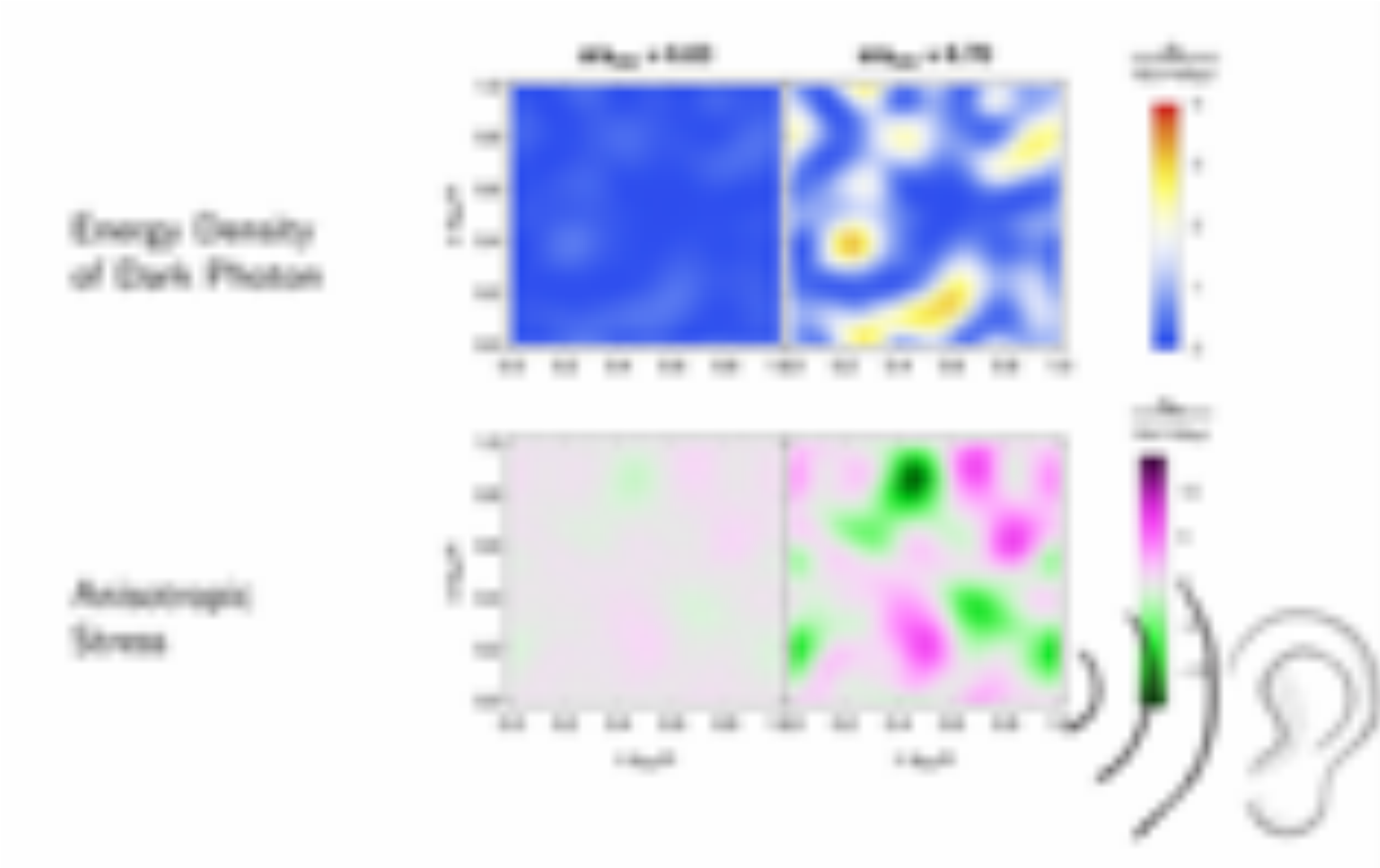
Gravity Waves →

$$h''_{ij}(\mathbf{k},\tau) + k^2 h_{ij}(\mathbf{k},\tau) = \frac{2}{M_P^2}\Pi_{ij}(\mathbf{k},\tau)\,,$$

