Gravitational Waves from a Dark Sector

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Outline

- Motivation for (non-abelian) Dark Sectors
- Phase Transition of SU(N) Theories
- GW Signal and ELISA

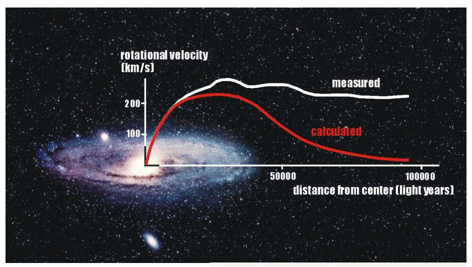
Based on 1504.07263

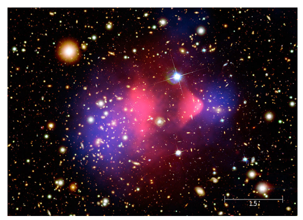
Motivation

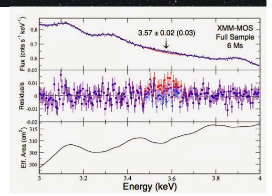
- Dark Sectors:
  - No or suppressed interaction with SM particles
  - “Dark” $SU(N_d)$ theory with n_f Dirac fermions
  - Confinement scale Λ_d
- Motivations:
  - Non-minimal Dark Matter models $M_{\rm DM} \sim \Lambda_d$
  - Naturalness

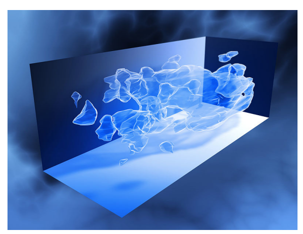
Dark Matter

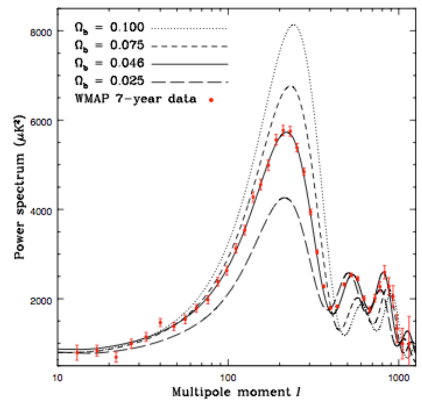
We have seen DM in the sky:



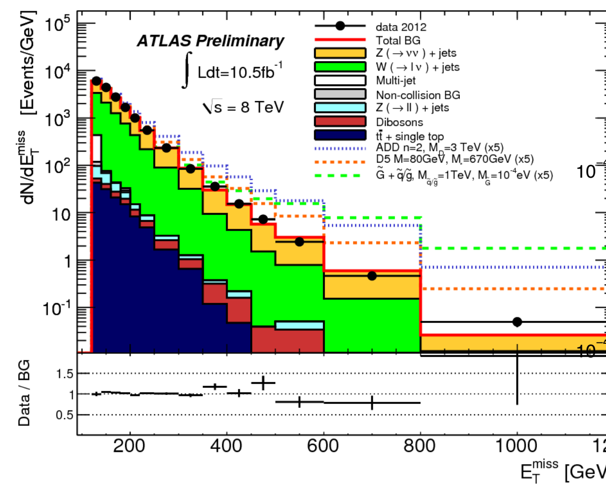


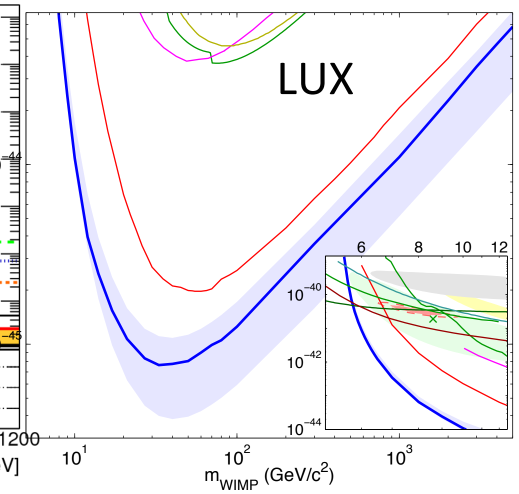






But no direct observation





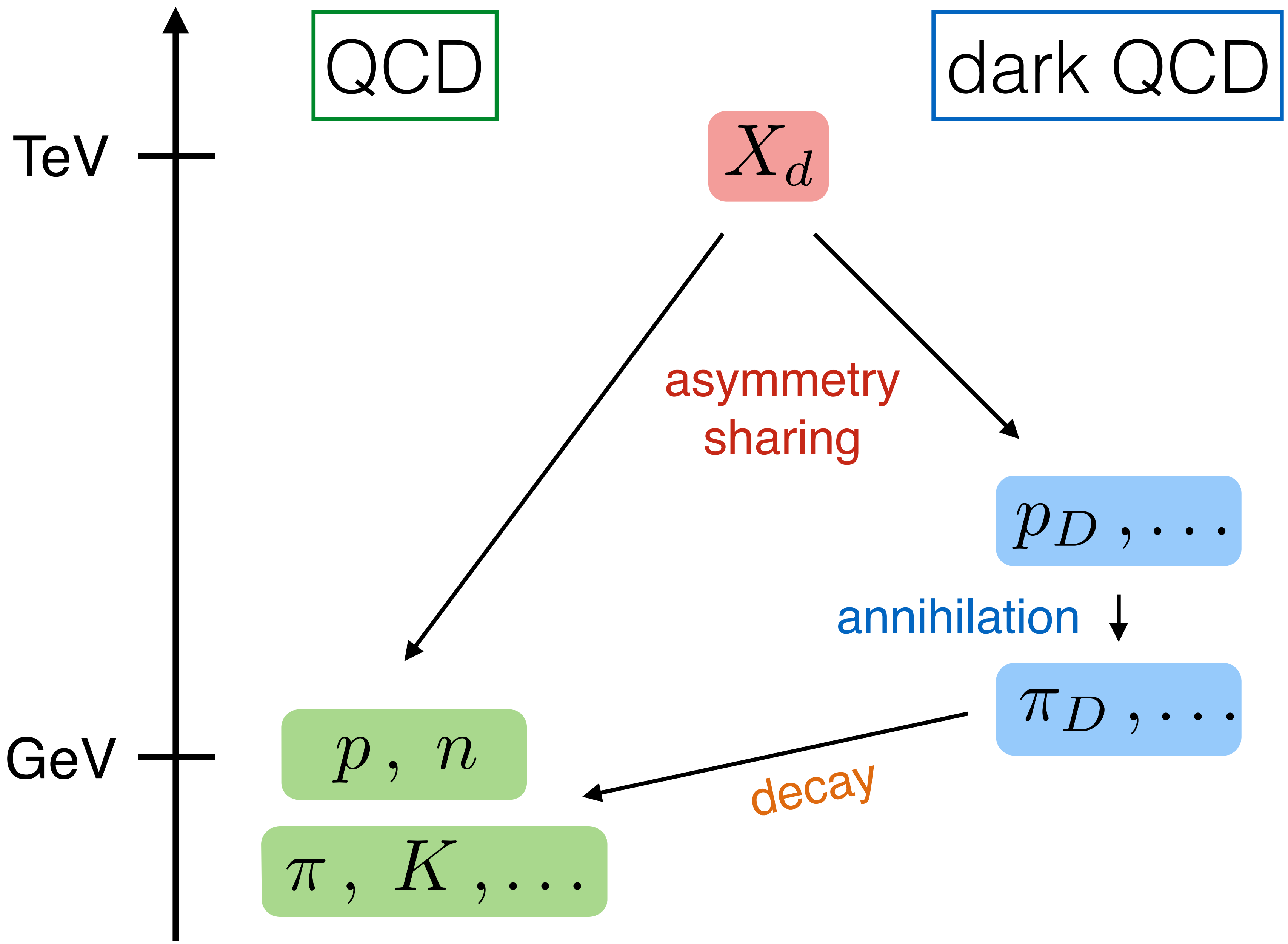
Maybe DM is just part of a larger dark sector

