Gravitational Waves from a Dark Sector

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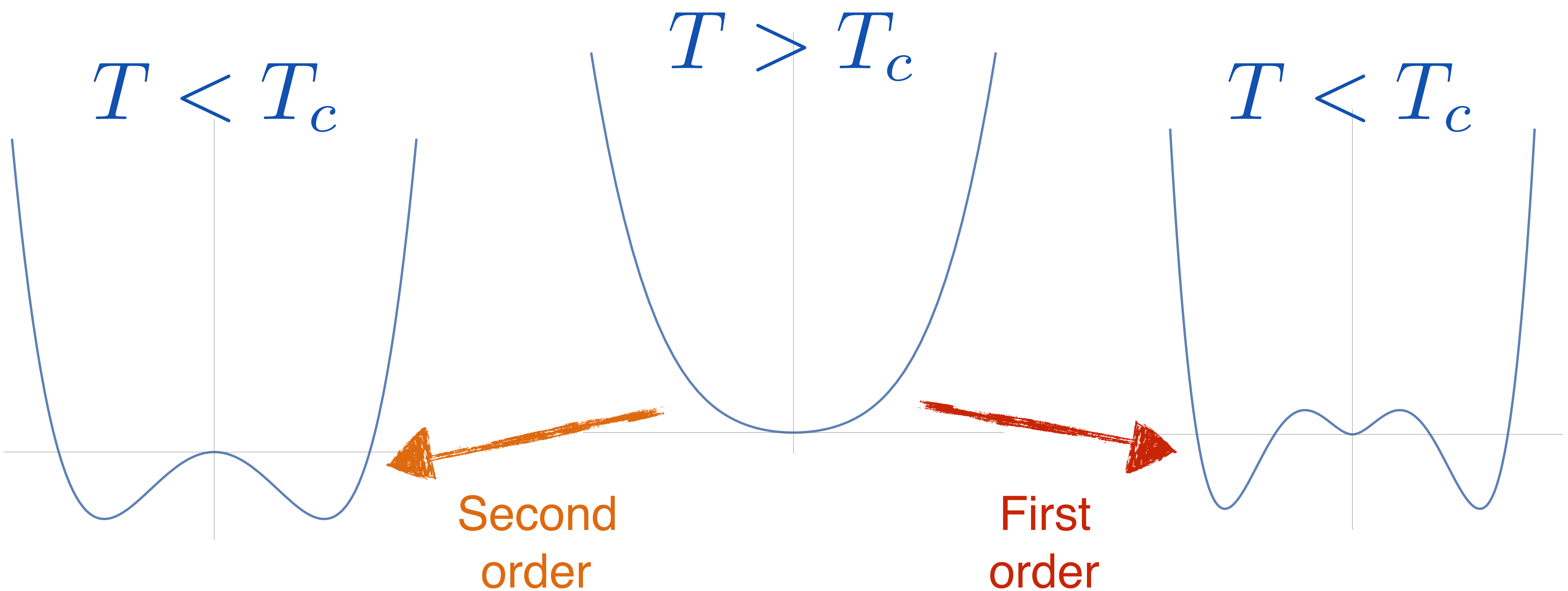
Cosmological Phase Transitions

- Early Universe in symmetric phase (e.g. unbroken electroweak symmetry)

