Gravitational waves from cosmological phase transitions

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Research Foundation Flanders
Opening new horizons

Introduction

BEH mechanism: spontaneous symmetry breaking is at work also at a fundamental level

Hot Big Bang picture: our Universe starts off hot and dense, then expands and cools down

Cosmological phase transitions

Key to address SM open questions: e.g. matter/antimatter asymmetry

Aftermath of phase transitions **directly observable in gravitational waves**

Outline

Part 1:

Phase transition at temperature T_c

$\langle \phi \rangle : G \to H$

Depending on the topology of the vacuum manifold G/H:

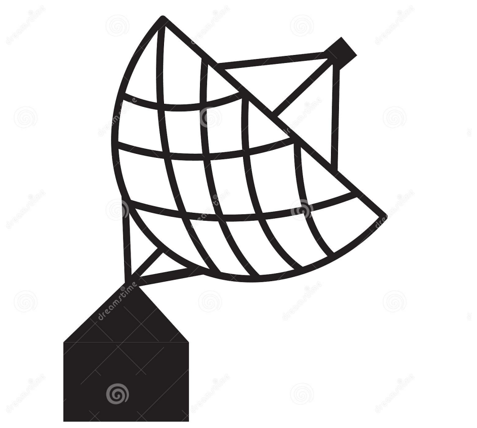
Formation of defects

Depending on the strength of the (1st order) transition:

Bubble nucleation

Non-trivial interplay:

Multi-step phase transitions and the role of impurities



Part 2: Application to Pulsar Timing Arrays

Defects

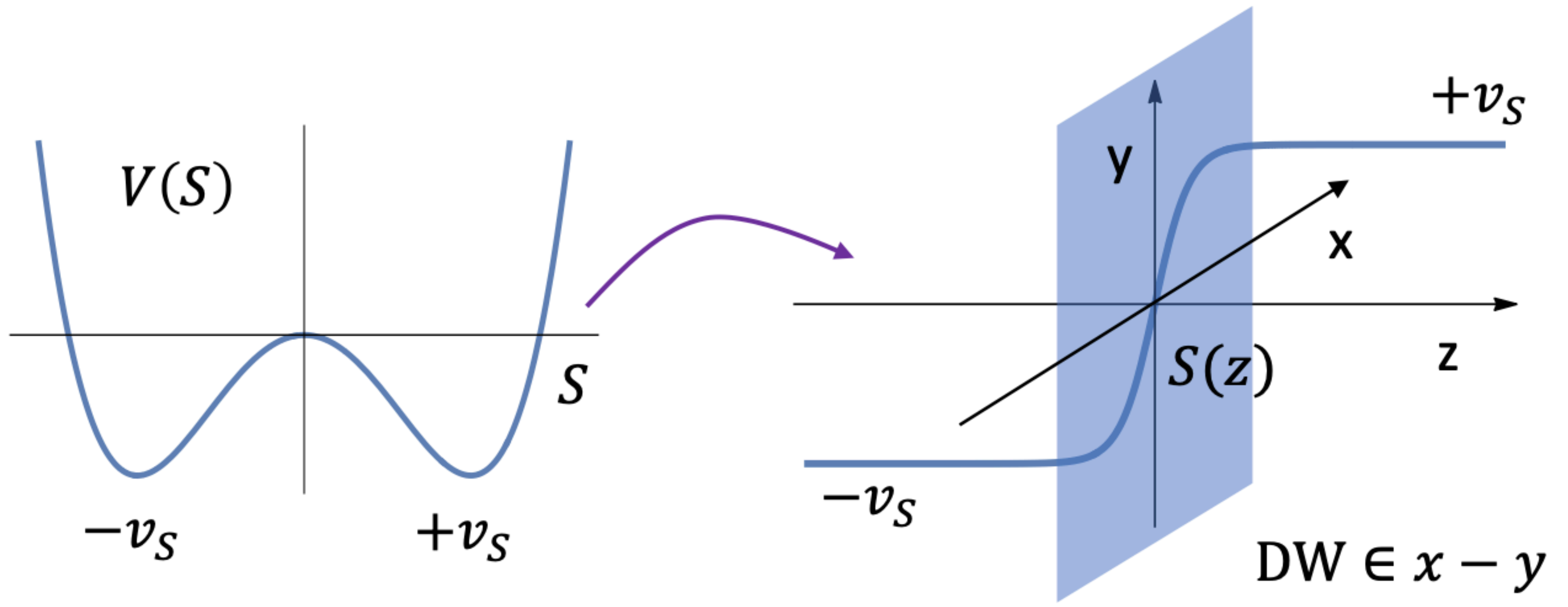
Topological classification

Defect	Dimension	Homotopy	Mass
Domain walls	2	$\pi_0(\mathscr{M})$	σL^2
Strings	1	$\pi_1(\mathscr{M})$	μL
Monopoles	point-like	$\pi_2(\mathscr{M})$	v^2/α

$\mathbb{Z}_2 \to$ nothing

Domain wall tension:

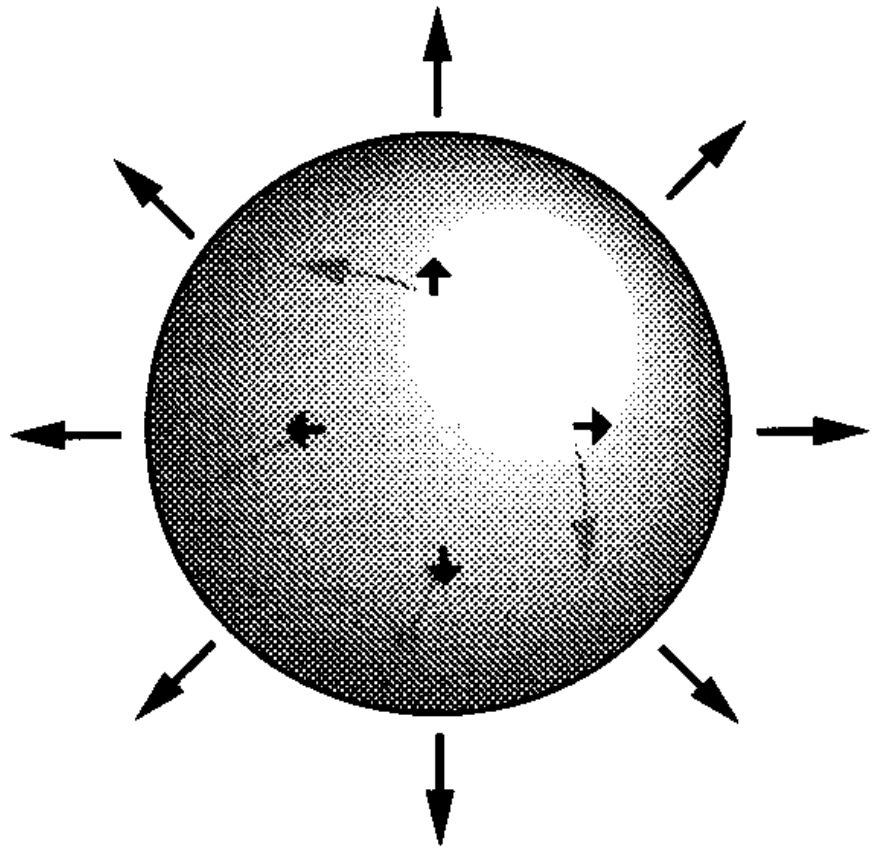
$\sigma \sim v_s^3$



SU(2) $\to$ U(1)

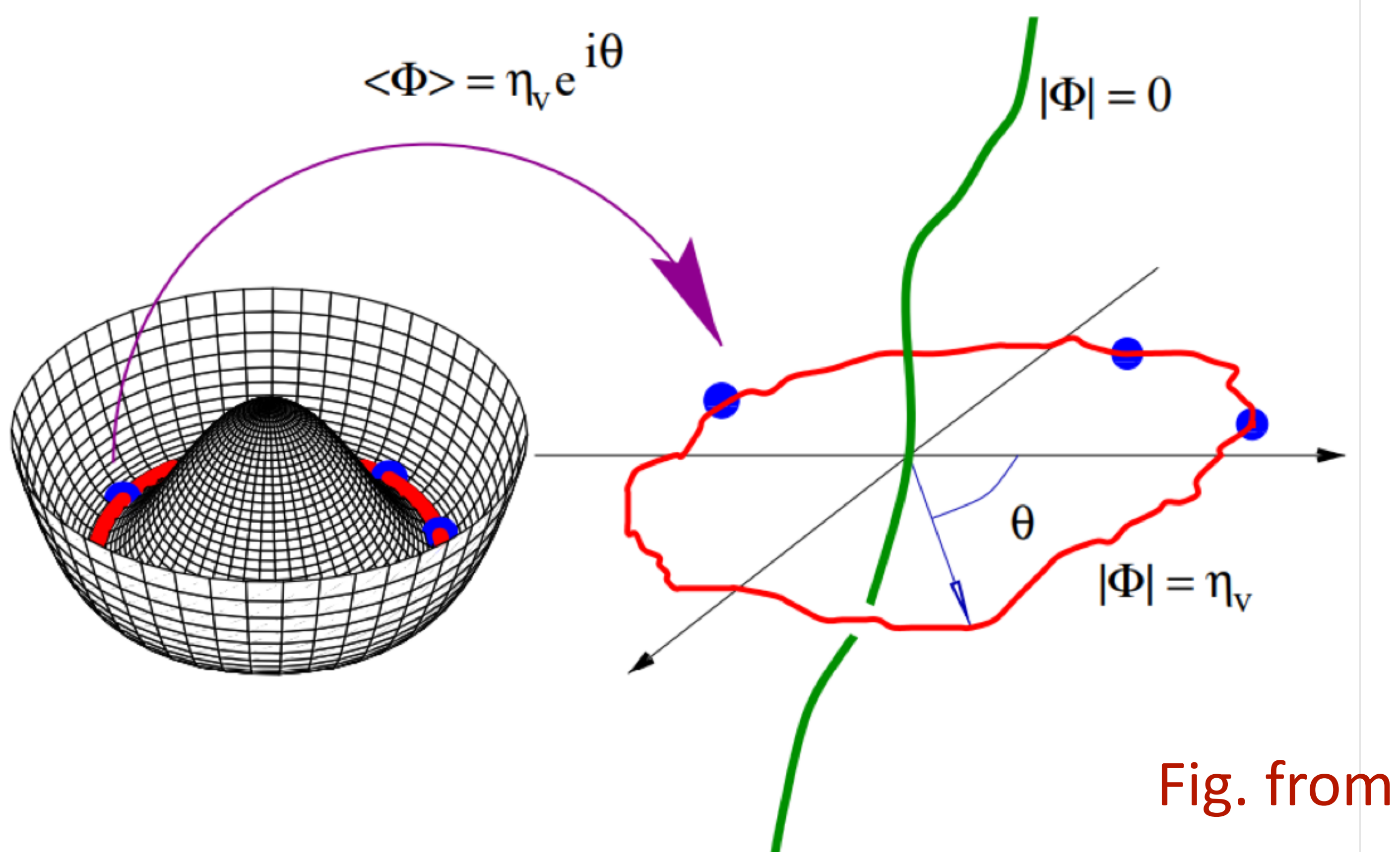
('t Hooft Polyakov Monopole)