- 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
- Advantages of Composite
  - DM mass scale and stability
  - Fast annihilation for ADM
  - Self-interactions for structure formation

Asymmetric, Composite DM



- SU(N) dark sector with neutral "dark quarks"
- Confinement scale $\Lambda_{\mathrm{darkQCD}}$
- DM is composite "dark proton"

Bai, PS, PRD 89, 2014
PS, Stolarski, Weiler, JHEP 2015

many other works!
Similar setup e.g.: Blennow et al; Cohen et al; Frandsen et al;
Reviews: Petraki & Volkas, 2013; Zurek, 2013;

Heavy Composite

- Confinement scales up to 100 TeV
  - Saturate unitarity bound for WIMP annihilation!

Griest, Kamionkowski, 1989

- If dark quarks charged under $SU(2) \times U(1)$
  - $M_{\rm DM} > 10~\rm TeV$ for fermionic DM (odd N_d)

    Appelquist et al, 1301.1693
  - $M_{\rm DM} > 100s~\rm GeV$ for bosonic DM (even N_d)

    Appelquist et al, 1503.04205
  - Based on lattice studies of electromagnetic form factors

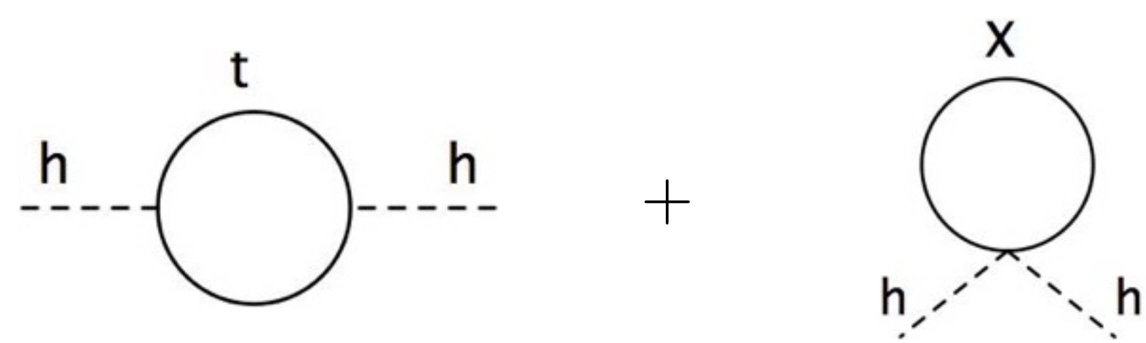
SIMP DM

Hochberg, Kuflik, Volansky, Wacker, 2014
+ Murayama, 2015

- Relic density from $3 \to 2$ annihilation
  - Suggests $M_{\rm DM} \sim 100$ MeV
  - (WIMP miracle suggests $M_{\rm DM} \sim 1$ TeV)
- SIMPlest model:
  - SU(N) dark sector with $N_d,\ n_f \geq 3$
  - $3 \to 2$ annihilation of dark pions through WZW term

Naturalness

- UV sensitivity of Higgs mass from top loop



- Naturalness requires coloured top partners X

- Alternative: Twin Higgs

Chacko, Goh, Harnik, 2005

  - Z_2 symmetric "mirror world"
  - Higgs mass regulated by top partners with dark colour
  - Minimal model: 3rd gen. partners only - pure YM dark sector below m_b'