← Anisotropic stress

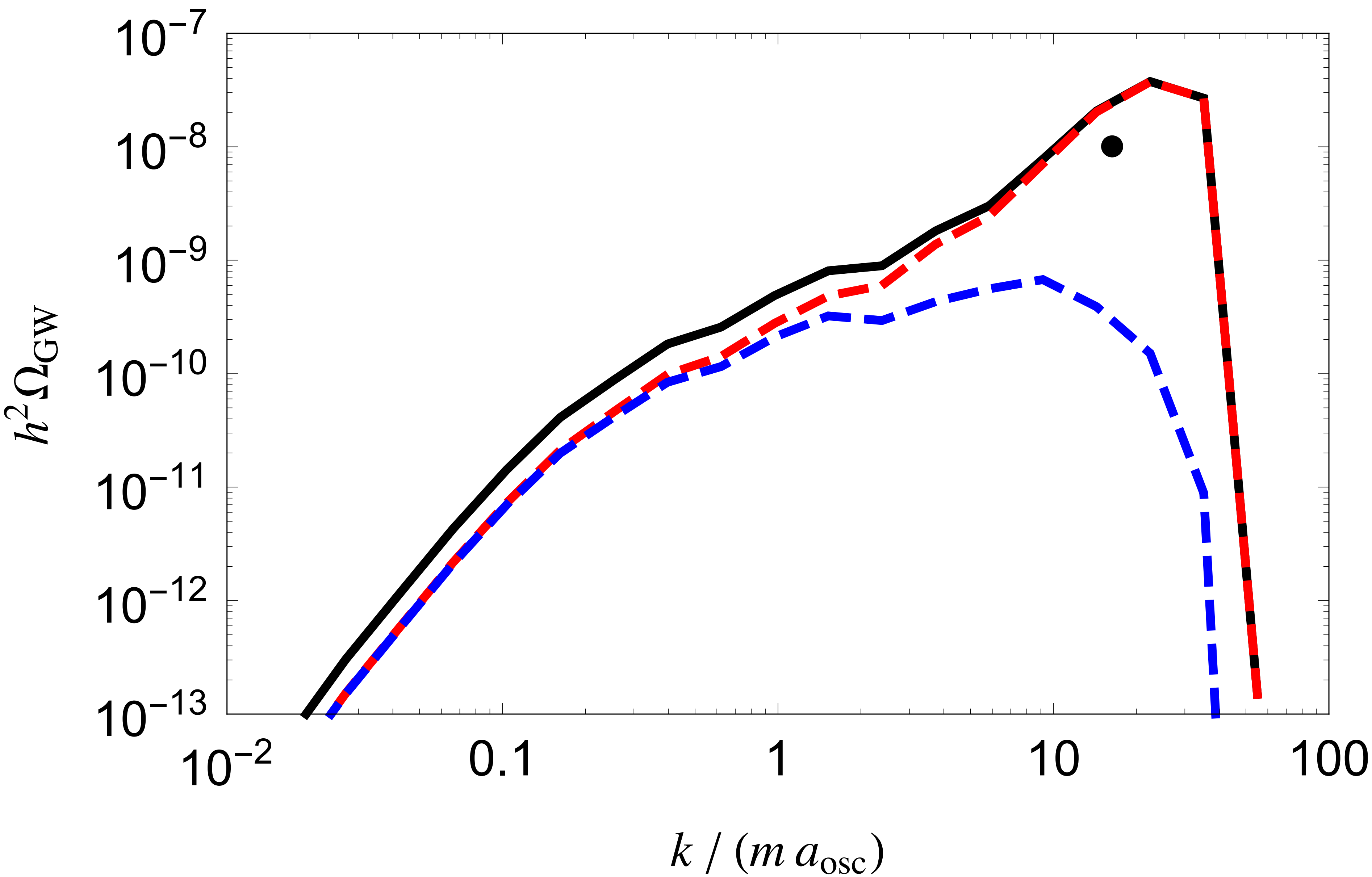
$$\hat{\Pi}_{ij}(\mathbf{k},\tau) = \frac{\Lambda_{ij}^{kl}}{a^2}\int \frac{d^3q}{(2\pi)^3}\left[\hat{E}_k(\mathbf{q},\tau)\hat{E}_l(\mathbf{k}-\mathbf{q},\tau) + \hat{B}_k(\mathbf{q},\tau)\hat{B}_l(\mathbf{k}-\mathbf{q},\tau)\right].$$