Fig. from Vilenkin & Shellard 1994



(a)

U(1) $\to$ nothing



String tension:

$\mu \sim \eta_v^2$

Fig. from Ringeval 2010

Defects

Formation

Kibble mechanism: [Zeldovich et al. 1975, Kibble 1976]

- Fluctuations of scalar field around T_c with finite correlation length $\xi(T) < d_H$
- Uncorrelated patches will generally select different points of vacuum manifold $\mathscr{M}$
- Thermal fluctuations freeze out at T_G this choice cannot be undone and defects will form at the boundary of different domains

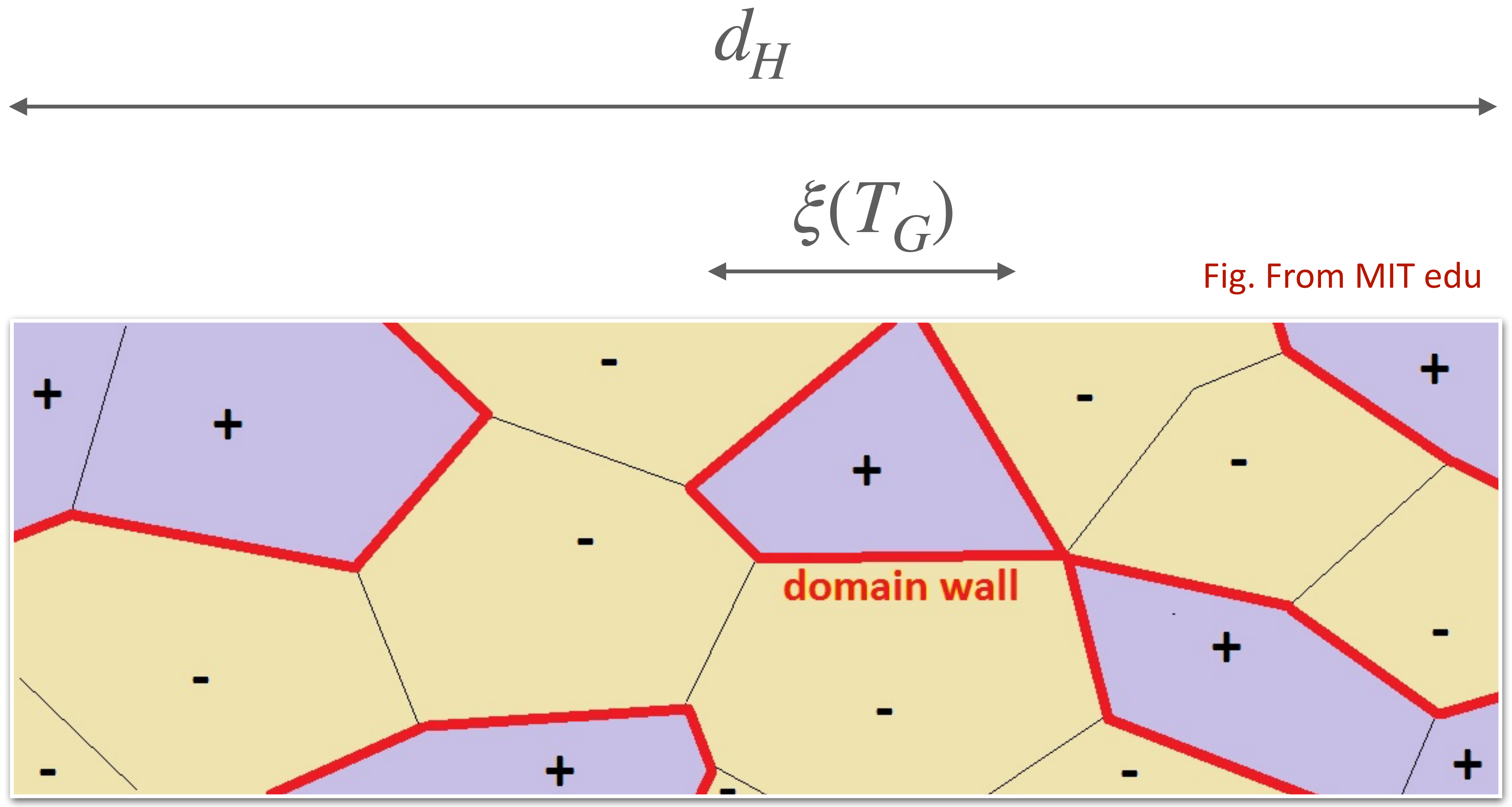


Fig. From MIT edu

- Independent of the details of the effective potential
- Size of the domains does depend on the underlying particle physics

Defects
Evolution

Evolution of the network encoded in $\xi(t)$.
Two limiting cases:

- **Causality-saturating** (scaling):

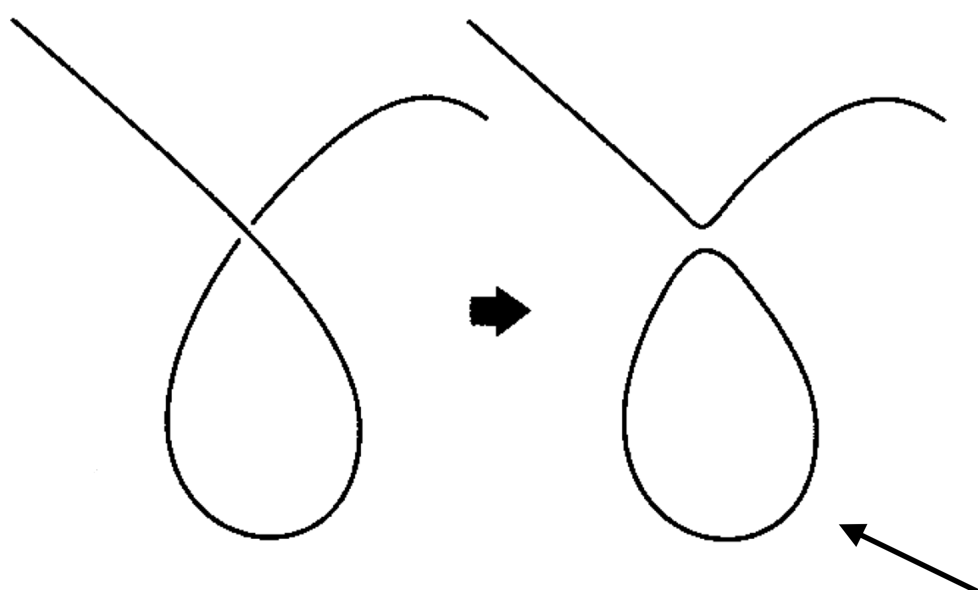
$$\xi(t) \sim d_H(t) \sim t$$

- **Kinematic** (driven by cosmological expansion only):

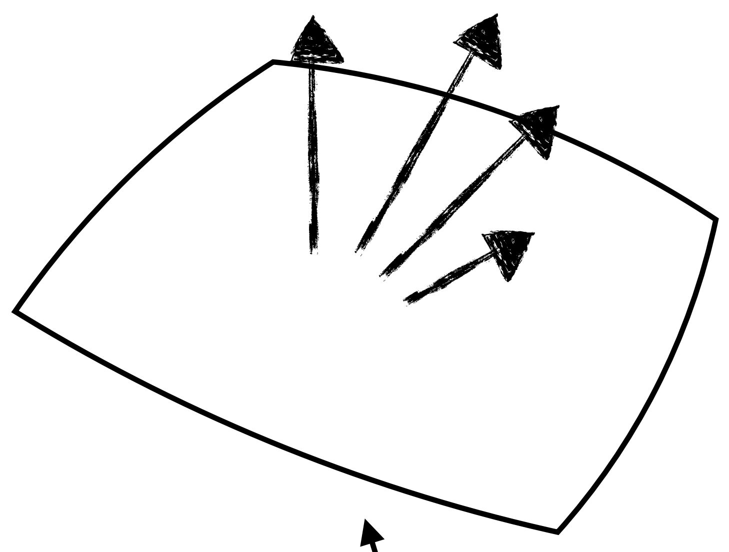
$$\xi(t) \sim \xi(t_0)\, a(t)$$

[Press, Ryden, Spergel 1989]