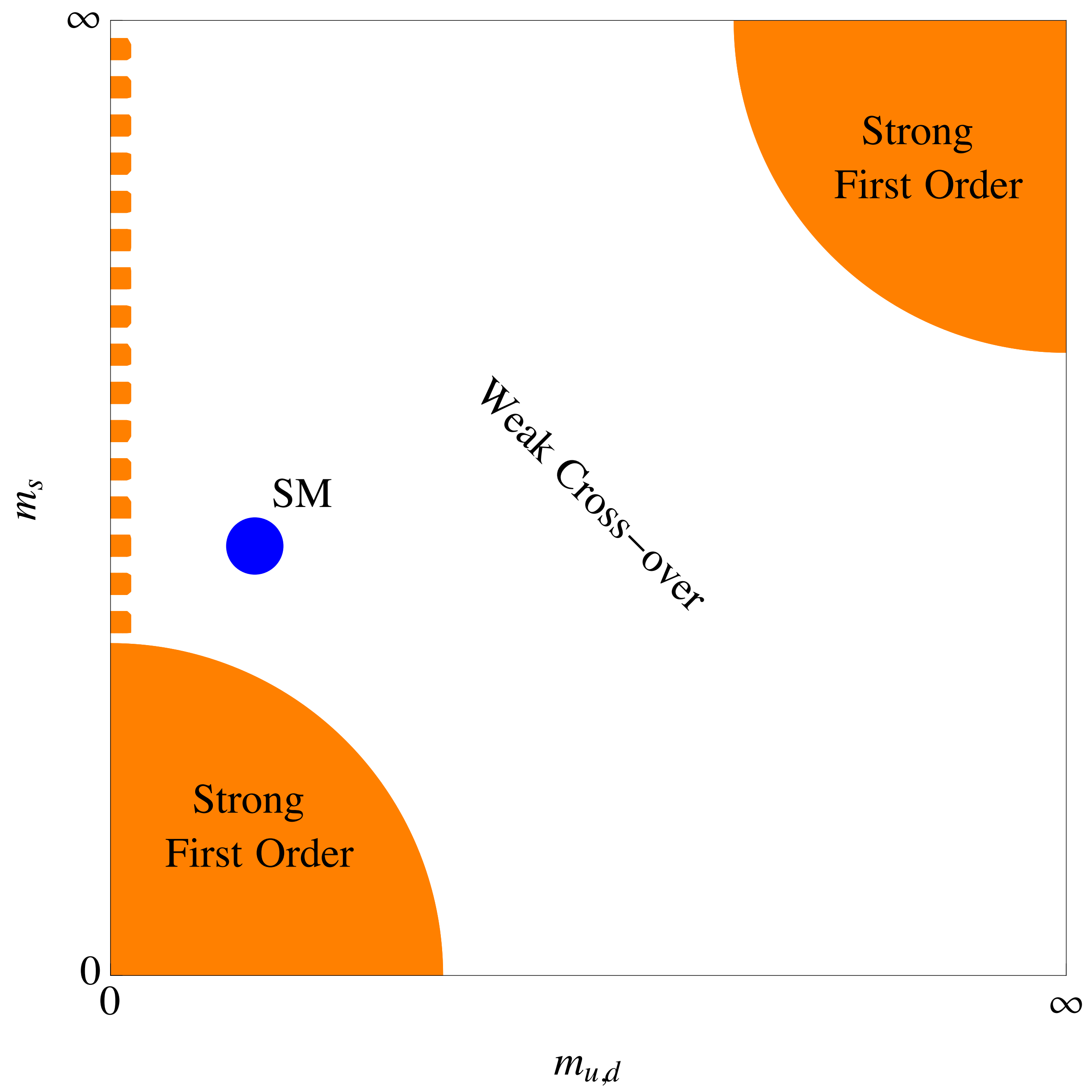
Craig, Katz, Strassler, Sundrum, 2015

The Dark Phase Transition

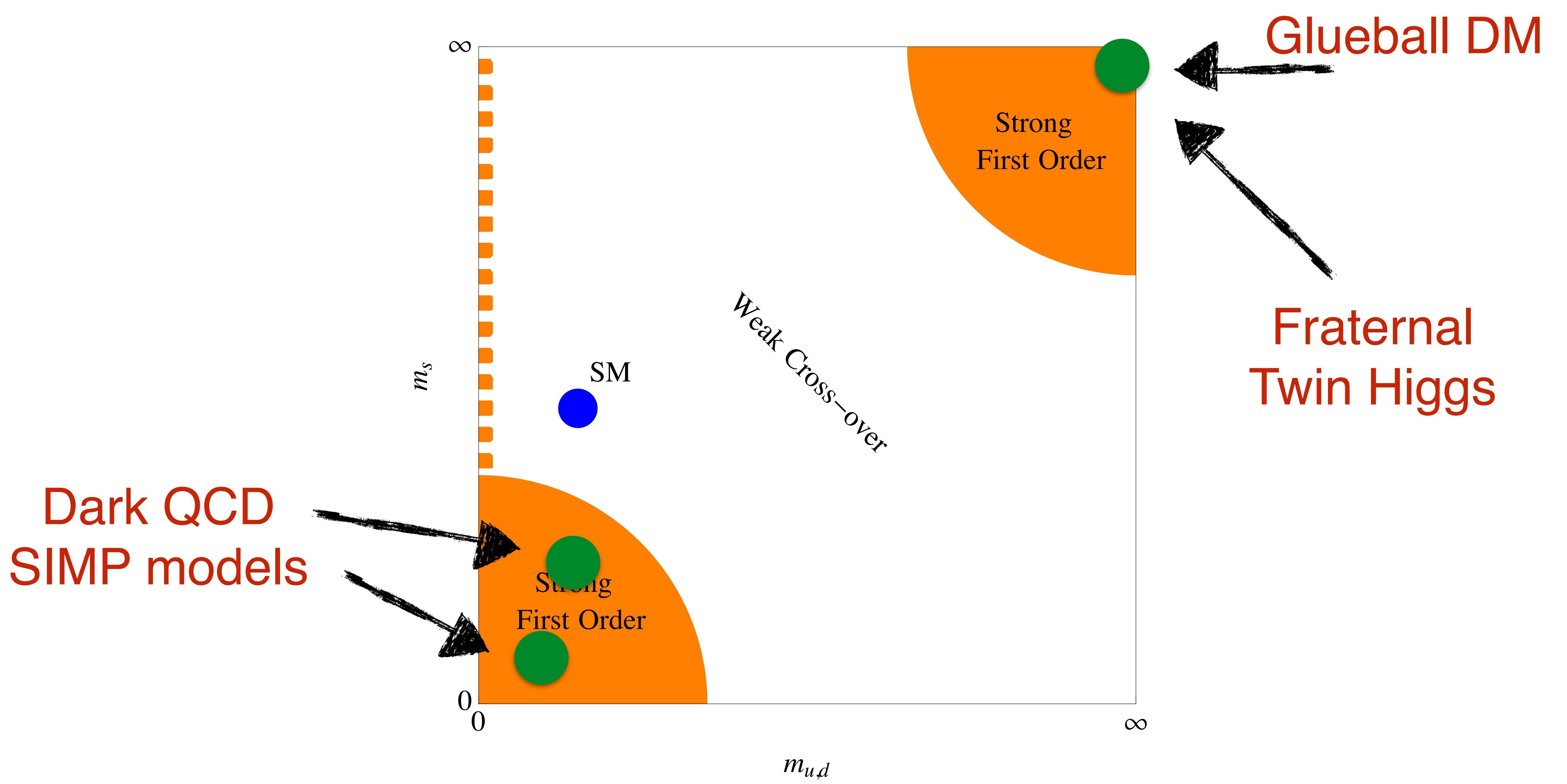
Phase Transition

- SU(N) dark sectors well motivated
- Confinement/chiral symmetry breaking phase transition at scale Λ_d
    - DM: $\Lambda_d \sim M_{\rm DM}$ (MeV - 100 TeV)
    - Naturalness: $\Lambda_d \sim \text{few} \times \Lambda_{\rm QCD}$
- First order PT in large class of models
- Still possible if LHC finds no new physics

QCD Phase Diagram



Phase Diagram II



SU(N) - PT

- Consider $SU(N_d)$ with n_f massless flavours

- PT is first order for
  - $N_d \geq 3 \;\;,\quad n_f = 0$ — Svetitsky, Yaffe, 1982; M. Panero, 2009
  - $N_d \geq 3 \;\;,\quad 3 \leq n_f < 4N_d$ — Pisarski, Wilczek, 1983

- Not for:
  - $n_f = 1$ (no global symmetry, no PT)
  - $n_f = 2$ (not yet known)