GW production II

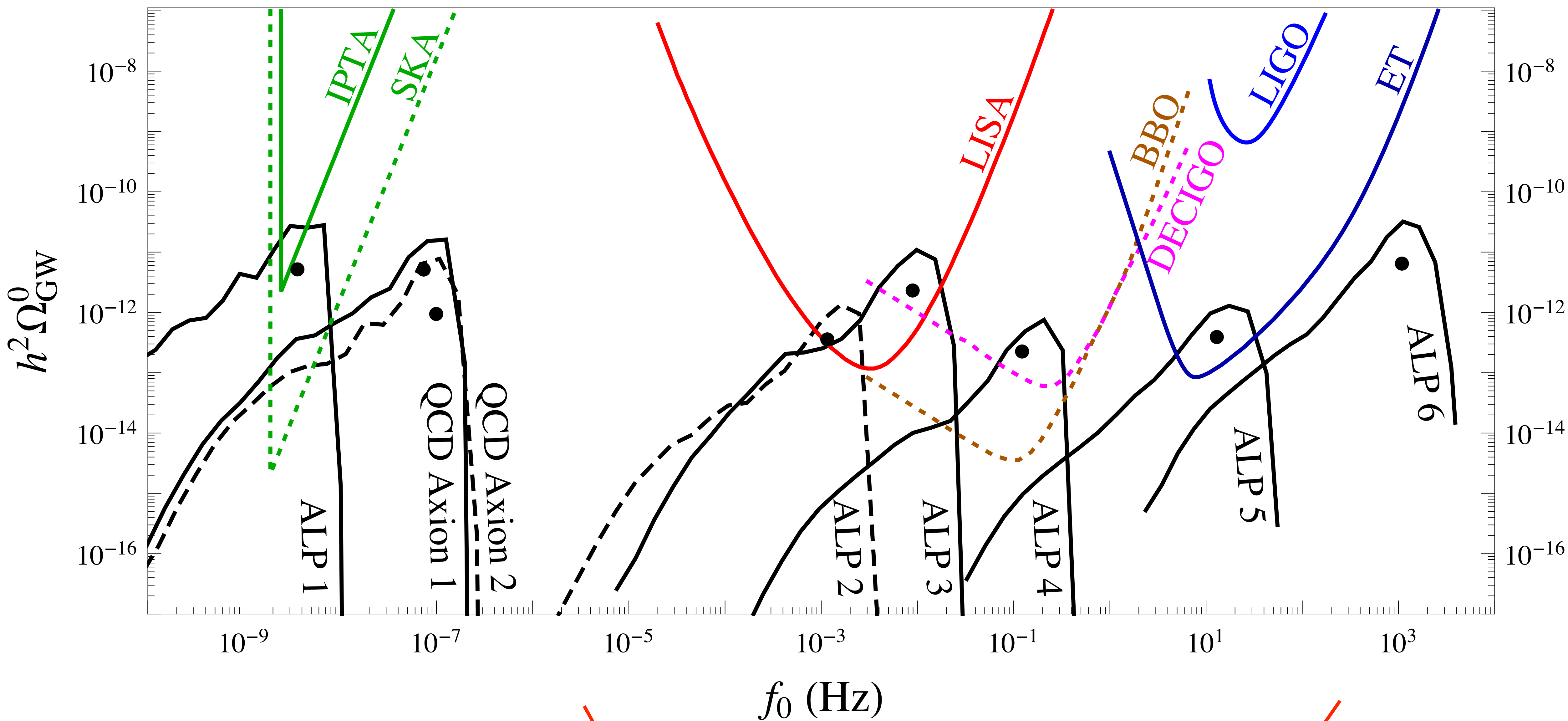


GW signal shape

$$k_{\text{peak}} \approx (\alpha\theta)^{2/3}\, m\,, \qquad \Omega_{\text{GW}}(k_{\text{peak}}) \approx \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}$$