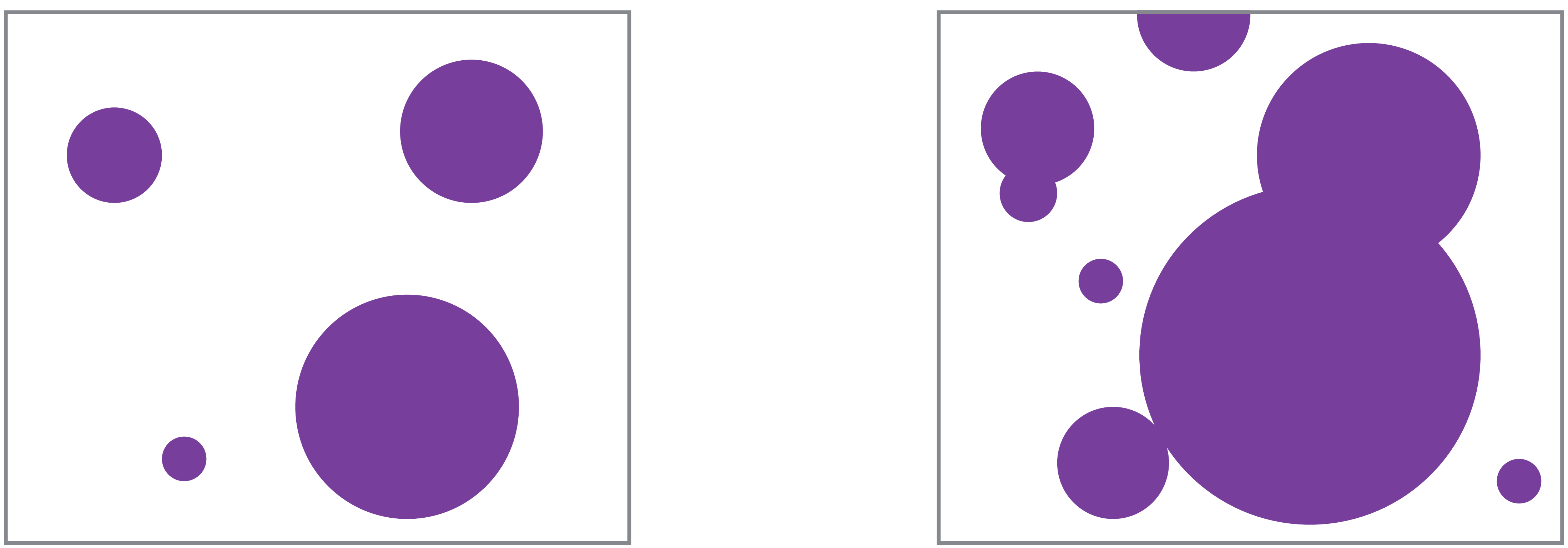


GWs from PTs

First order PT ➞ Bubbles nucleate, expand

Bubble collisions ➞ Gravitational Waves

See talks by Hindmarsh, Weir for more details



Peak Frequency

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

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

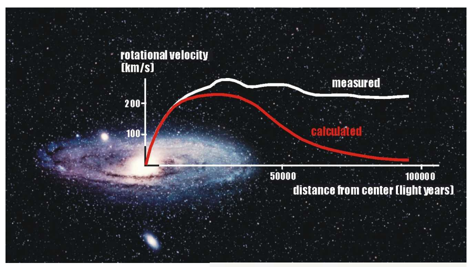
GWs as window to dark matter sector

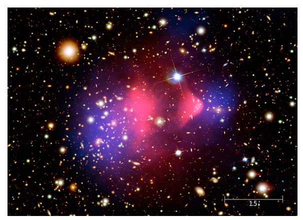
- Motivation for (non-abelian) Dark Sectors
- Phase Transition of SU(N) Theories
- GW Signals from PTRs to ELISA

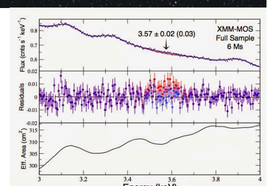
Based on PRL 115 (2015) 18, 181101

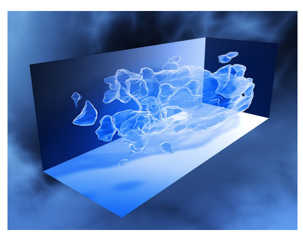
Dark Matter

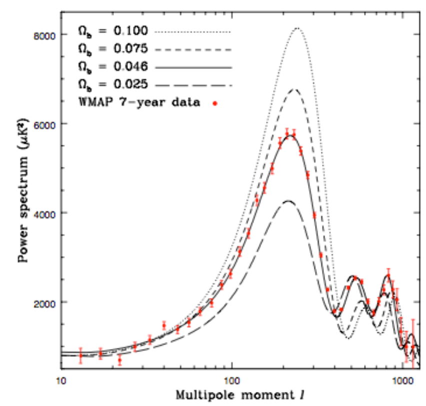
We have seen DM in the sky:



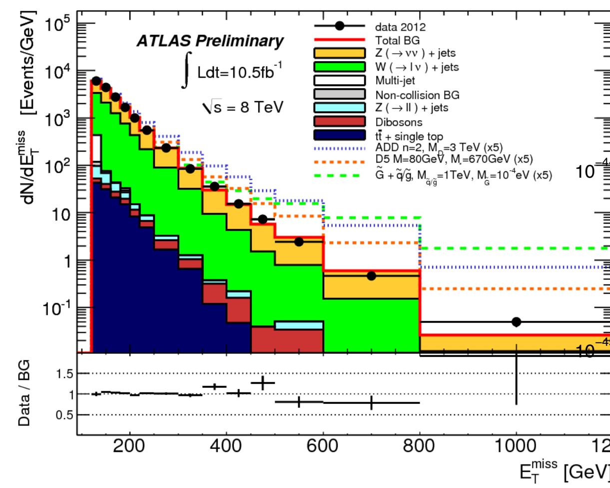


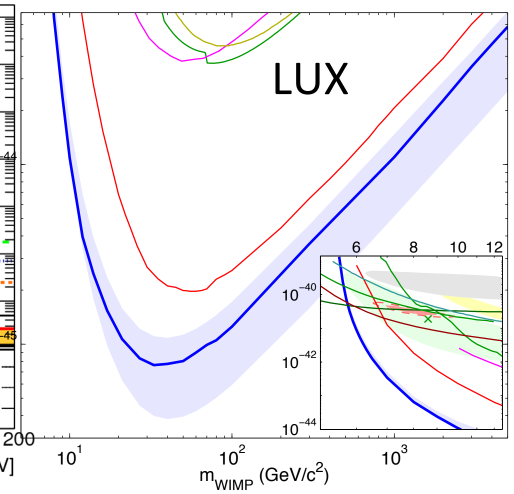






But no direct observation

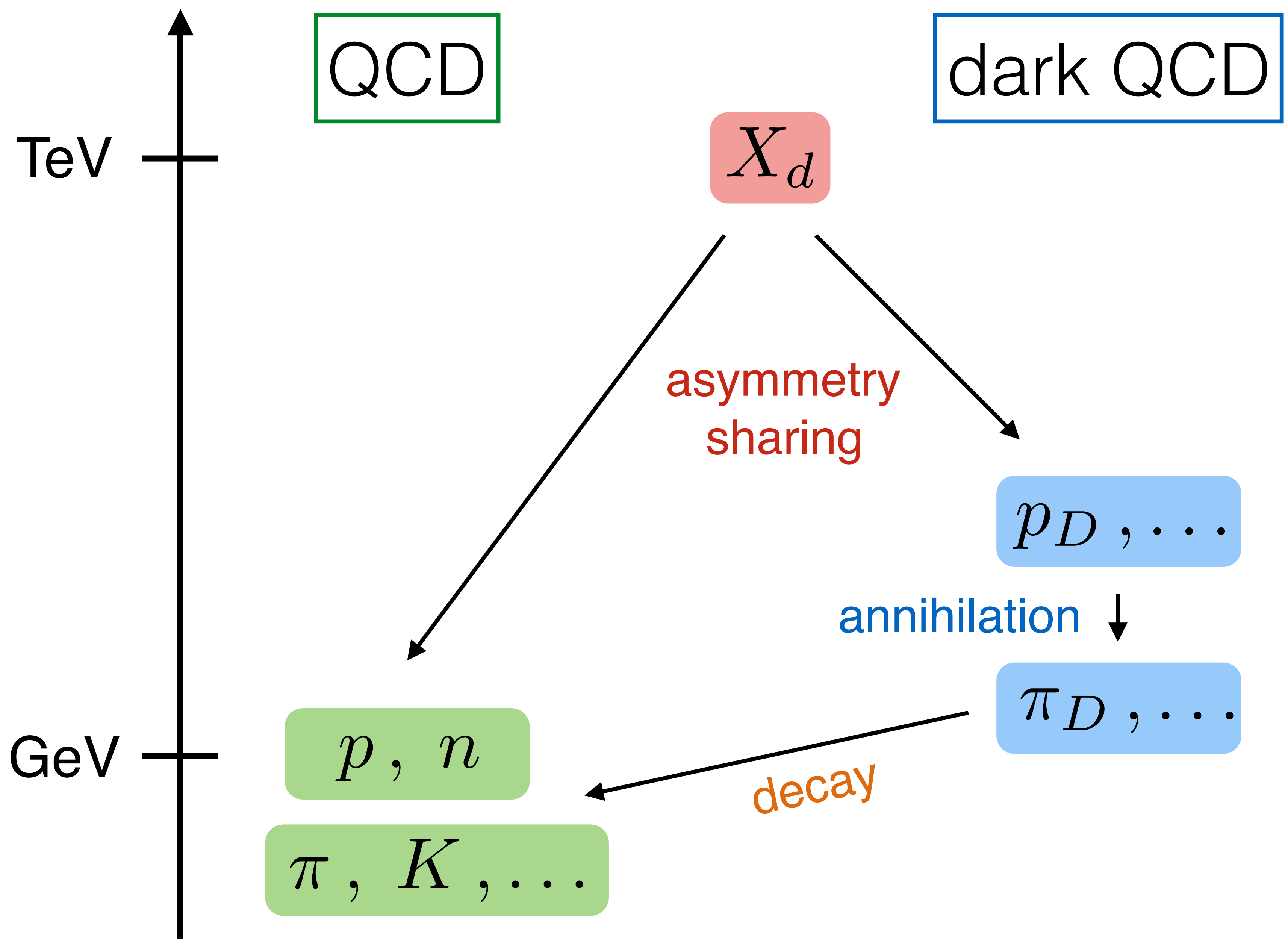




Maybe DM is just part of a larger dark sector

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

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;