SU(N) - PT 2

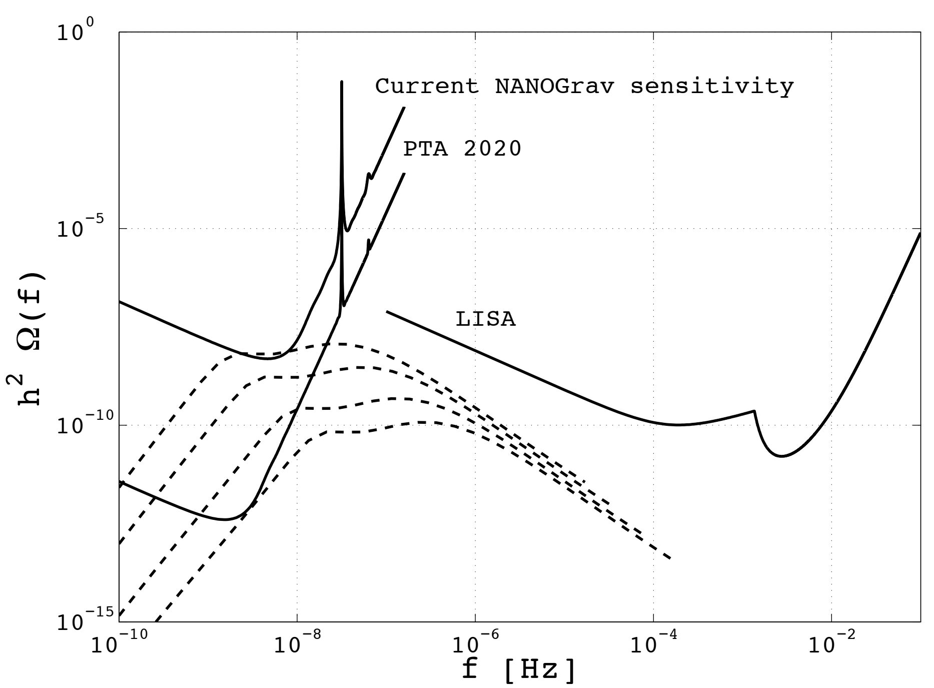
- One more parameter: Θ angle
- Effect on PT not well studied

  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



GW signals

GW spectra

- Lot of work on GW from 1st order PT
  - Still difficult to simulate or model
- Here in addition:
  - Transition is non-perturbative
  - Parameters not known - take an optimistic guess

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

$$v = 1$$

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

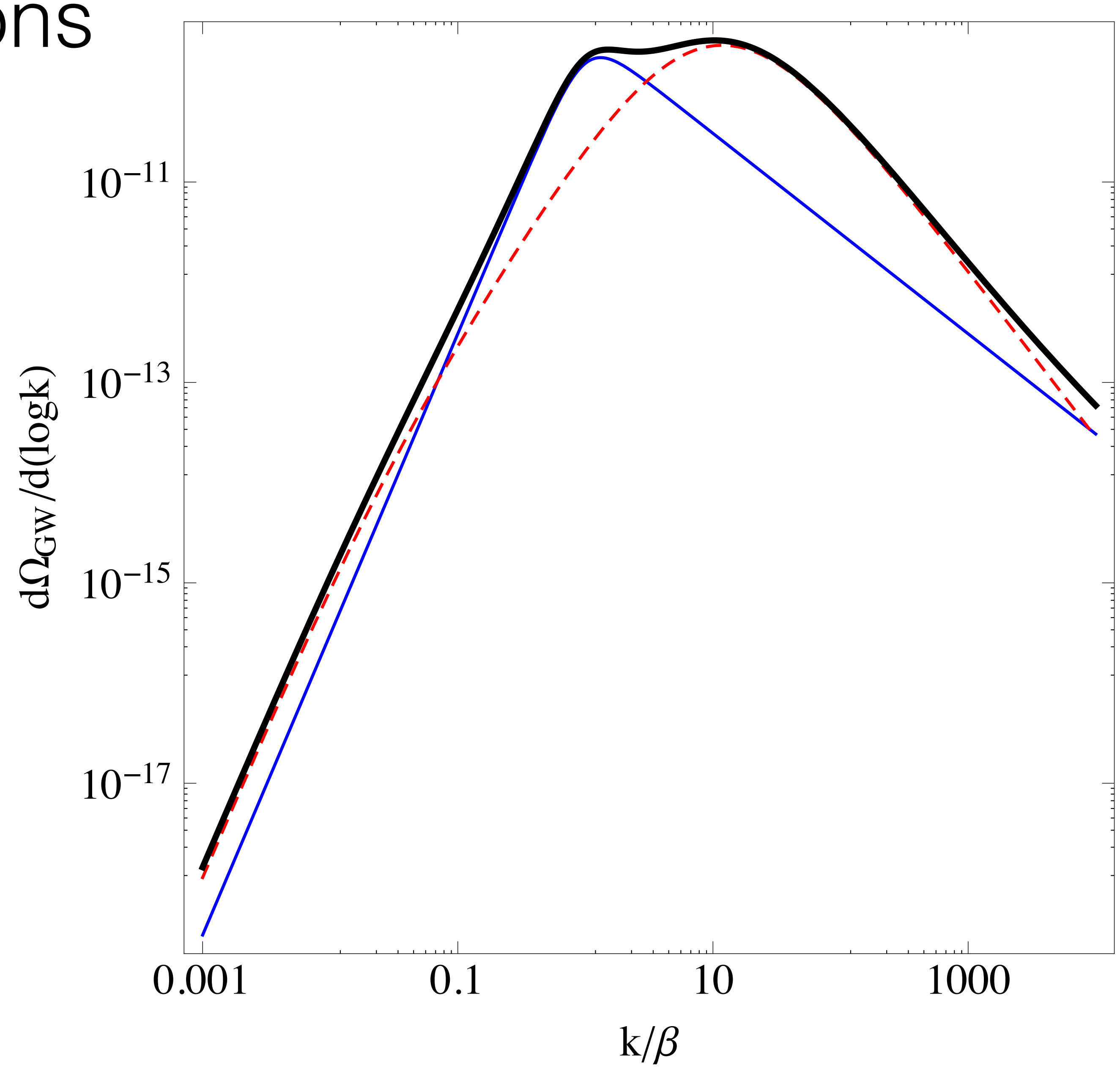
Shape

- From Bubble collisions and turbulence

$$\frac{d\Omega_{\rm GW}^{(B)}h^2}{d\log k} \simeq \frac{2}{3\pi}h^2\Omega_{r0}\left(\frac{\mathcal{H}_*}{\beta}\right)^2 \Omega_{S*}^2 v^3 \frac{(k/\beta)^3}{1+(k/\beta)^4}\,,$$

$$\frac{d\Omega_{\rm GW}^{(MHD)}h^2}{d\log k} \simeq \frac{8}{\pi^6}h^2\Omega_{r0}\left(\frac{\mathcal{H}_*}{\beta}\right) \Omega_{S*}^{3/2} v^4 \frac{(k/\beta)^3}{(1+4k/\mathcal{H}_*)\,(1+(v/\pi^2)(k/\beta))^{11/3}}$$

Caprini, Durrer, Siemens, 2010
Huber, Konstandin, Servant, …



- k conformal wave number

$\beta \sim (1-100)\mathcal{H}_*$

Sound waves not included yet!