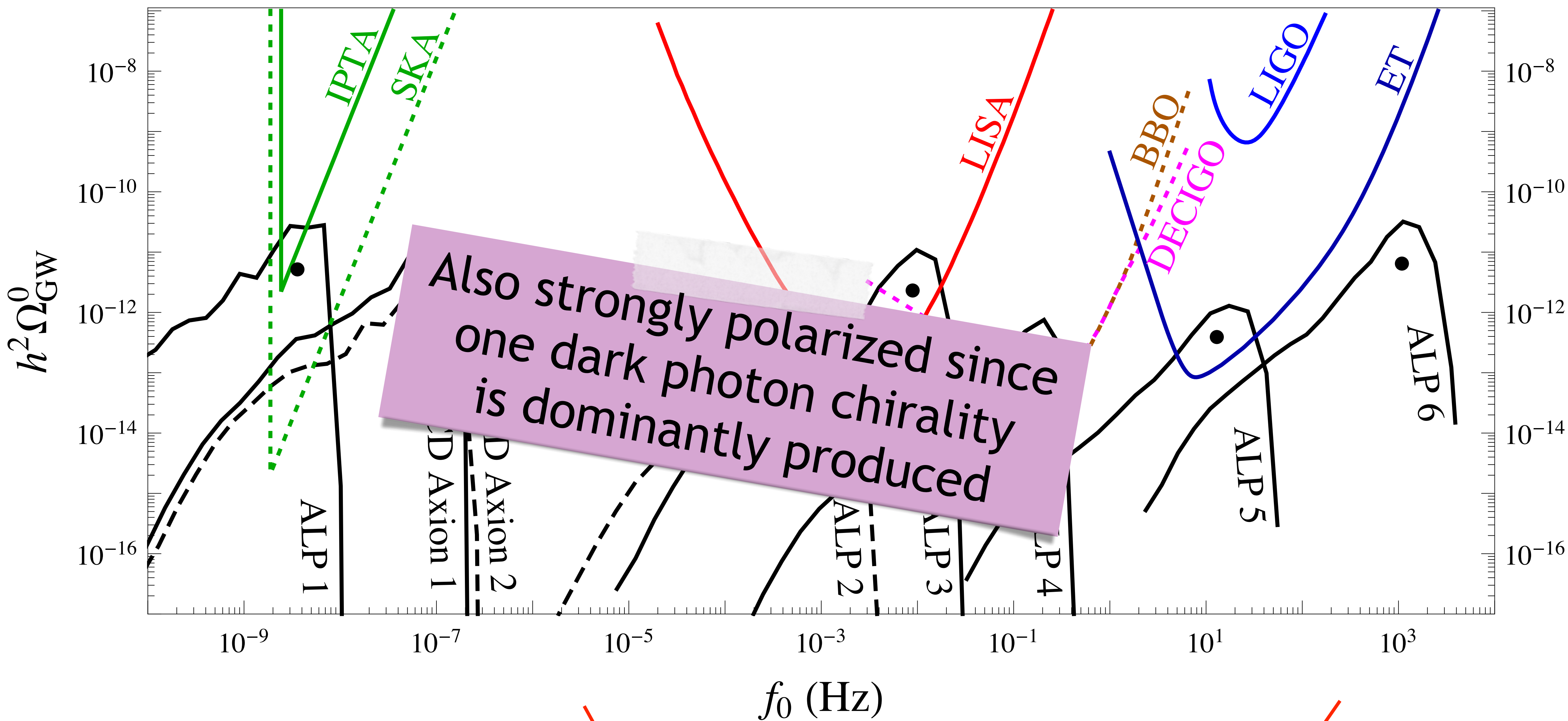


Signals



$$f_0 \approx m \left(\frac{T_0}{T_*}\right) (\alpha\theta)^{2/3} = \sqrt{\frac{m}{M_P}}\, T_0\, (\alpha\theta)^{2/3}\,, \qquad \Omega^0_{GW} \approx \Omega^0_\gamma \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}$$