Loop chopping (strings)



Particle production and wall collisions (domain walls)



$$\Omega = \rho_d/\rho_c \sim G t^2 \rho_d$$

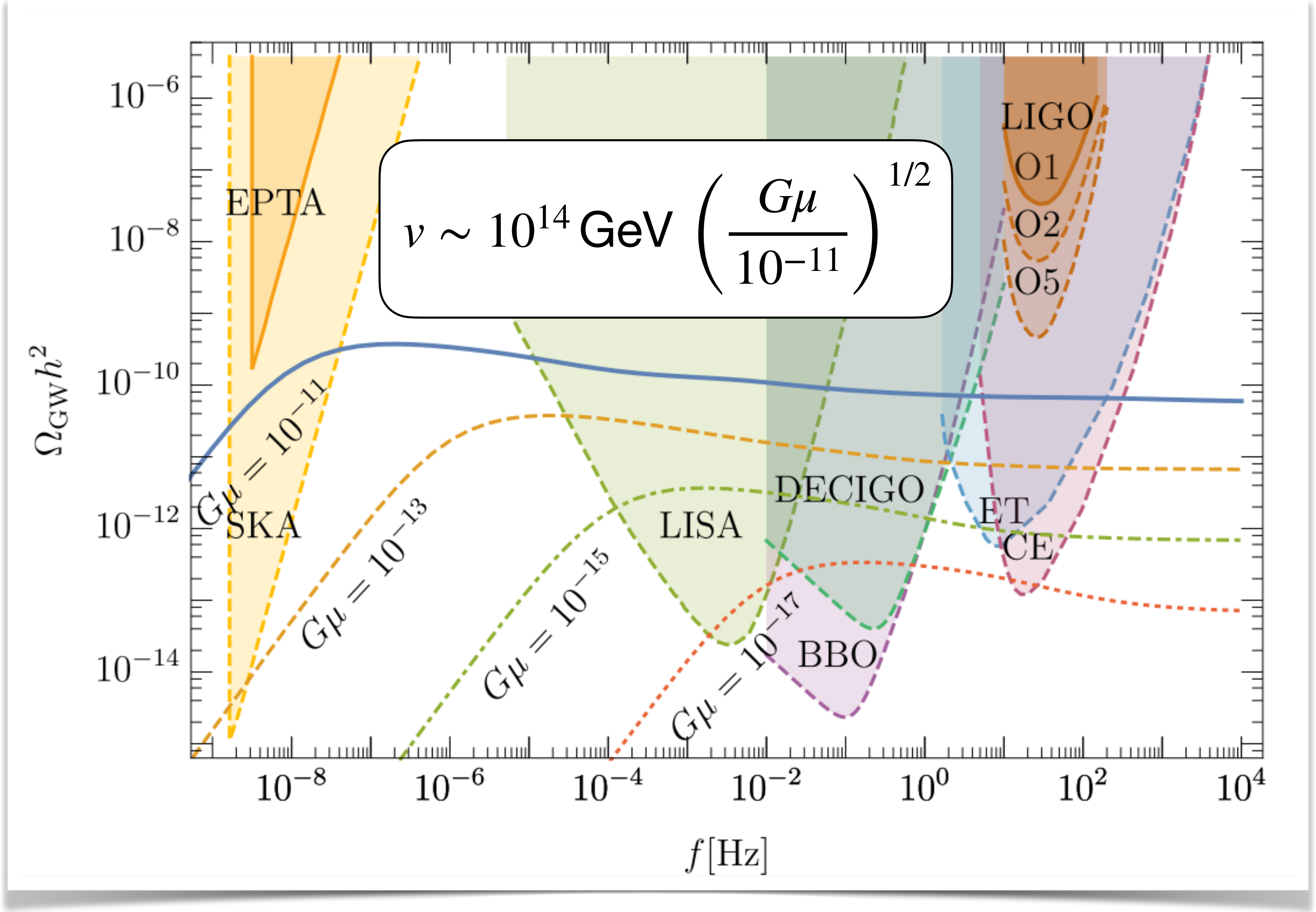
Requires efficient energy losses

	Energy density	**Kinematic**	**Causality-saturating**
Domain walls	$\rho_{dw} = \dfrac{\sigma}{\xi(t)}$	$\Omega \sim \dfrac{G\sigma t^2}{\xi(t_0)a(t)}$	$\Omega \sim G\sigma t$
Cosmic strings	$\rho_{cs} = \dfrac{\mu}{\xi(t)^2}$	$\Omega \sim \dfrac{G\mu t^2}{\xi(t_0)^2 a(t)^2}$	$\Omega \sim G\mu$

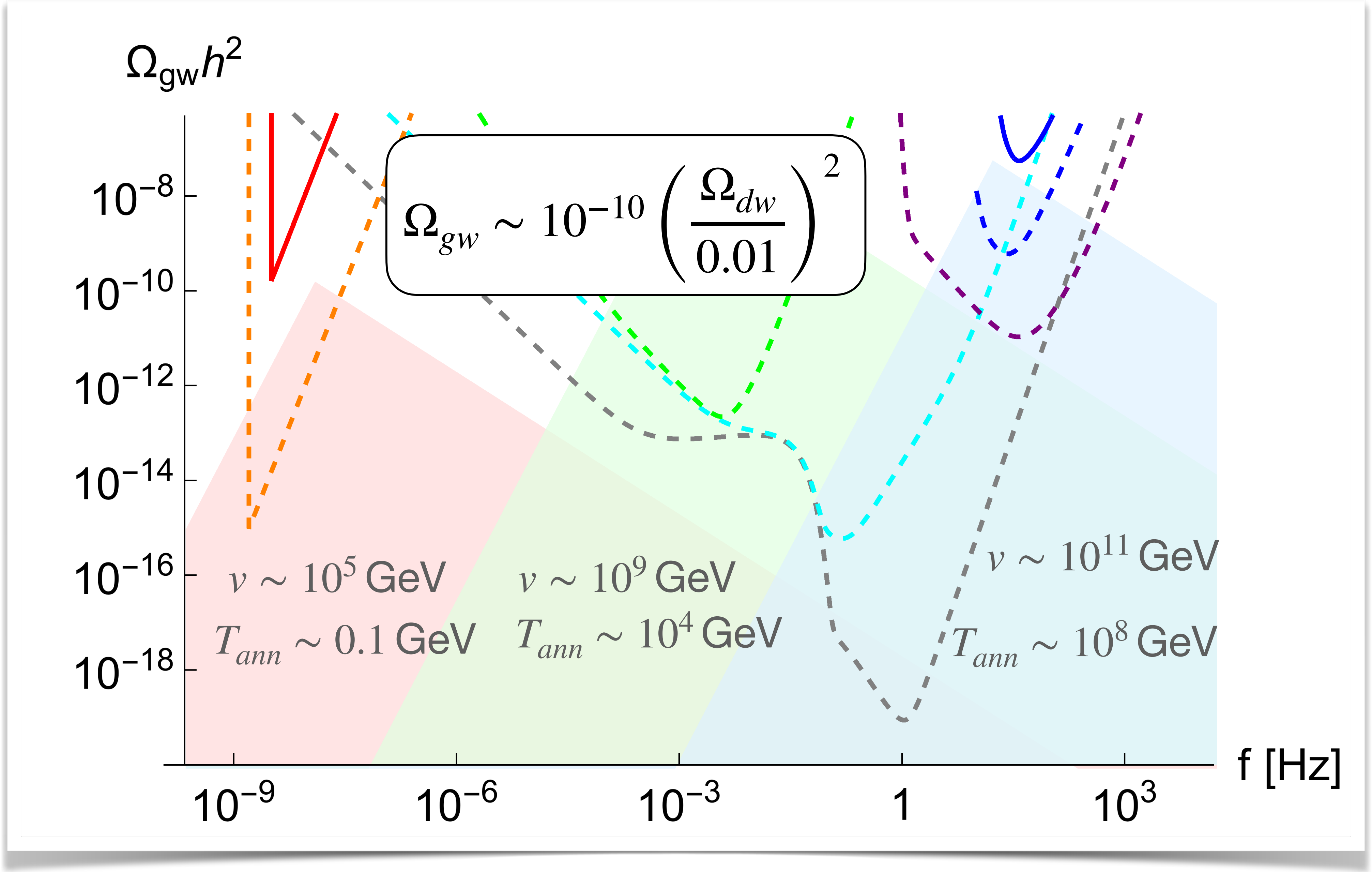
Note: the domain wall network must annihilate before it comes to dominate!