Hindmarsh, Huber, Rummukainen, Weir, 2013, 2015

Frequency - DM scale

- Redshift:

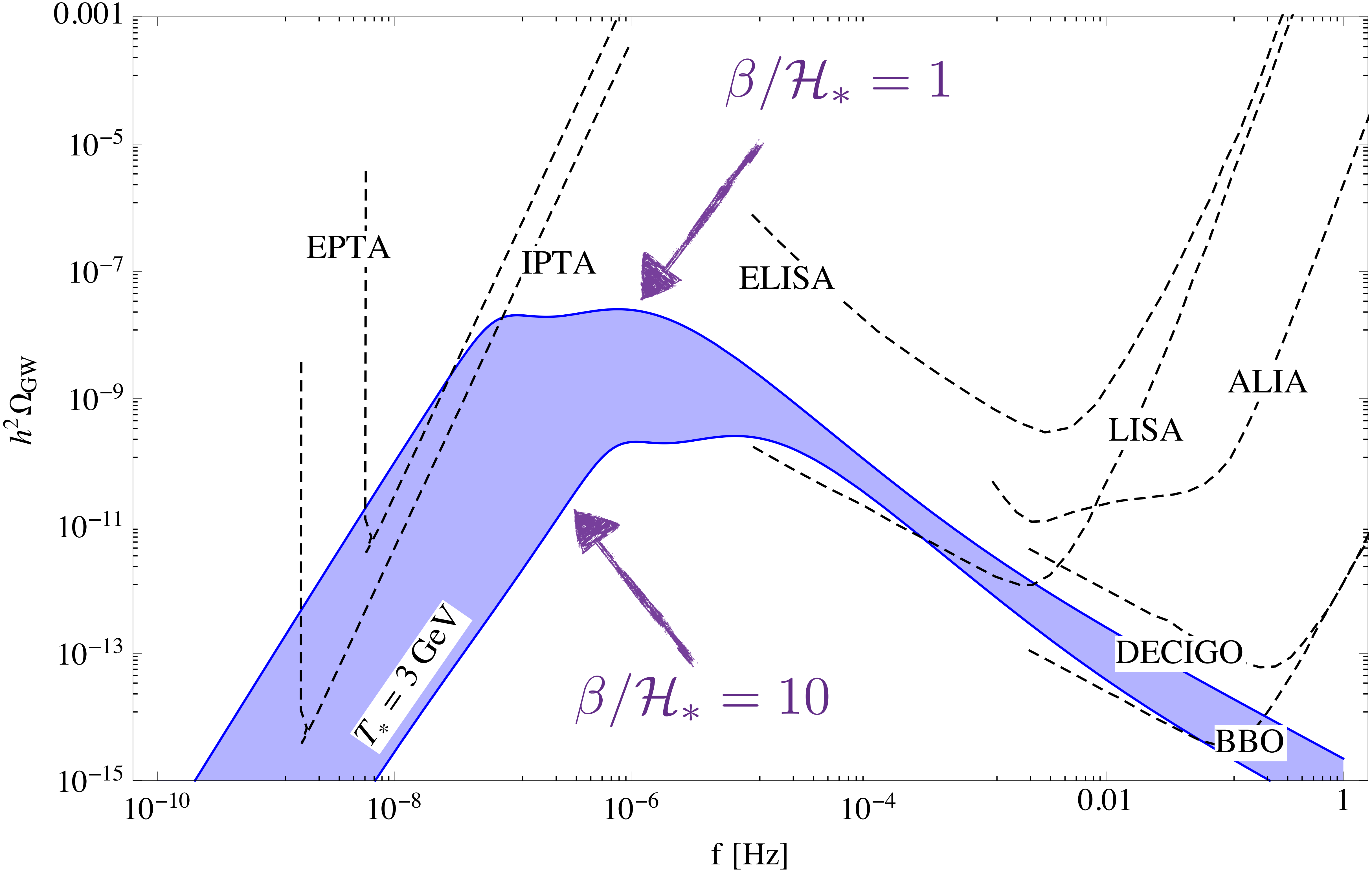
$$f = \frac{a_*}{a_0} H_* \frac{f_*}{H_*} = 1.59 \times 10^{-7}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \times \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \times \frac{f_*}{H_*}$$

DM mass

- Peak regions: $k/\beta \approx (1 - 10)$

$$f^{(B)}_{\mathrm{peak}} = 3.33 \times 10^{-8}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \left(\frac{\beta}{\mathcal{H}_*}\right)$$

T* ~ Few GeV



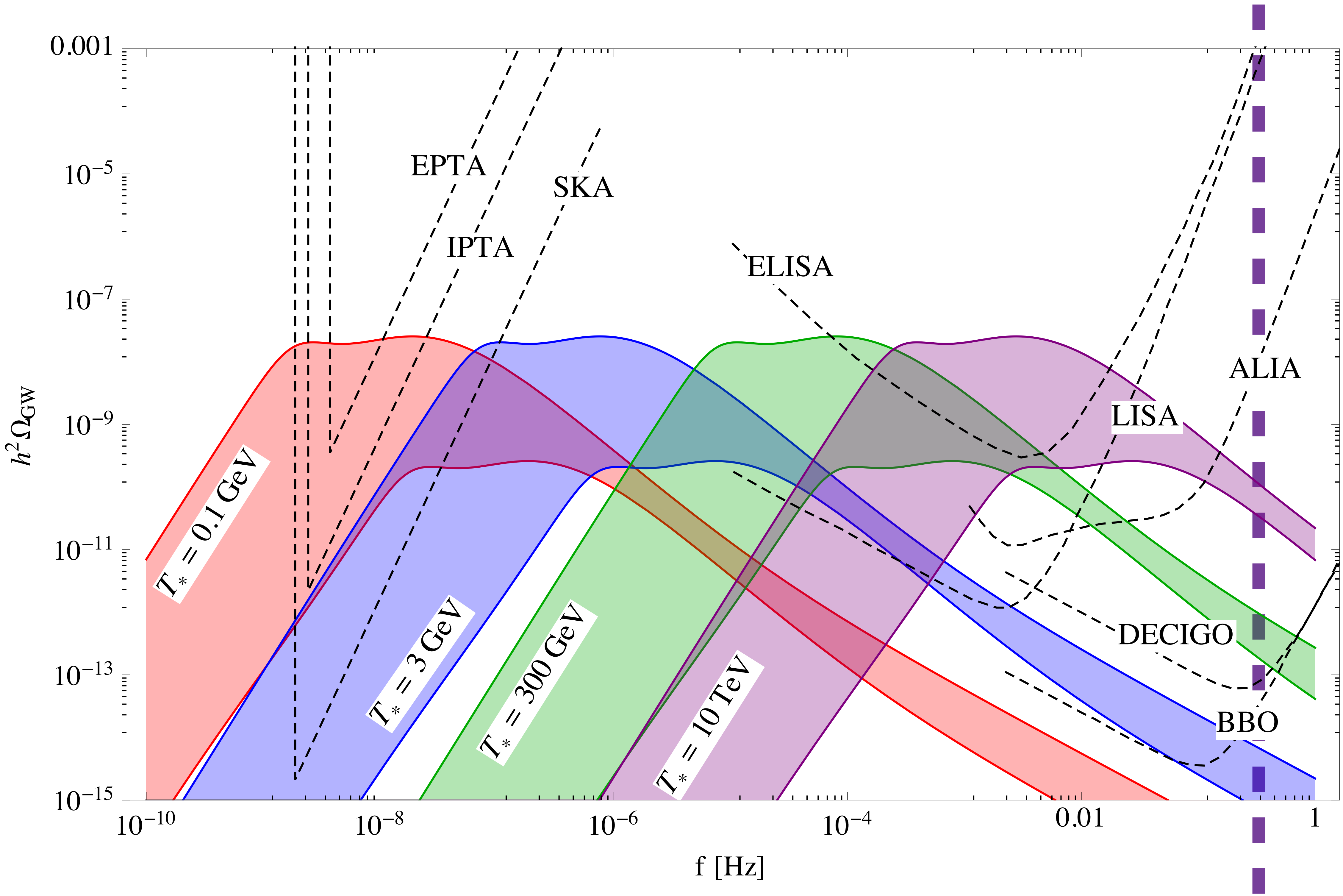
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$h^2\Omega_{GW}$
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
f [Hz]
EPTA
IPTA
ELISA
LISA
ALIA
DECIGO
BBO
$T_* = 3$ GeV
$\beta/\mathcal{H}_* = 1$
$\beta/\mathcal{H}_* = 10$