Signals

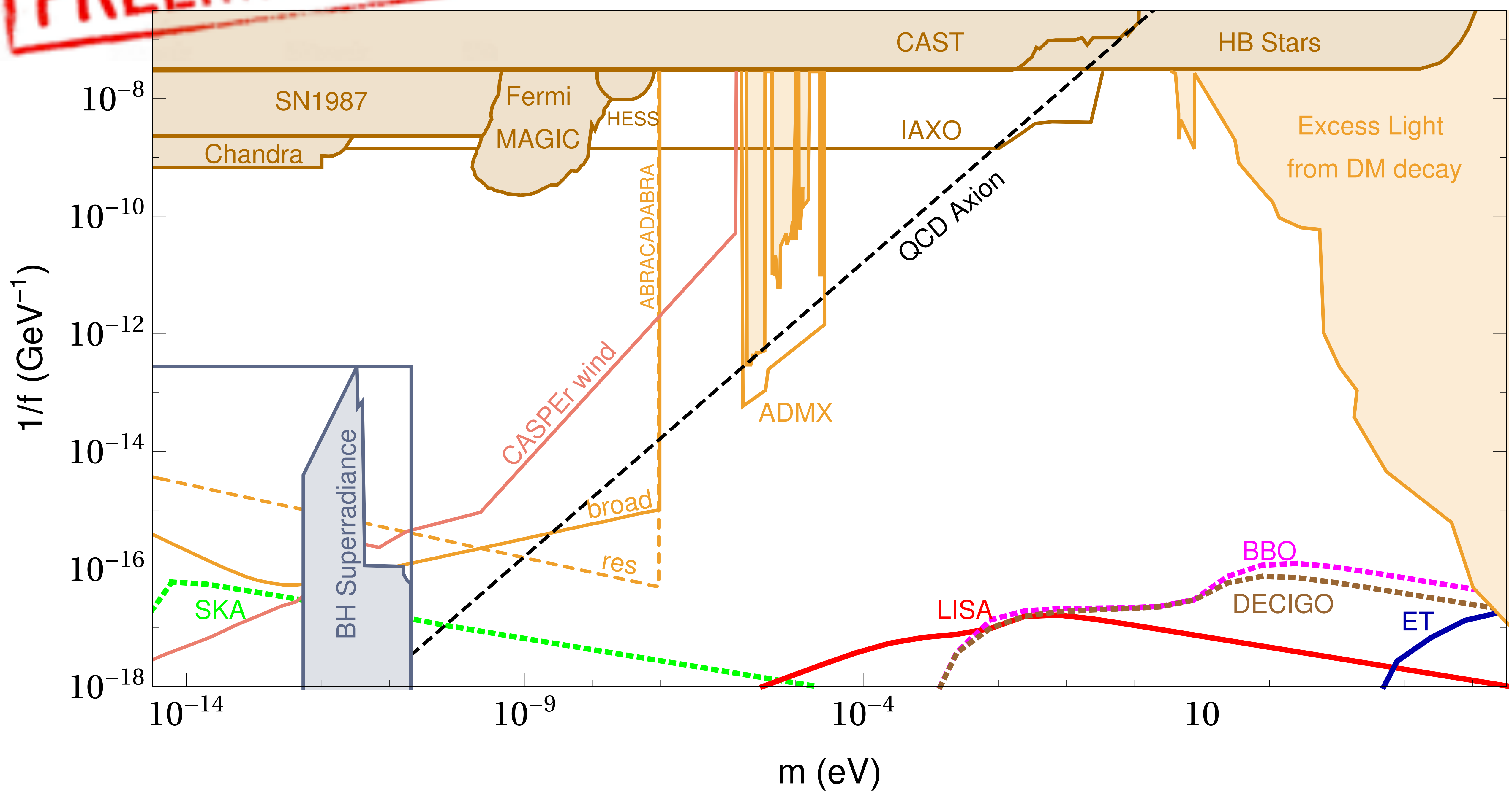


$$f_0 \approx m \left(\frac{T_0}{T_*}\right) (\alpha\theta)^{2/3} = \sqrt{\frac{m}{M_P}}\, T_0\, (\alpha\theta)^{2/3},$$

$$\Omega^0_{\rm GW} \approx \Omega^0_\gamma \left(\frac{f}{M_P}\right)^4 \left(\frac{\theta^2}{\alpha}\right)^{\frac{4}{3}}$$

Constraints on ALP plane

PRELIMINARY



Machado, Ratzinger, PS, Stefanek, 2019 (to appear)