Defects

Gravitational waves



[Cui et al. 1808.08968]



Saikawa's review 2017

Cosmic strings:

- Emission dominated by the loops
- Loops are long lived, act as long-lasting source
- Spectrum is flat up to matter-radiation equality

Domain walls:

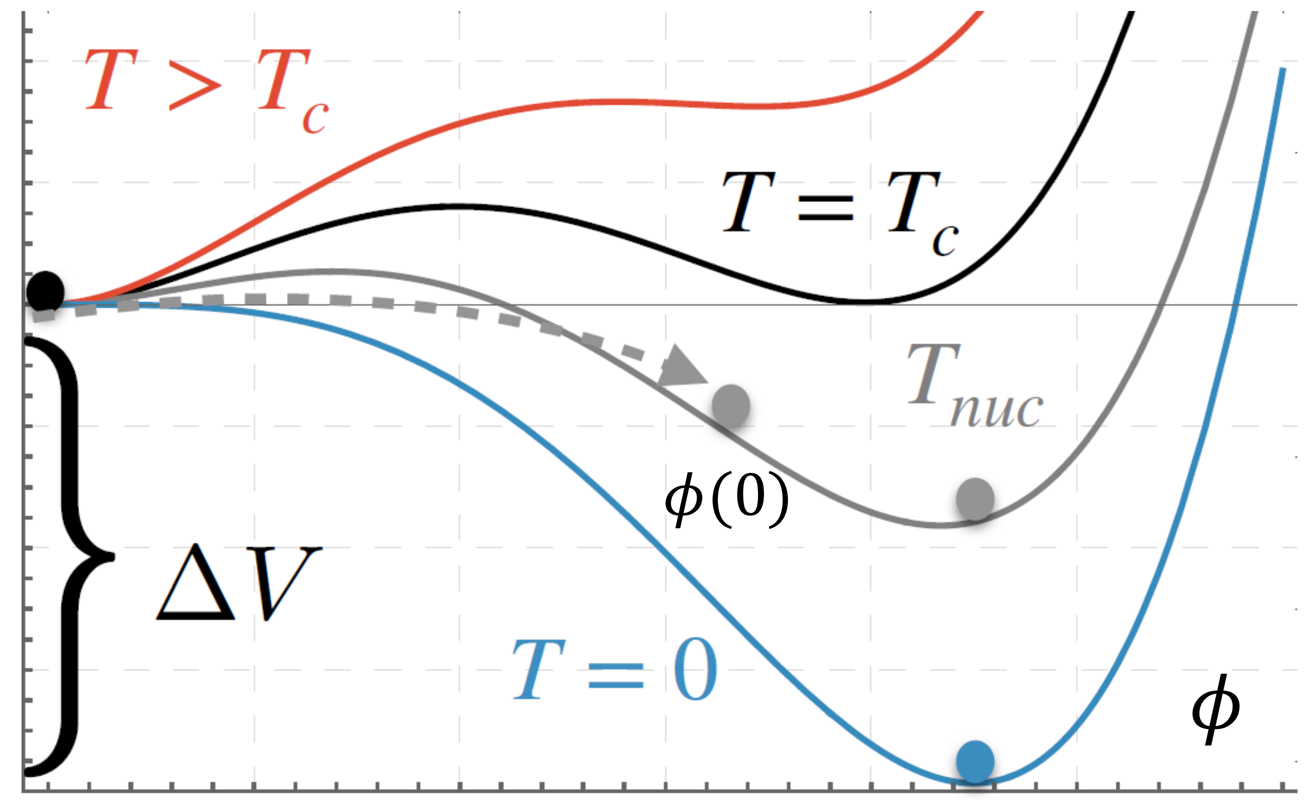
- Emission dominated by oscillations of large walls
- Main contribution at the time of network annihilation
- Spectrum is peaked at corresponding frequency

First order transitions

Tunneling and bubble nucleation

Discontinuity in the order parameter $\langle\phi\rangle$, **barrier** separating the false and the true vacuum.

The transition proceeds via bubble nucleation as a result of **quantum** and/or **thermal tunneling**.



$\beta = 1/T$

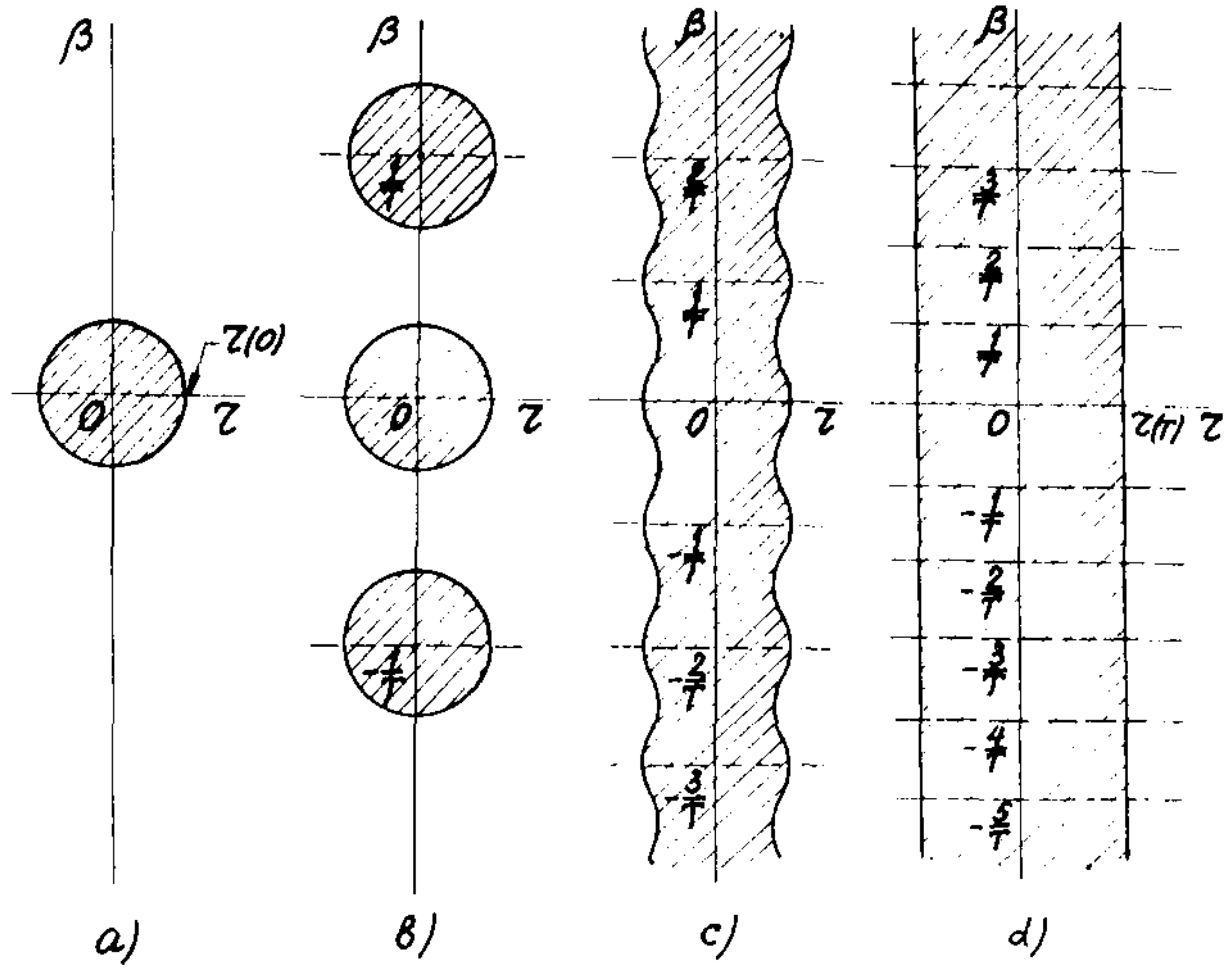


Fig. from Linde 1983 NPB

Assume **thermal fluctuations in homogeneous space time**: O(3) "bounce" solution to EOM

$$\phi''(r) + \frac{2}{r}\phi'(r) = \frac{\partial V}{\partial \phi}, \qquad \phi'(0) = 0, \quad \phi(\infty) = 0$$

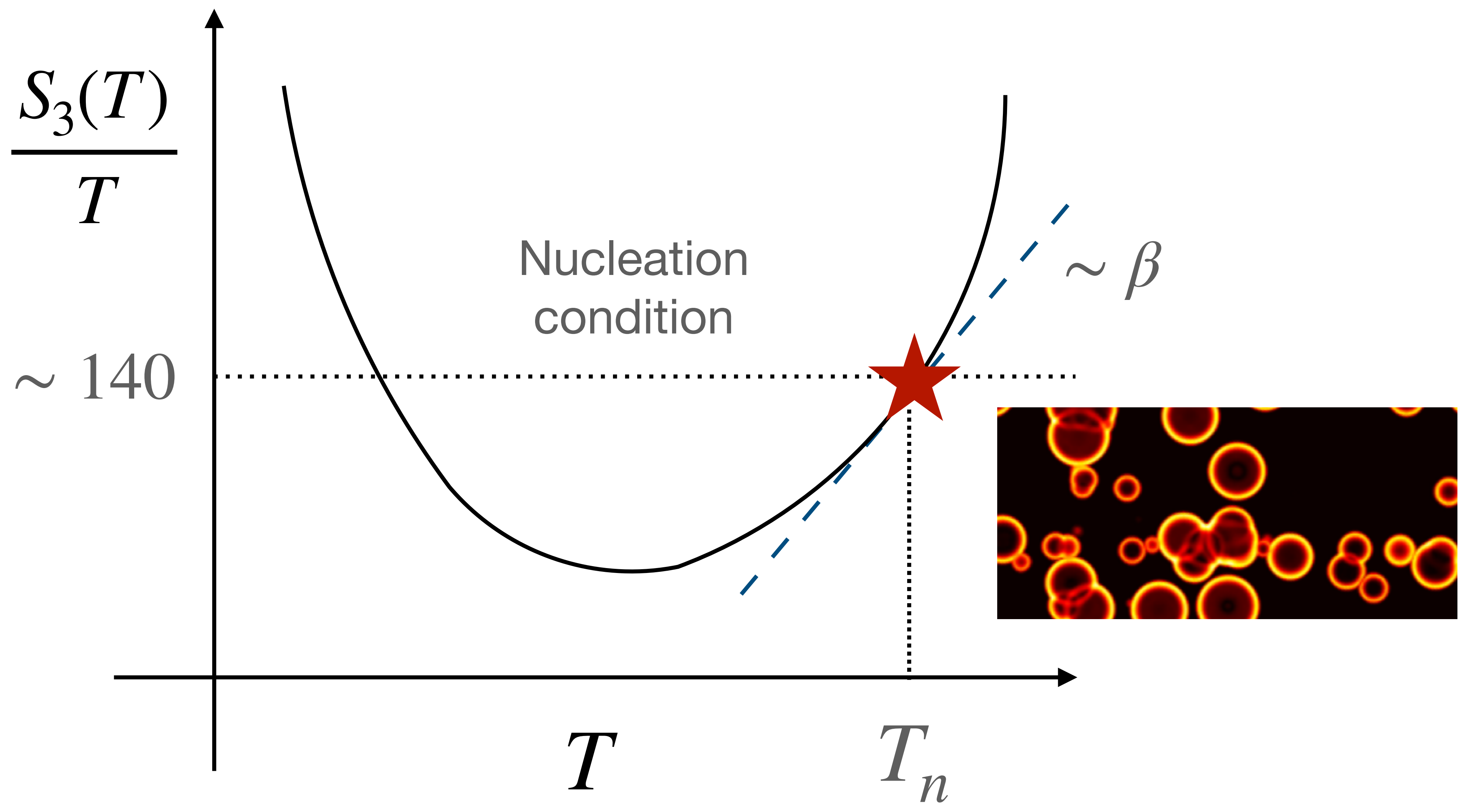
The corresponding action determines the **nucleation rate per unit volume**:

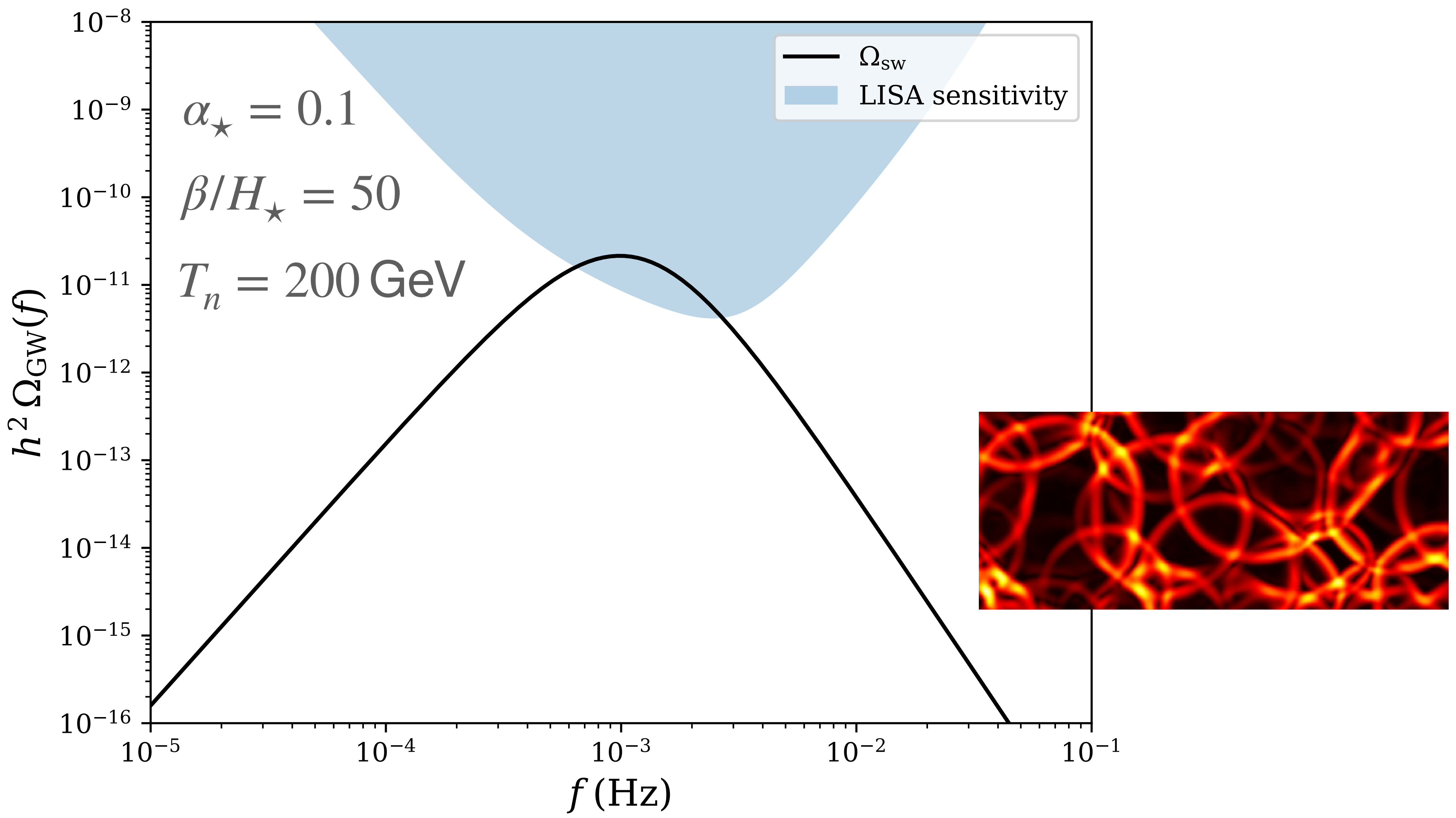
$$\gamma_V(T) \sim T^4 \exp(-S_3/T)$$

First order transitions

Thermodynamics and gravitational waves

Bubble figs. From Jinno, Konstandin, Rubira, Stomberg 2209.04369





Energy released in the plasma

$$\alpha_\star \simeq \Delta V/\rho_r$$

Bubble wall velocity

$$\Delta V = \Delta P^{(0)} - \gamma_w \Delta P^{(1)}$$

Nucleation temperature

$$\frac{S_3(T_n)}{T_n} \simeq 4\log(M_{Pl}/T_n) - 11.4 \sim 140$$

Duration of the transition

$$\frac{\beta}{H_\star} = T\frac{d}{dT}(S_3/T)\Big|_{T_n} \sim 100$$

Peak frequency and amplitude for **sound waves**:

$$f|_{peak} \sim 10^{-5}\,\text{Hz}\left(\frac{\beta}{H_\star}\right)\left(\frac{T_*}{100\,\text{GeV}}\right), \qquad h^2\,\Omega_{sw}|_{peak} \sim 10^{-6}\left(\frac{H_\star}{\beta}\right)(\kappa_v\,\alpha_\star)^2$$

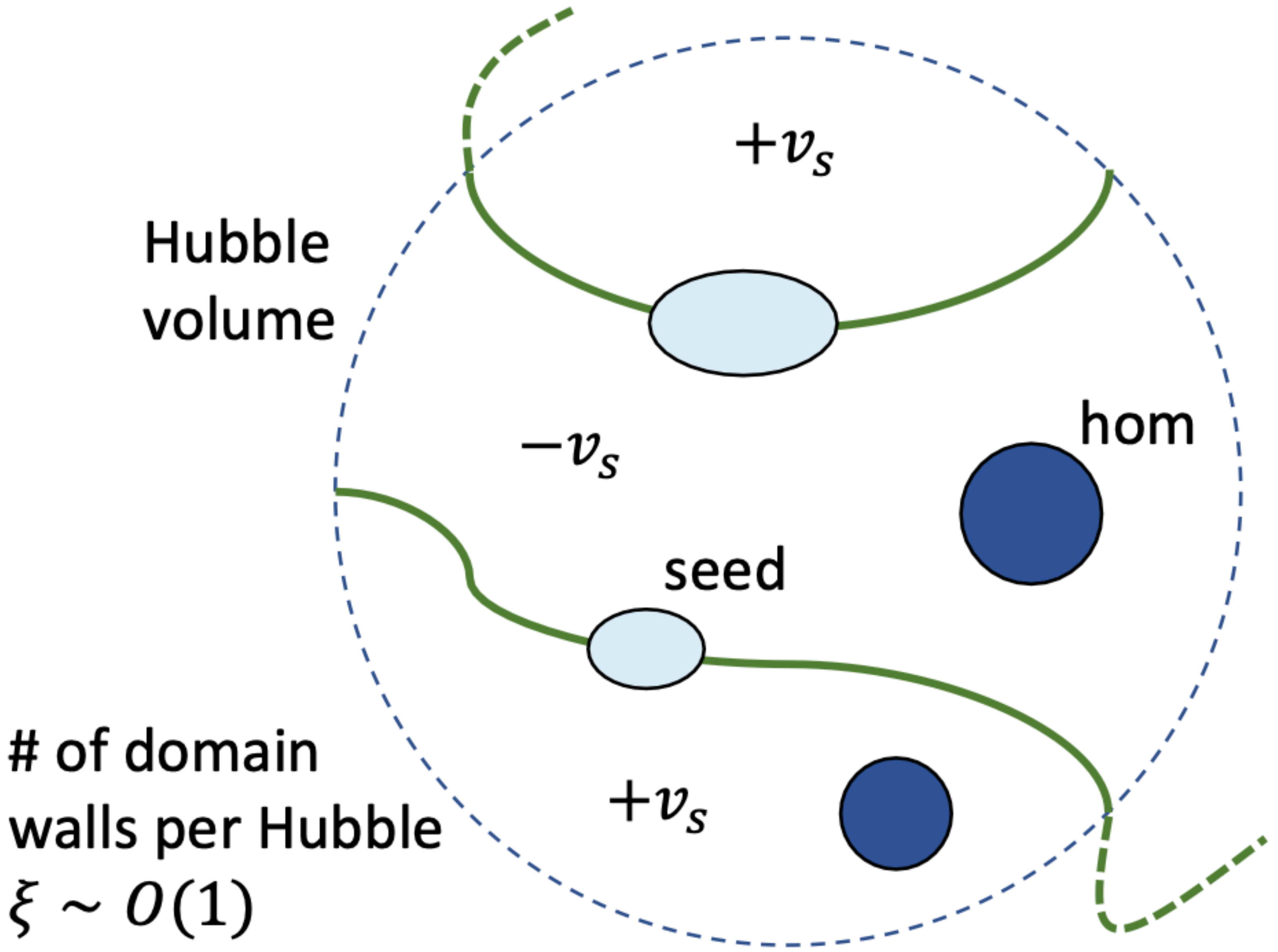
Other contributions: **bubble collisions** and **turbulence**