SIMP

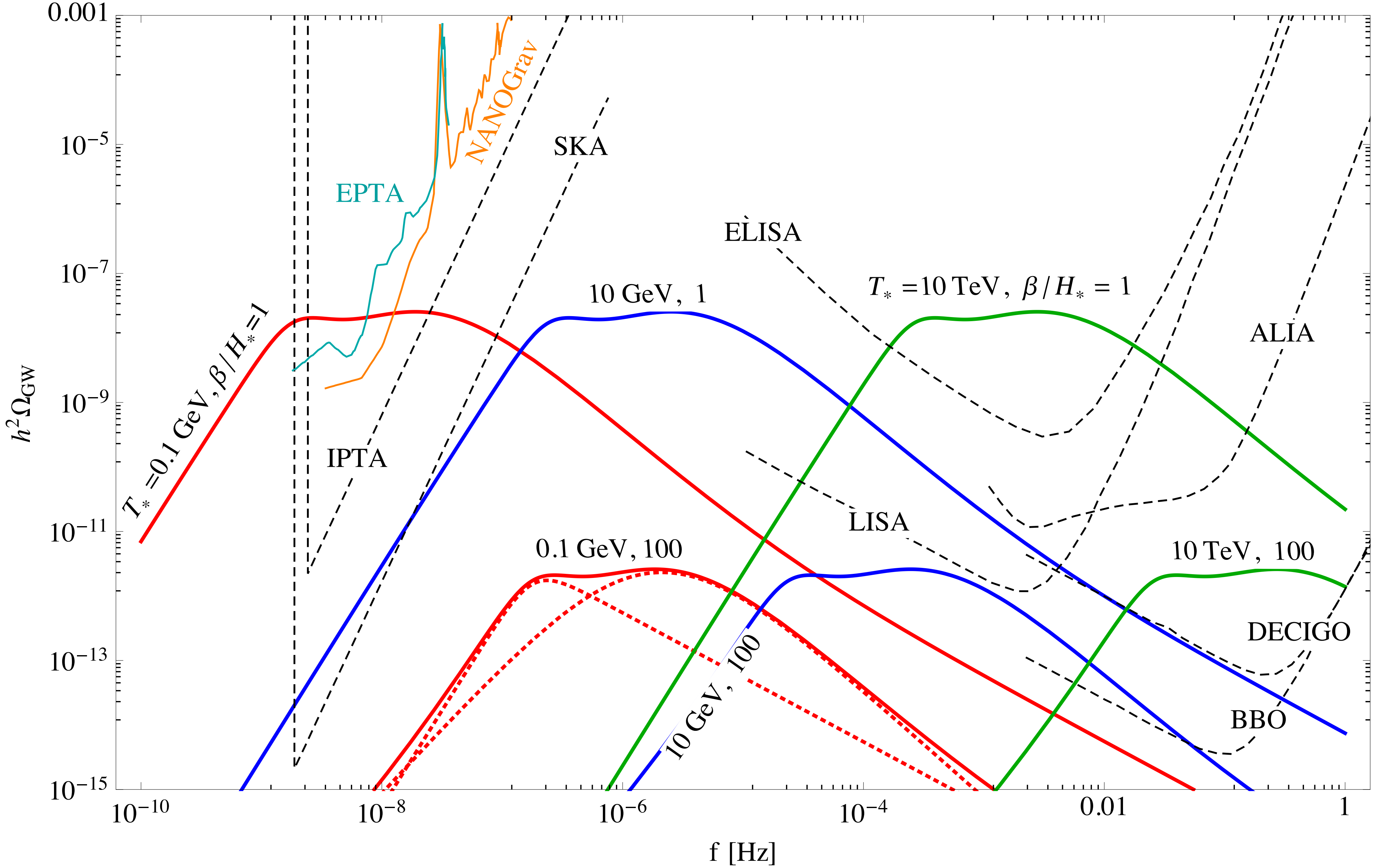
Composite ADM
Twin Higgs

Composite
WIMP-y

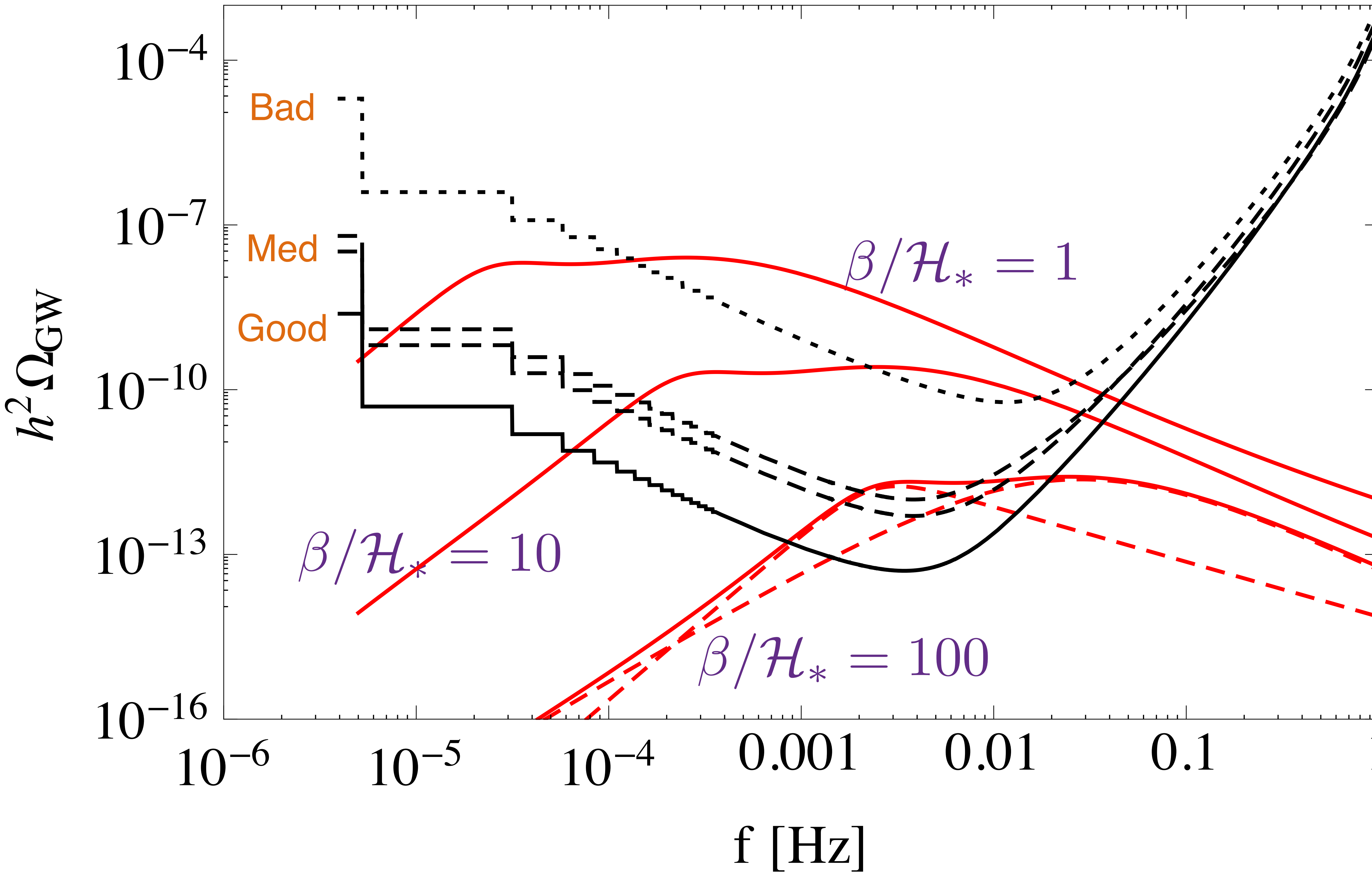
DM
Unitarity



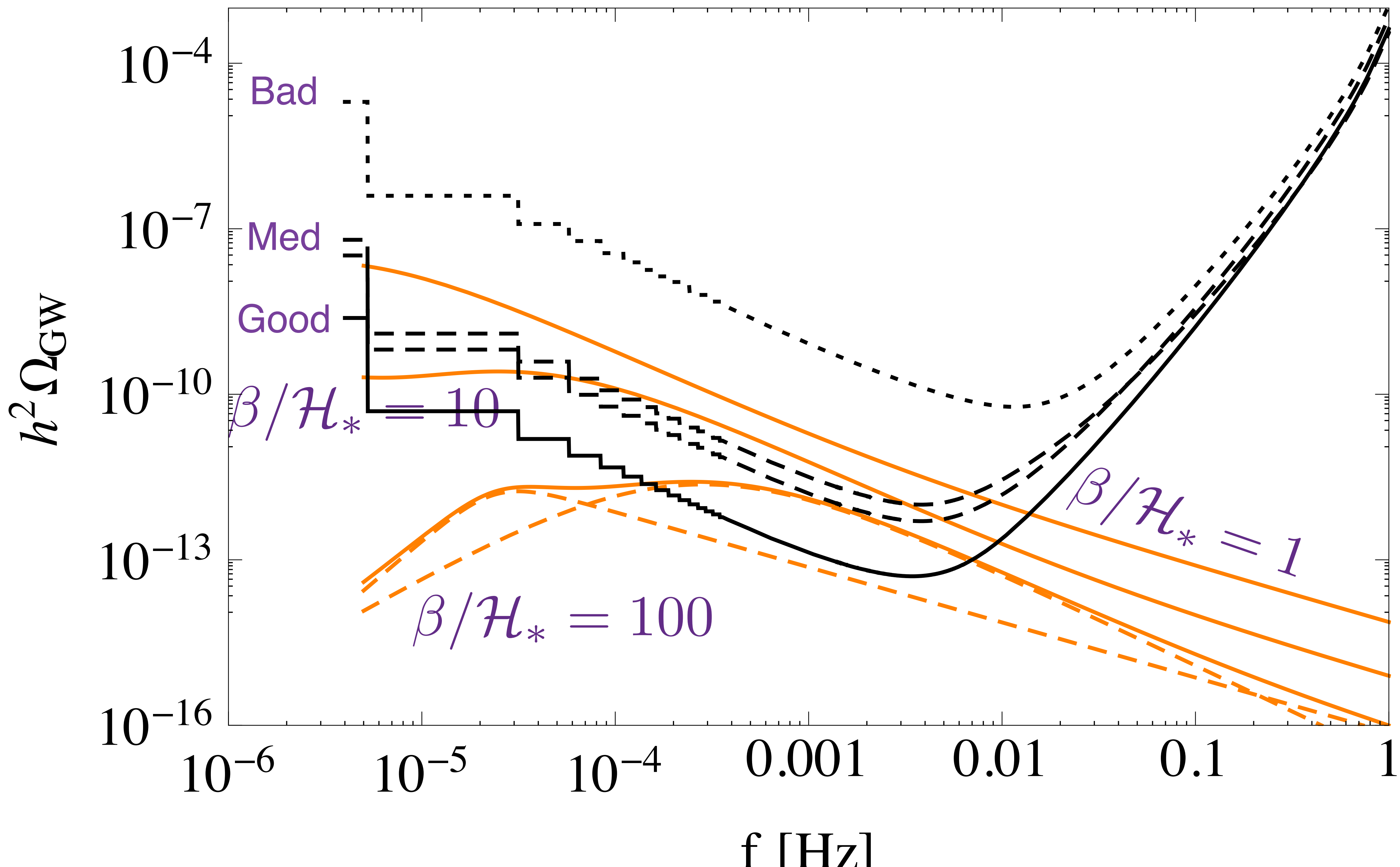
Broader Range of Signals



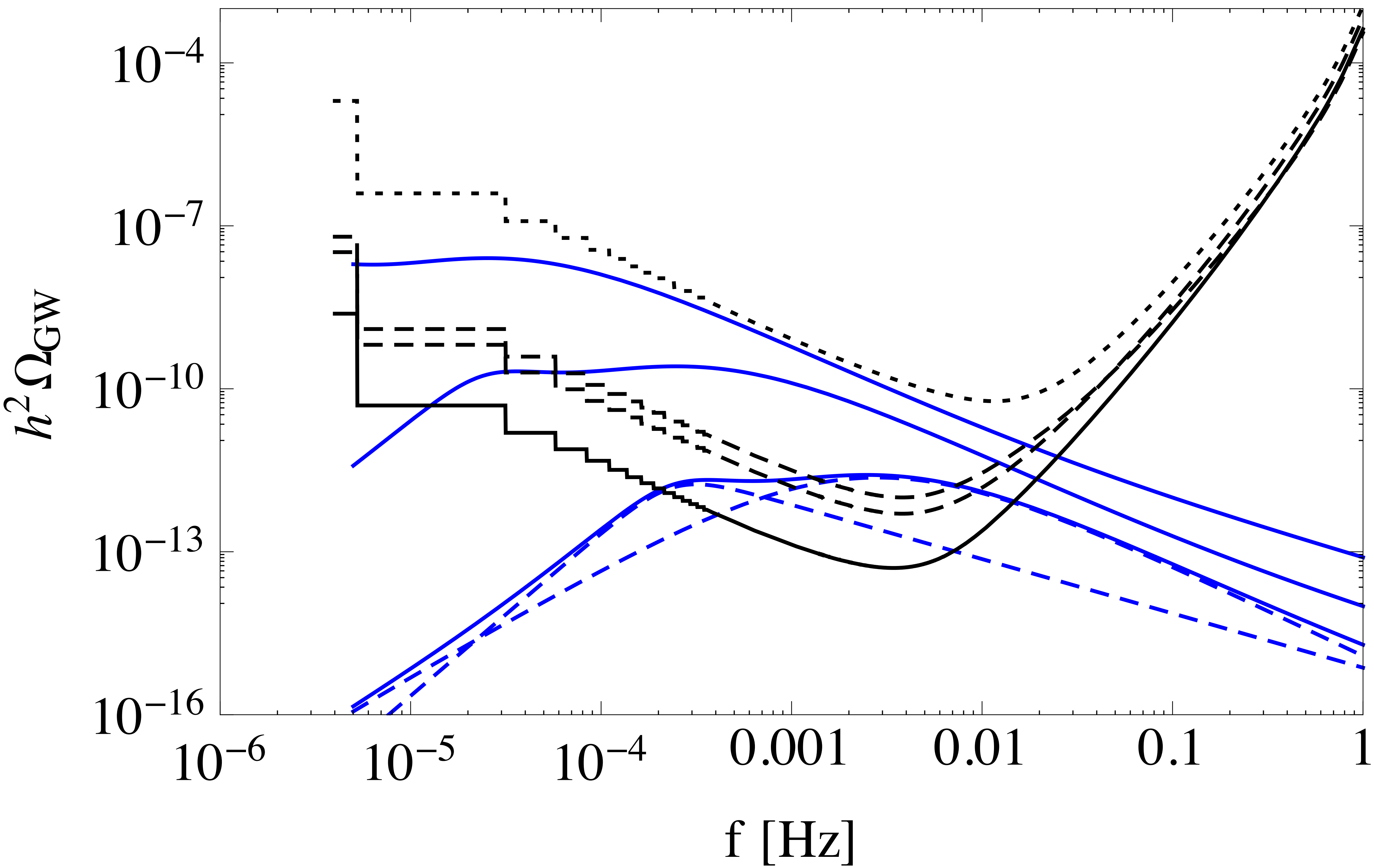
ELISA plots: T*=1 TeV



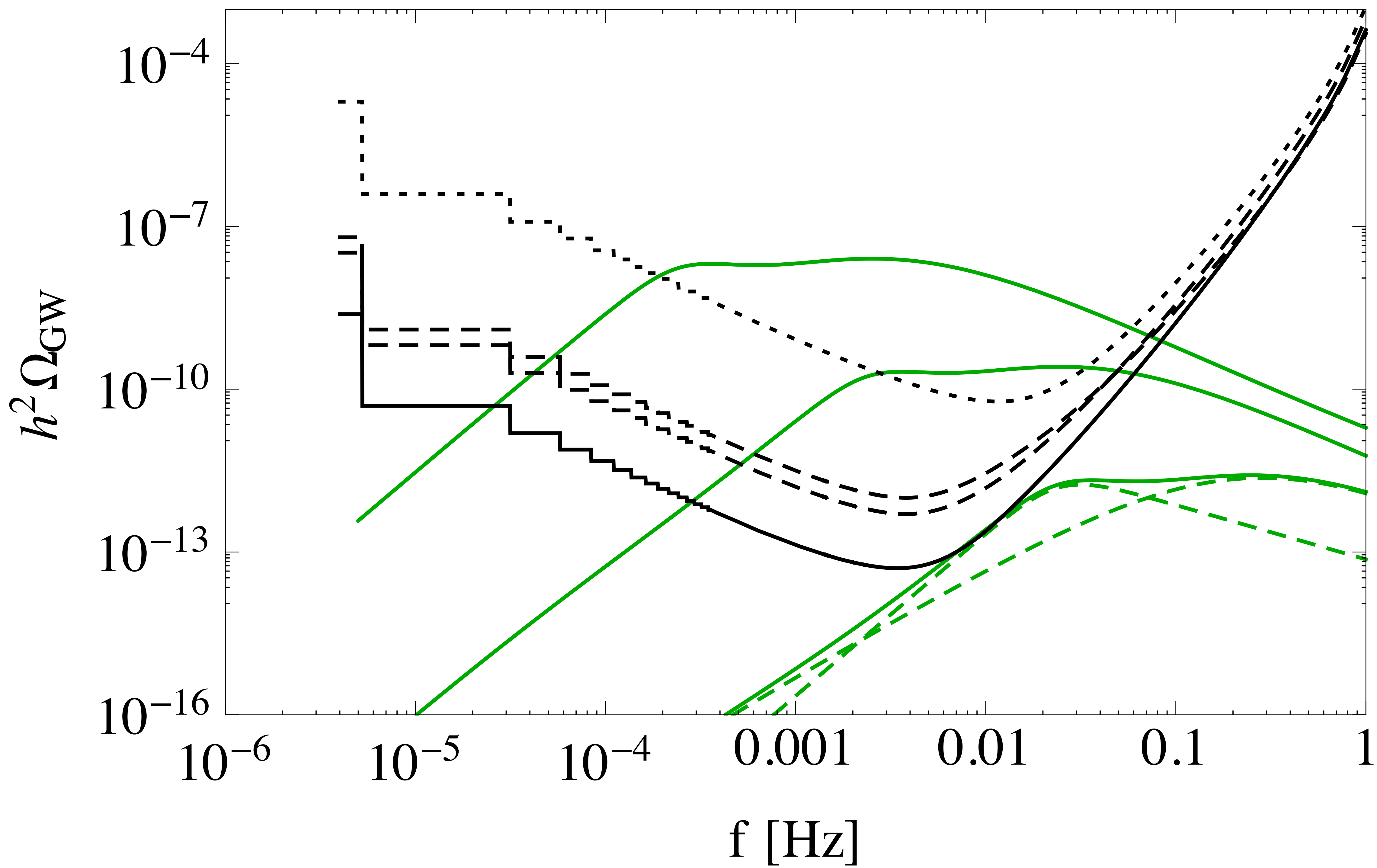
ELISA plots: T*=10 GeV



ELISA plots: T*=100 GeV



ELISA plots: T*=10 TeV



Signal Strength

- Strong signal motivated by radion stabilized RS models (holographic PT)?
- $n_f = 0$ case doable on the lattice
  - Signal as function of N_d. No other parameters!
  - Theta dependence?
- $n_f \geq 3$ difficult on the lattice
  - Holography? Large N?

Summary

- SU(N) dark sectors well motivated, often feature first order PT (also: Dark Baryogenesis!)
- Some Dark Matter models suggests GW signal in range of ELISA
  - Less dependent on LHC results, frequencies above/below strong EWPT scenario possible
  - GW - DM connection, possible first trace of very heavy DM
  - More precise study (lattice) needed for accurate predictions