Audible Axioms

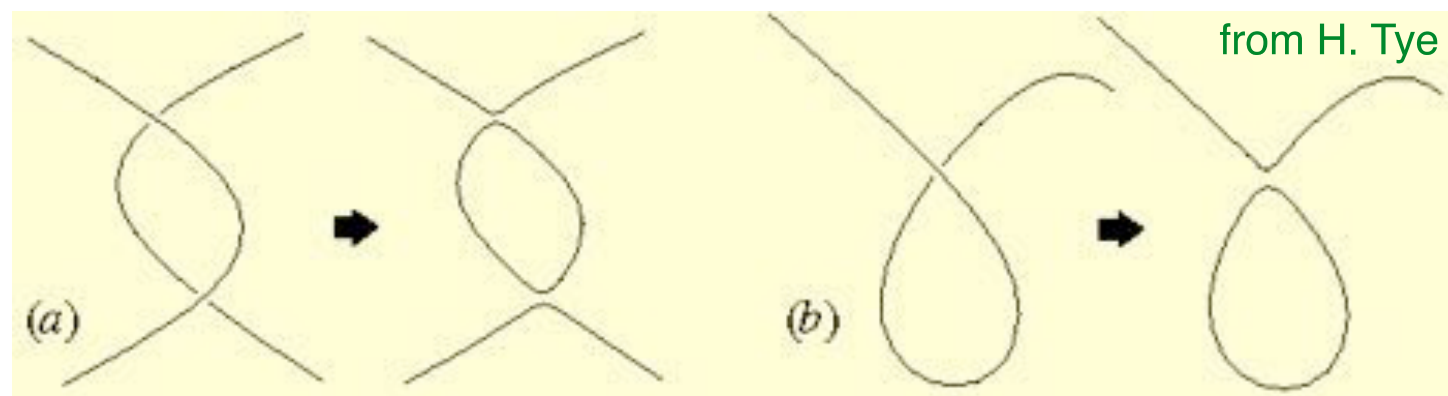
Summary

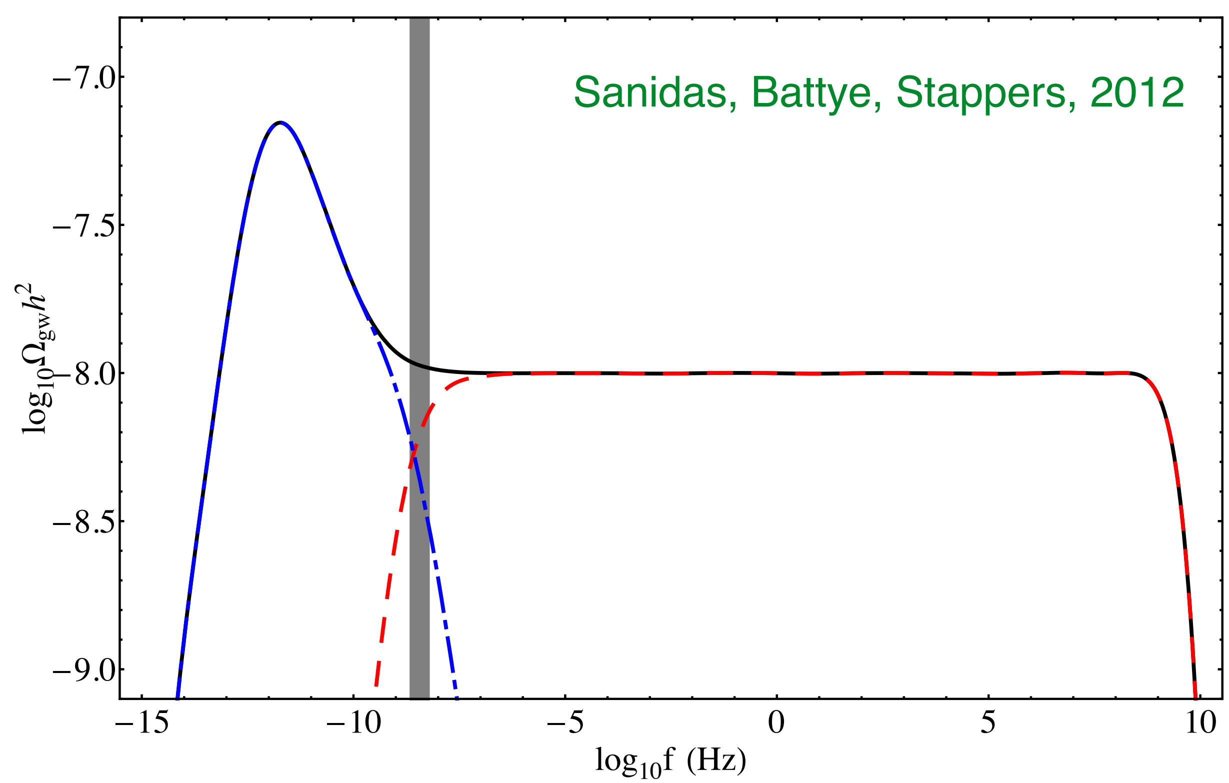
- Gravitational waves offer unique window into the early universe
- Can hope to observe GWs from a strong EWPT
- Could be first (or only) way to obtain signals from a strongly coupled hidden sector
- New way to probe axions/ALPs
- Lots of room for new ideas!

Cosmic strings

See also talk by W. Buchmüller

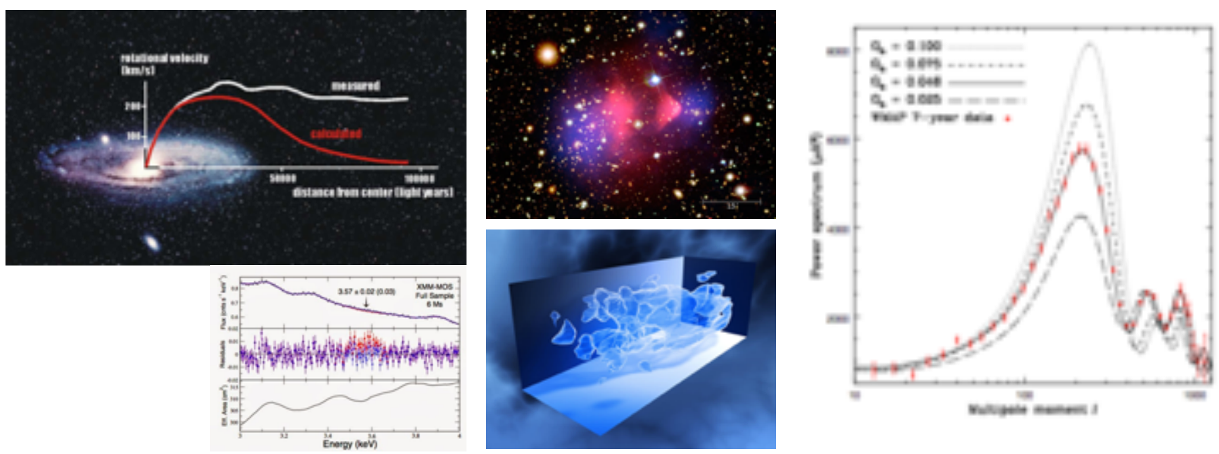
- Topological defects or stretched superstrings
- Formed after inflation or in PTs
- Interact and form loops
- Loops loose energy by GW radiation