DM Motivation

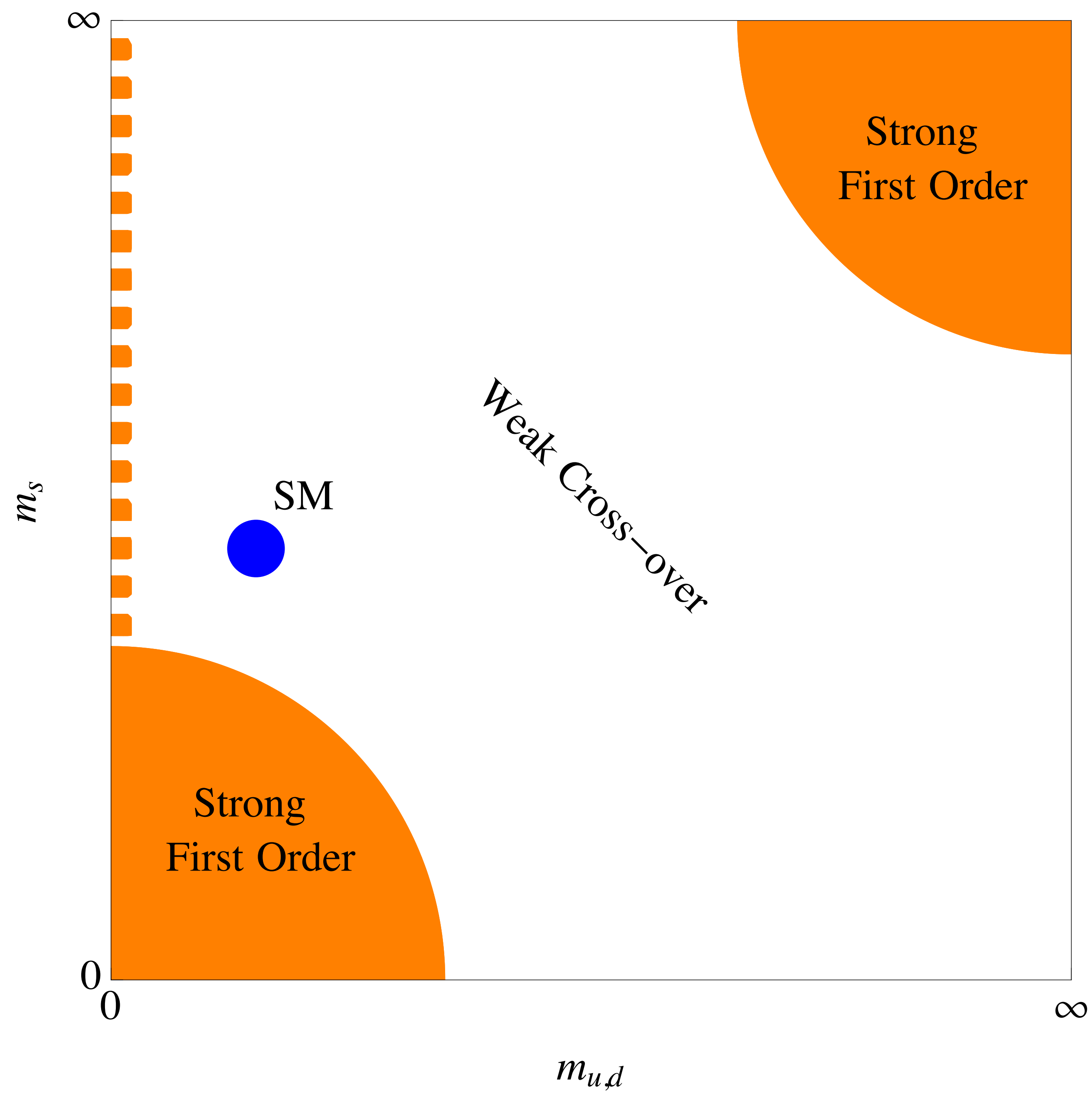
- New mechanisms for relic density, extend mass range:
  - Asymmetric DM - GeV-TeV scale
  - Strong Annihilation - 100 TeV scale
  - SIMP - MeV scale
    Hochberg, Kuflik, Volansky, Wacker, 2014; + Murayama, 2015
- Advantages of Composite
  - DM mass scale and stability
  - Fast annihilation for ADM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