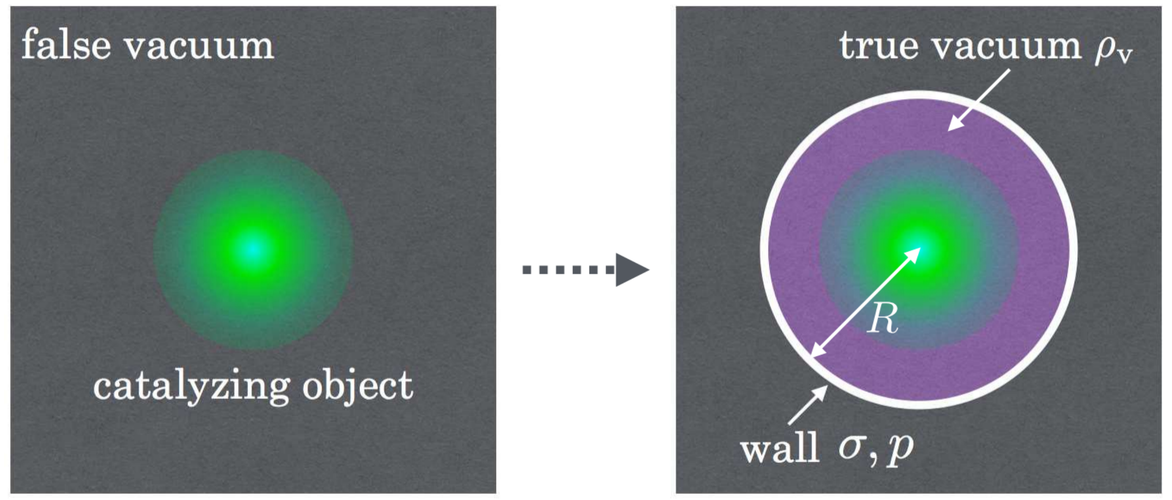
Defects as nucleation seeds

General idea

Impurities inside the horizon provide new “decay channel” for the false vacuum.