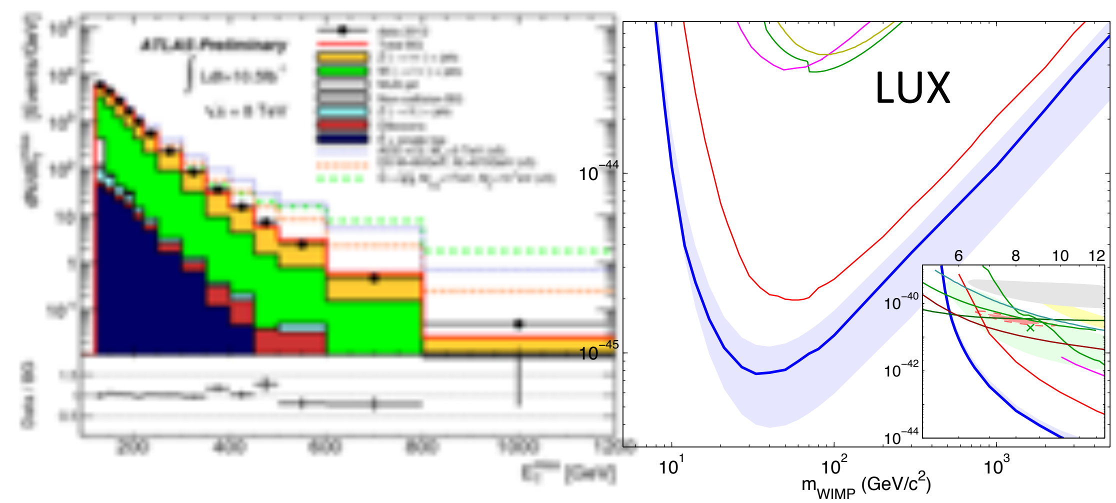


Dark Matter

We have seen DM in the sky:



But no direct observation



Maybe DM is just part of a larger dark sector

- Example: Proton is massive, stable, composite state
- DM self interactions solve structure formation problems
- New signals, new search strategies!

DM Motivation

- New mechanisms for relic density, extend mass range:
  - Asymmetric DM - GeV-TeV scale
  - Strong Annihilation - 100 TeV scale
  - SIMP - MeV scale
    Hochberg, Kuflik, Volansky, Wacker, 2014; + Murayama, 2015
- Advantages of Composite
  - DM mass scale and stability
  - Fast annihilation for ADM
  - Self-interactions for structure formation

GW spectra

- Lot of work on GW from 1st order PT
  - Still difficult to simulate or model

See talks by Hindmarsh, Weir for more details

- Here in addition:
  - Transition is non-perturbative
  - Parameters not known - take an optimistic guess

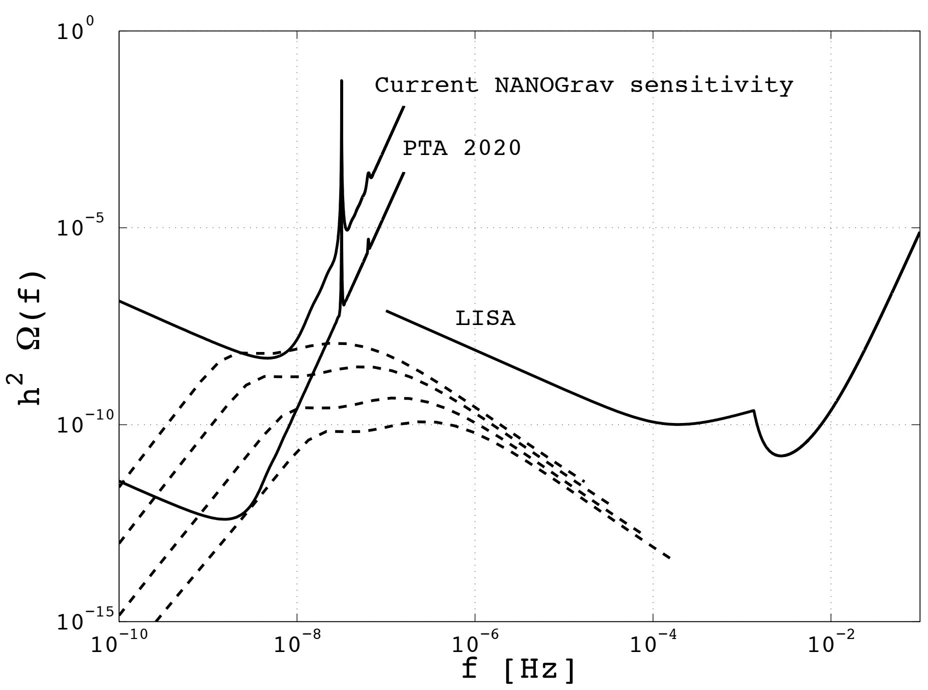
$$\beta/H_* = 1 - 100$$

$$v = 1$$

$$\frac{\kappa\alpha}{1+\alpha} = 0.1$$

SU(N) - PT 2

- One more parameter: Θ angle
- Effect on PT not well studied
  M. Anber, 2013
  Garcia-Garcia, Lasenby, March-Russell, 2015
- $N_d,\ n_f$ dependence of PT strength?
  Panero, 2009
- Finite density/chemical potentials?
  - QCD FOPT?
    Schwarz, Stuke, 2009
  - GW signal:
    Caprini, Durrer, Siemens, 2009