The Dark Phase Transition

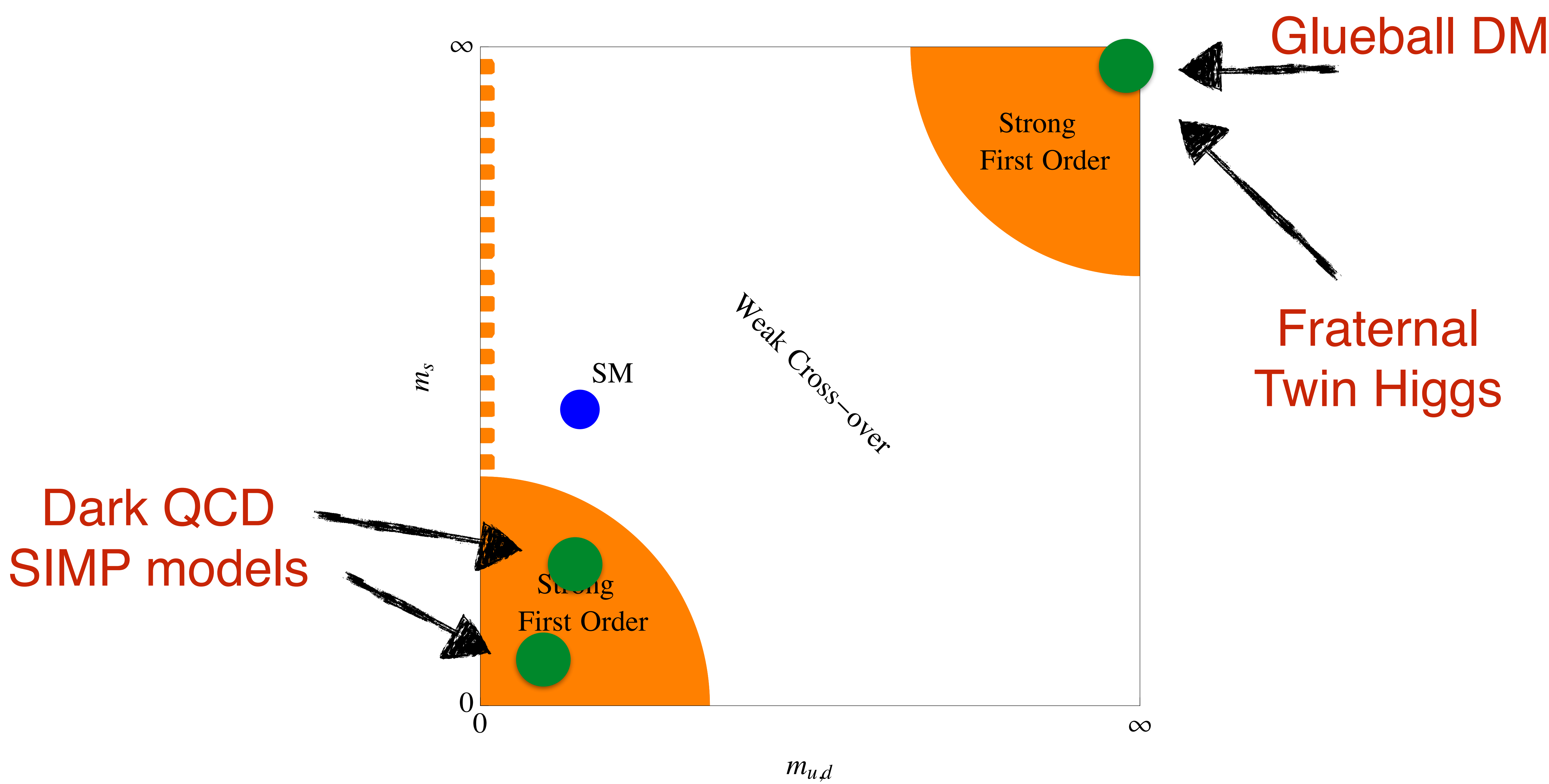
Phase Transition

- 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: $\Lambda_d \sim {\rm few} \times \Lambda_{\rm QCD}$
- First order PT in large class of models
- Still possible if LHC finds no new physics