P.J. Steinhardt NPB 1981, Y. Hosotani PRD 1983, E. Witten PRD 1984



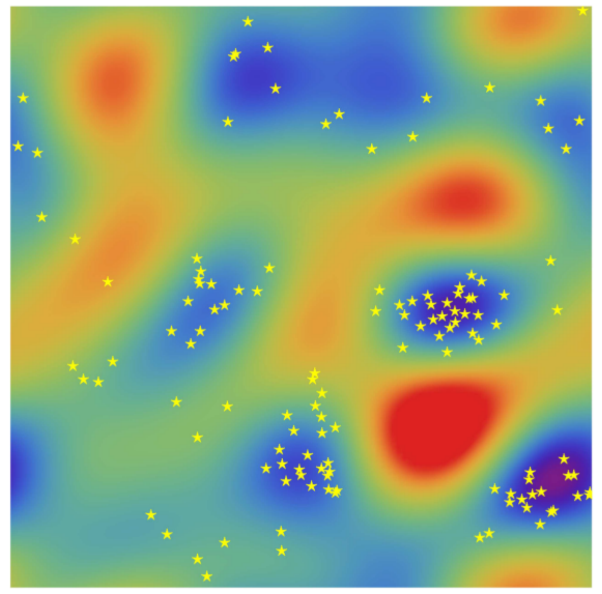


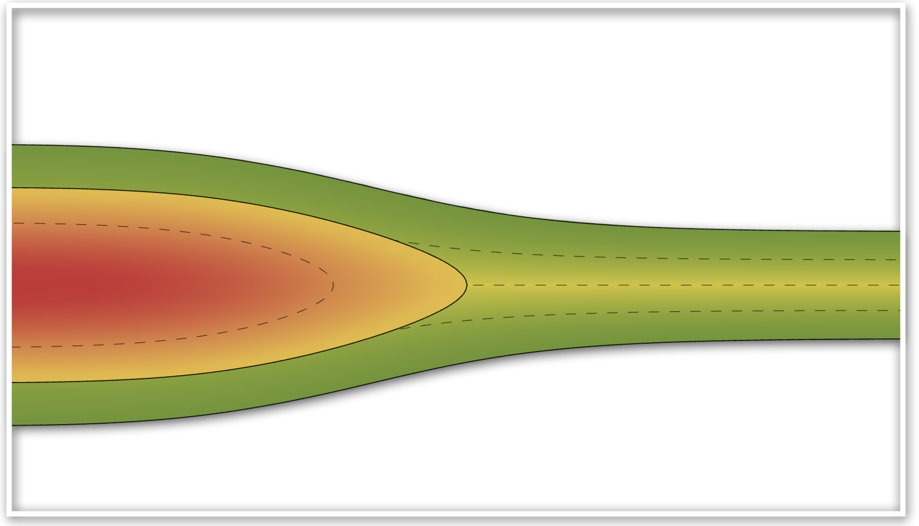
- Compact objects

Fig. from Oshita, Yamada, Yamaguchi [1808.01382], PLB

- Primordial density fluctuations

Fig. from Jinno, Konstandin, Rubira, van de Vis, [2108.11947], JCAP





- Topological defects

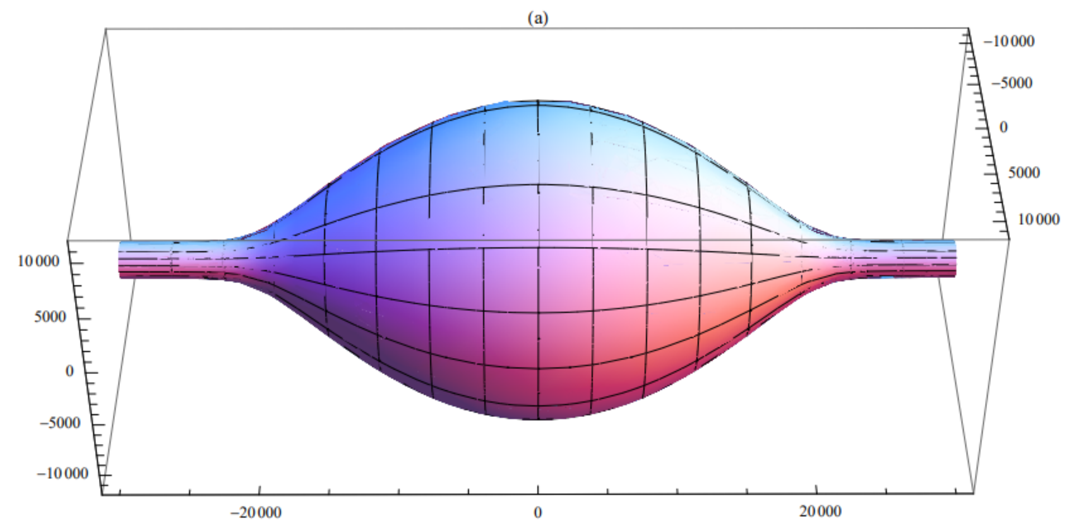


Fig. from Lee et al., [1310.3005], PRD

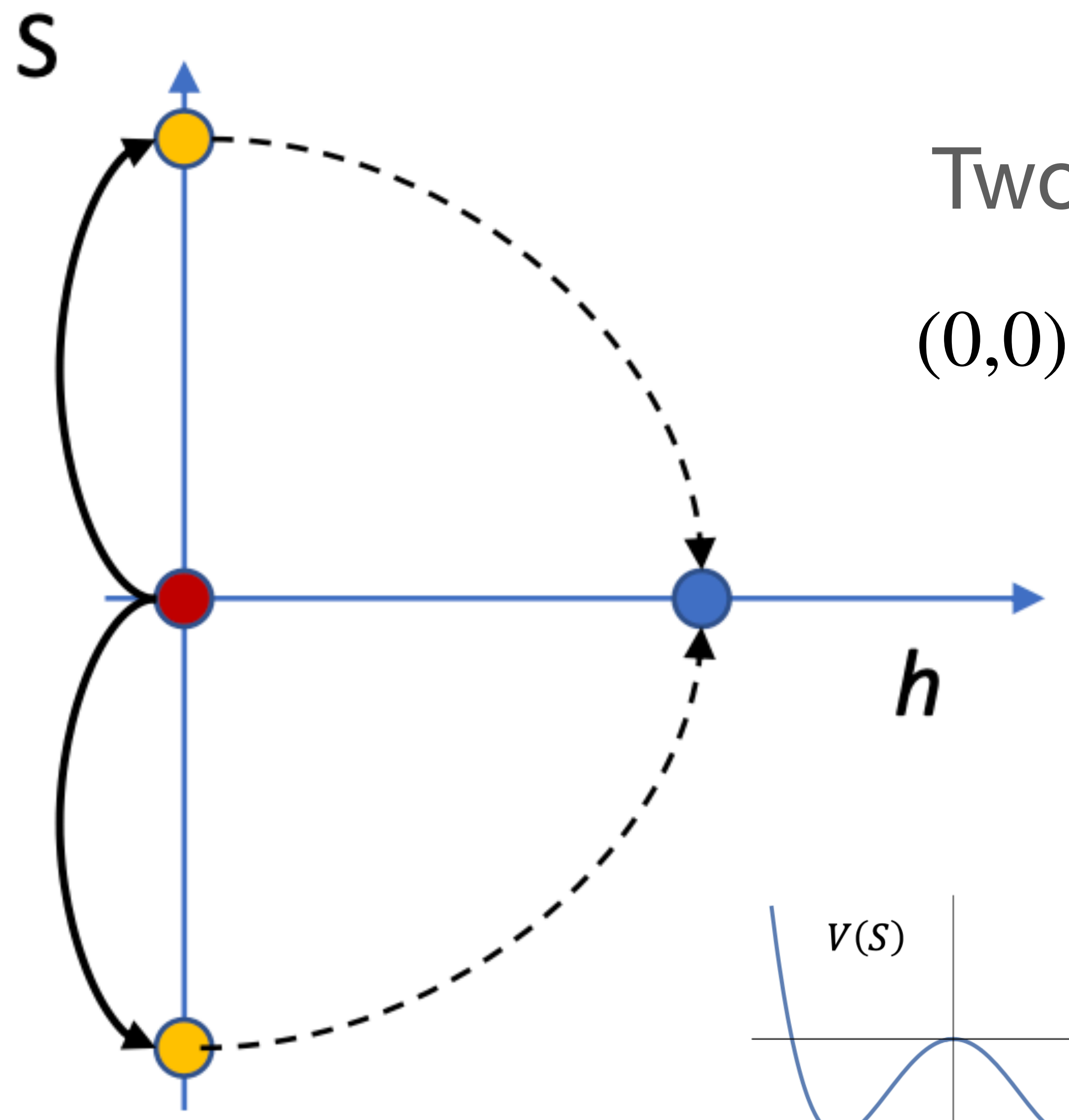
Defects as nucleation seeds

Case of study: electroweak phase transition

SB, Mariotti [2203.16450], PRL
Agrawal, **SB**, Mariotti, Nee, in prep.

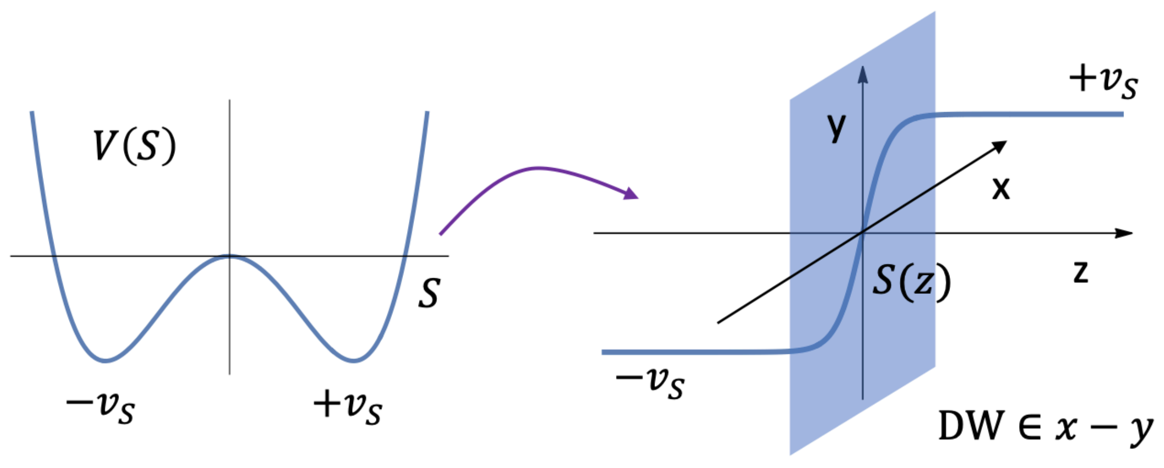
Singlet-extended SM (xSM) with $\mathbb{Z}_2 : S \to -S$

$$V(h,S) = \lambda\,(h^\dagger h - v^2)^2 + \eta\,(S^2 - v_s^2)^2 + \kappa\, h^\dagger h\, S^2$$



Two step transition

$$(0,0) \to (\pm v_s, 0) \to (0, v)$$

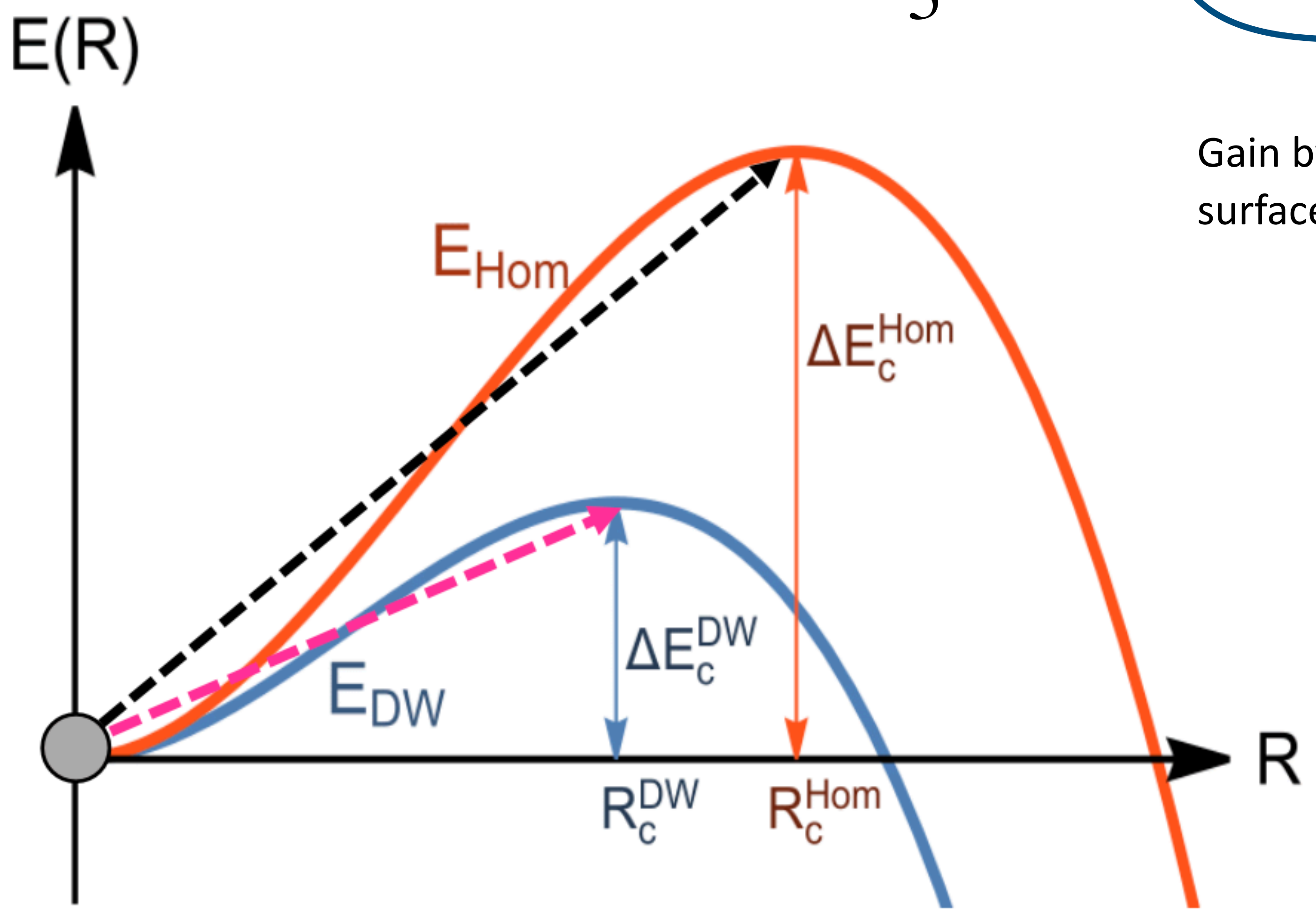


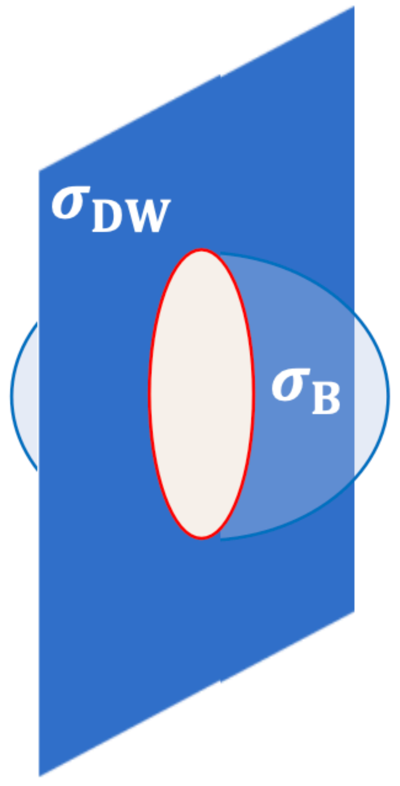
See e.g. Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

- **1st step**: domain wall network forms
- **2nd step**: domain wall network seeds the second step and disappears

$$E(R) \simeq 4\pi R^2\,\sigma_B - \frac{4}{3}\pi R^3 \epsilon - \pi R^2 \sigma_{DW}$$