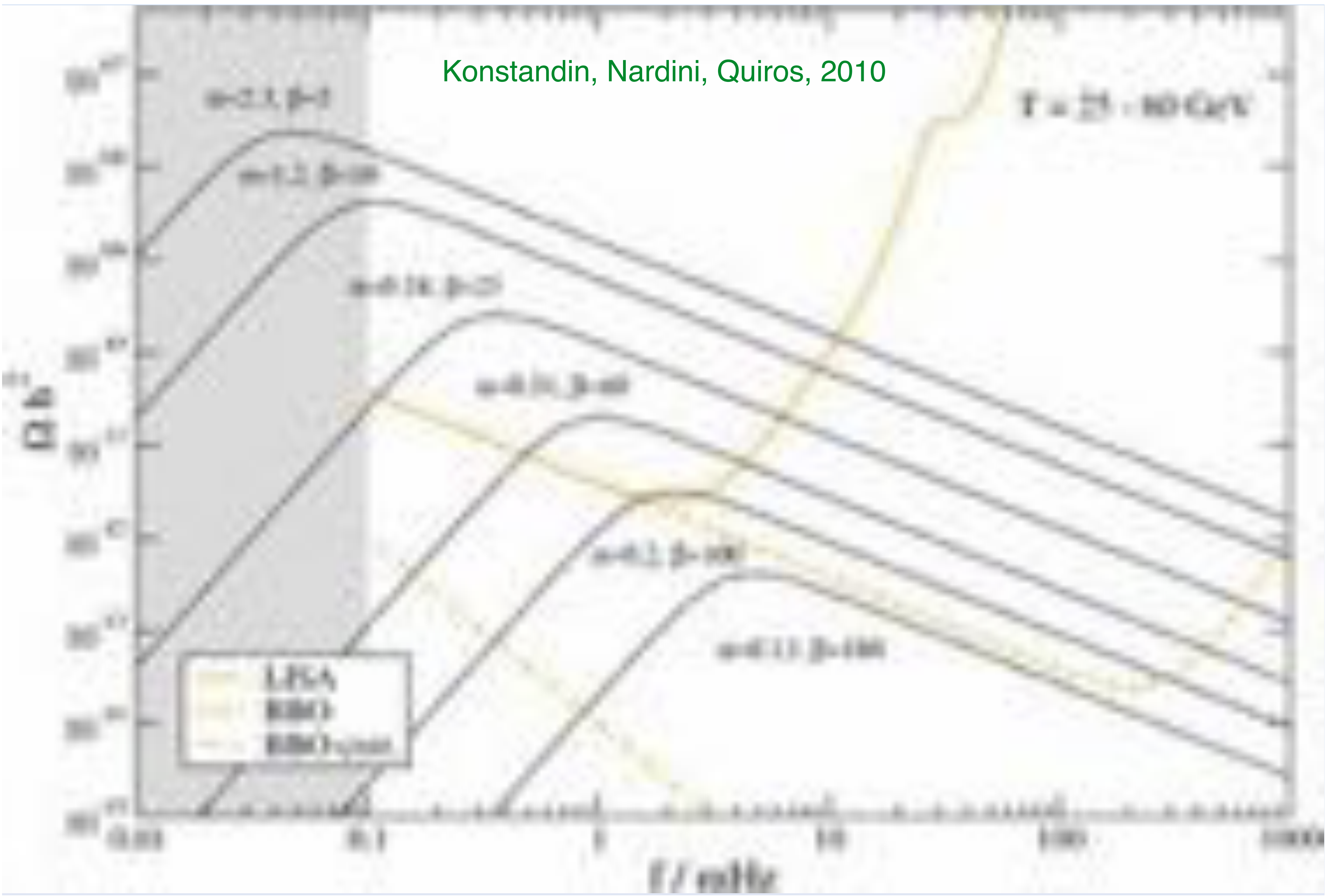


Electroweak Baryogenesis

- Baryogenesis requires departure from thermal equilibrium
- EWPT also provides B and CP violation, but no first order transition
- Strong motivation to study BSM scenarios with a strong EWPT. Examples:
  - Modified Higgs self-coupling
  - Extended scalar sectors
  - Radion in warped extra dimensions

For more details, see talks by Geraldine, Michael, Jeremy

Example: Radion in RS



Example: Strong EWPT