QCD Phase Diagram



Phase Diagram II

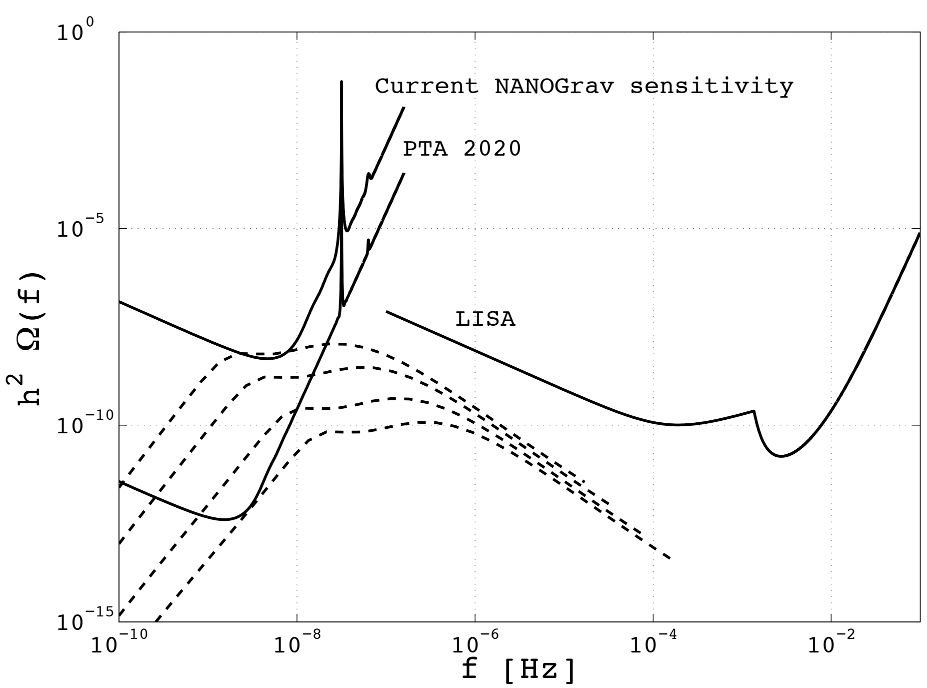


SU(N) - PT

- 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

See talks by Hindmarsh, Weir for more details

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

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

$$v = 1$$

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

Reminder - DM scale

- Redshift:

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DM mass

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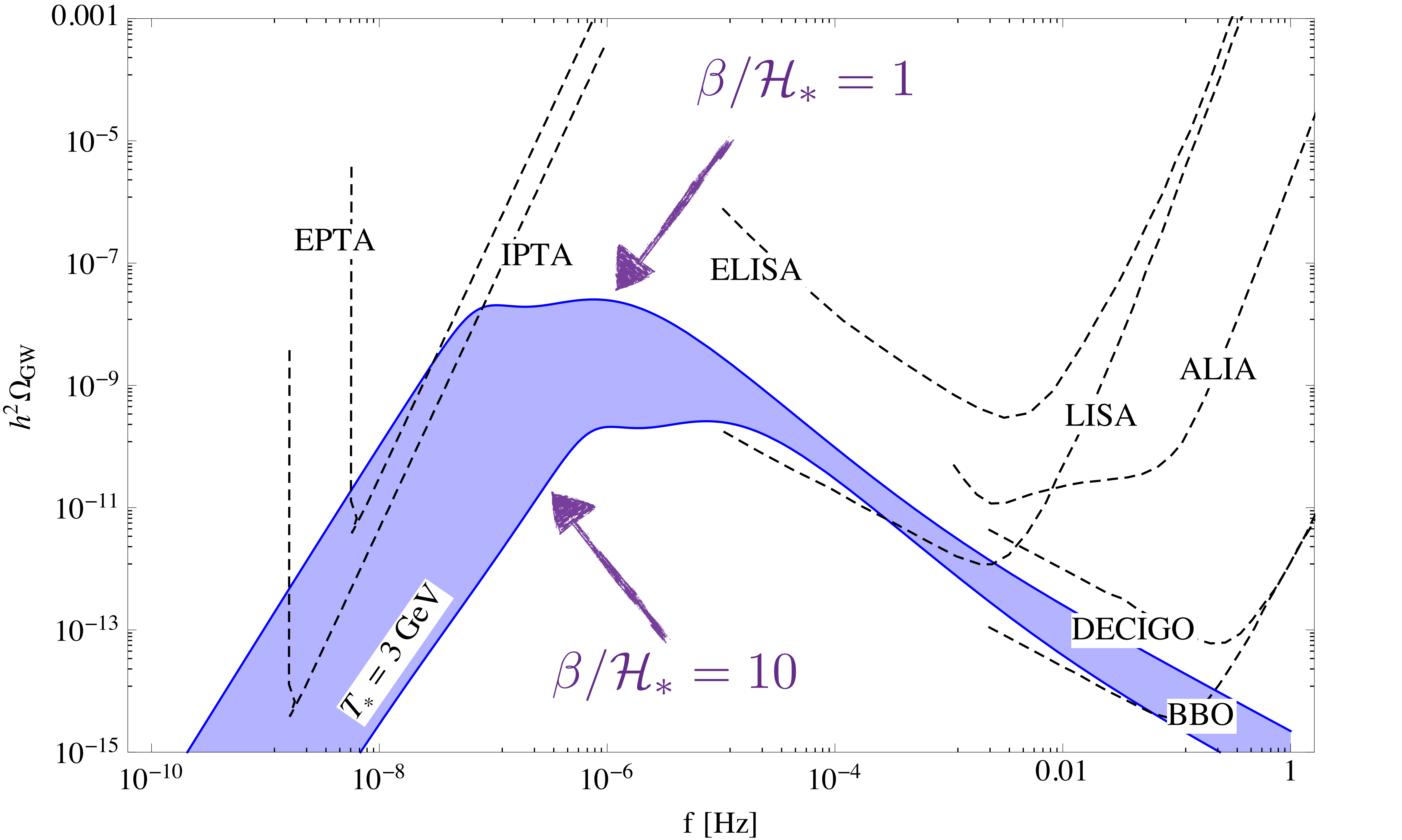
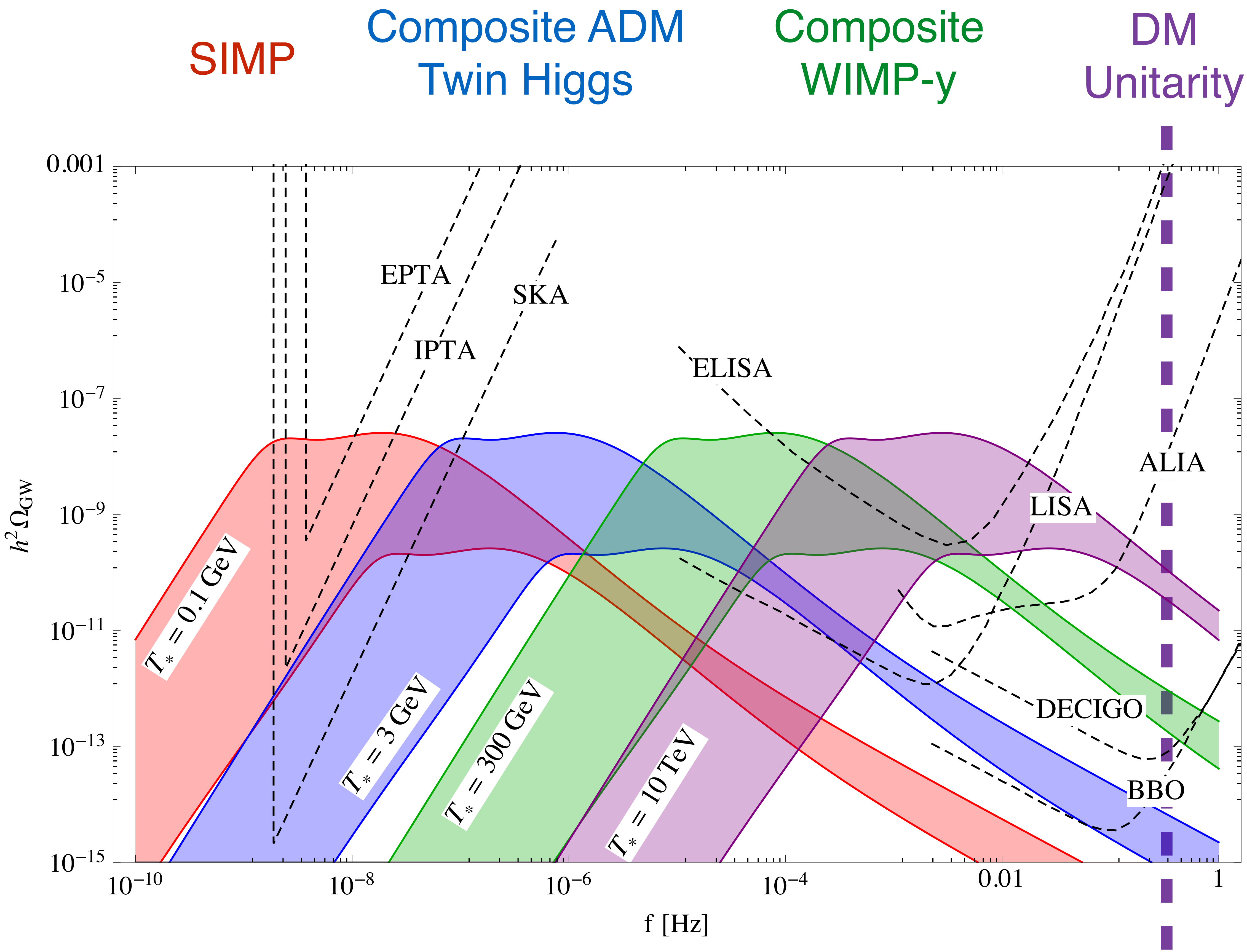
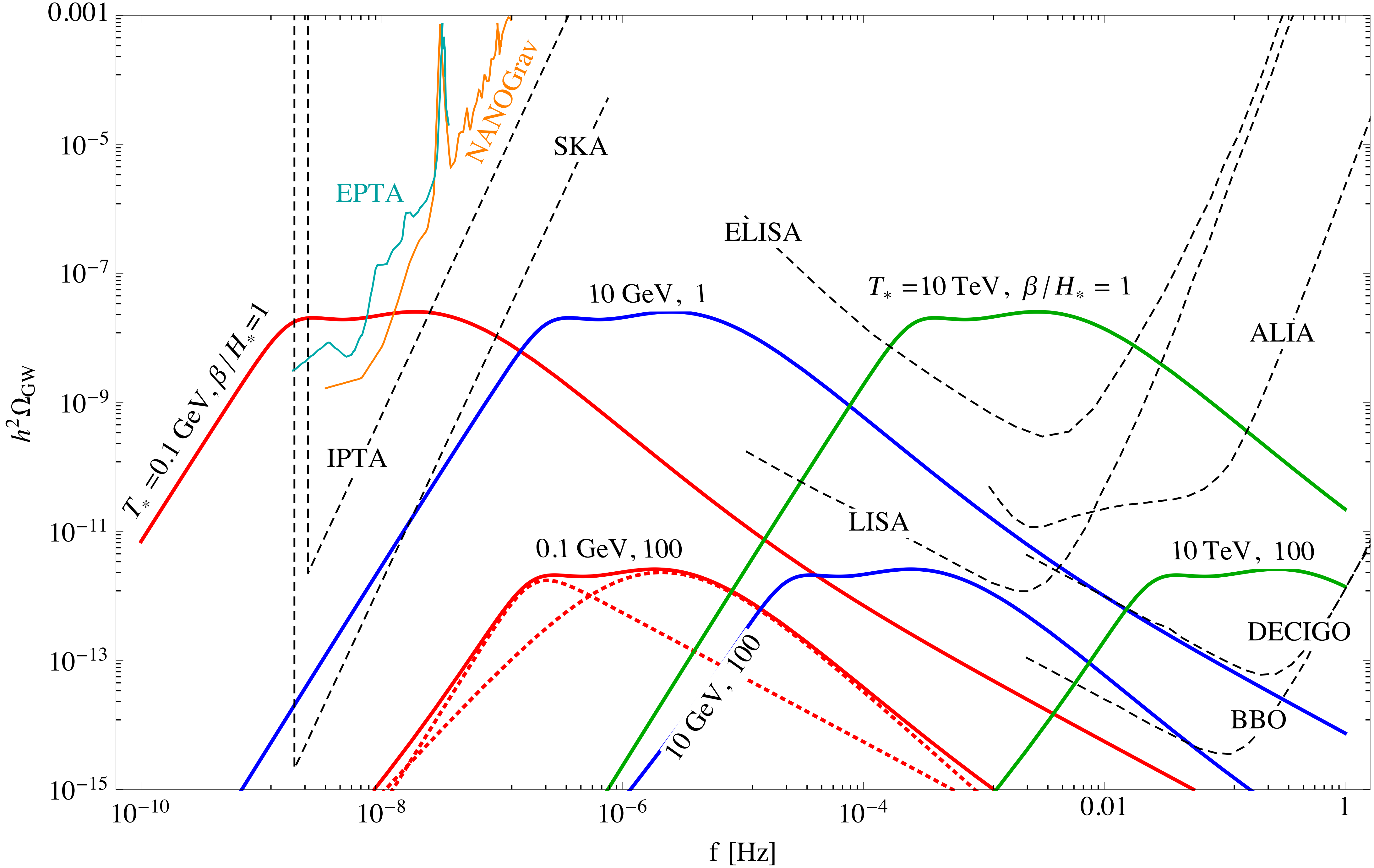
T* ~ Few GeV



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


SIMP
Composite ADM
Twin Higgs
Composite
WIMP-y
DM
Unitarity
EPTA
SKA
IPTA
ELISA
ALIA
LISA
DECIGO
BBO
T* = 0.1 GeV
T* = 3 GeV
T* = 300 GeV
T* = 10 TeV
0.001
10^-5
10^-7
10^-9
10^-11
10^-13
10^-15
h^2 Ω_GW
10^-10
10^-8
10^-6
10^-4
0.01
1
f [Hz]

Broader Range of Signals



Summary

- SU(N) dark sectors well motivated, often feature first order PT (also: Dark Baryogenesis!)
- Exciting possibility to probe
  - GeV scale dark sectors with PTA data (already putting limits!)
  - TeV scale dark sectors with ELISA (see upcoming publication of ELISA Cosmology working group)
- Any ideas to probe the 10^{-6} Hz gap?