Gain by eating up domain wall surface

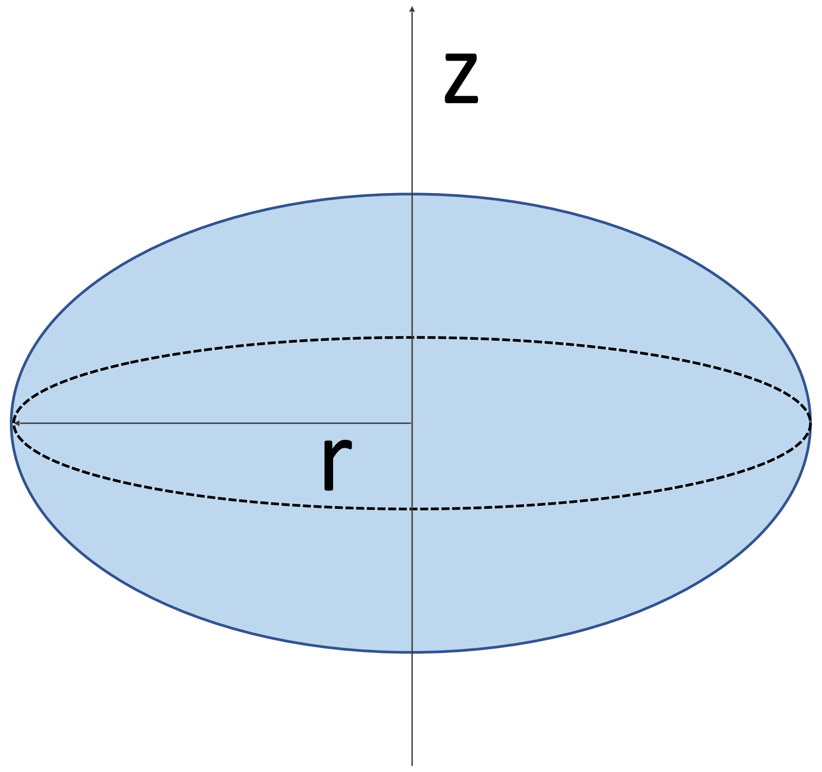




How to calculate the bounce action?

Critical bubble

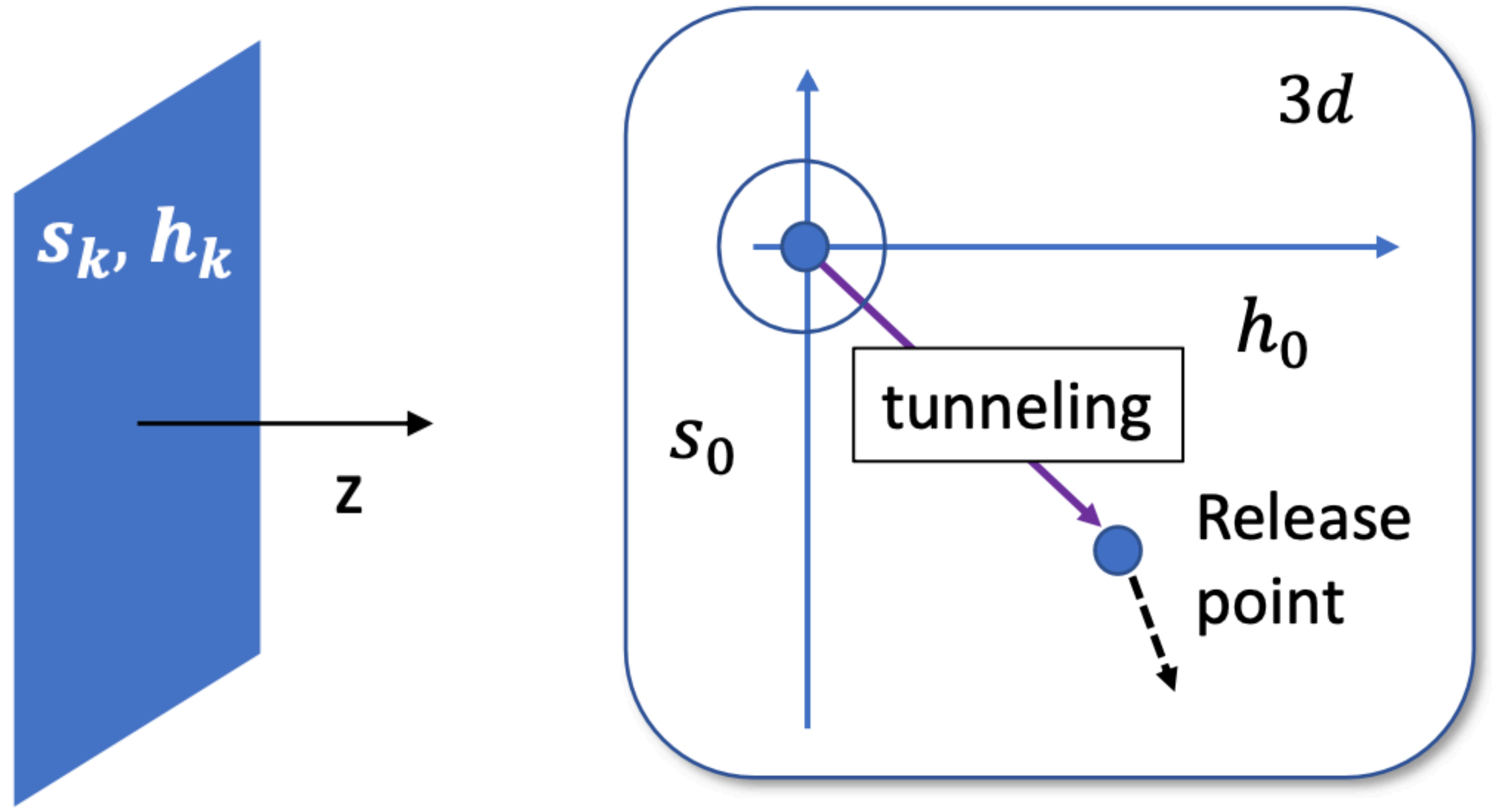
$r \in$ DW plane



$h_c(r, z)$

$S_c(r, z)$

Kaluza-Klein decomposition

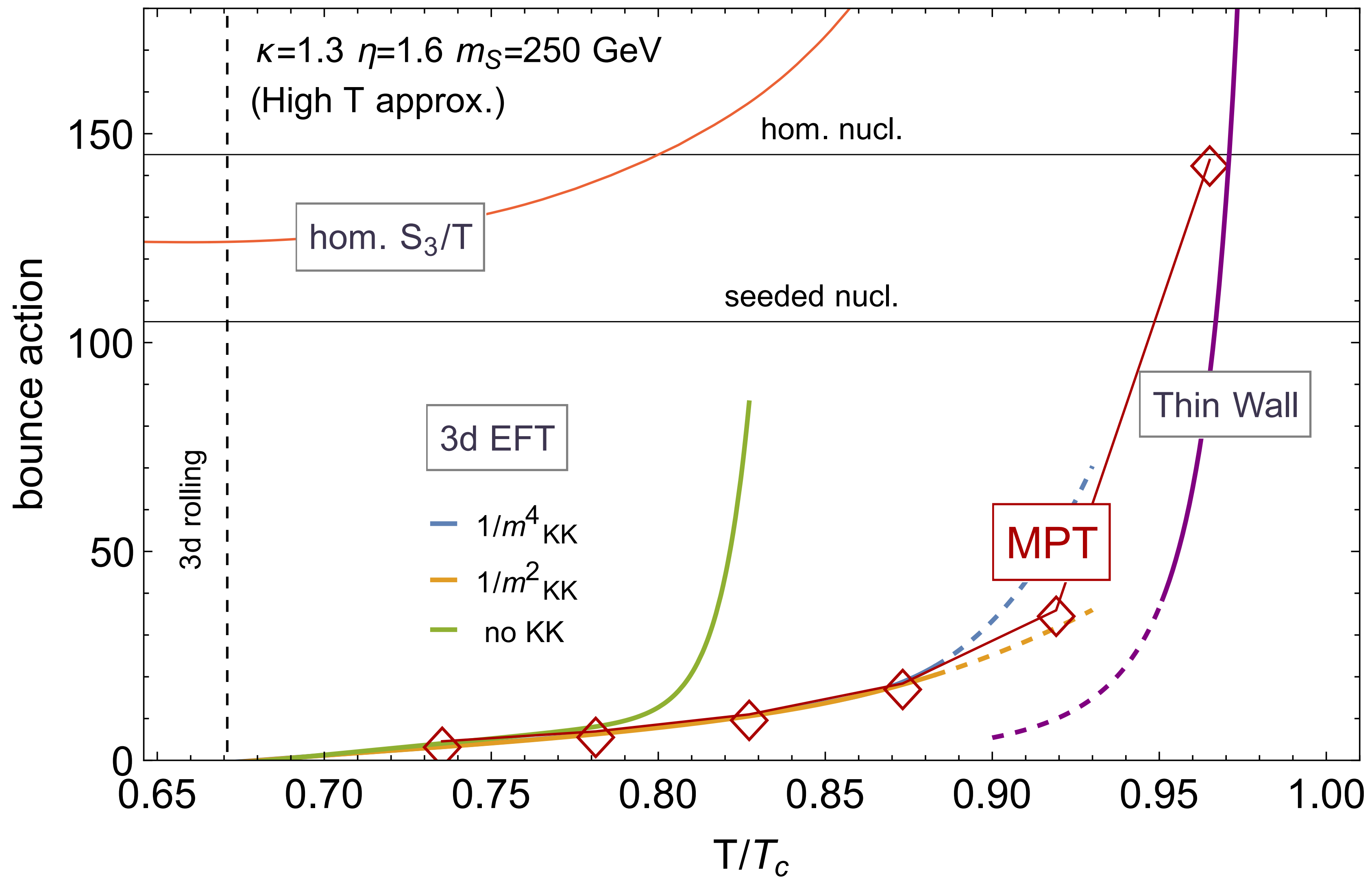


Coupled system of PDEs

Agrawal, **SB**, Mariotti, Nee, in prep.

$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{\partial^2\phi}{\partial z^2} = \frac{\partial V}{\partial\phi}, \quad \phi = h, S$$

Domain wall profile as the “false vacuum”

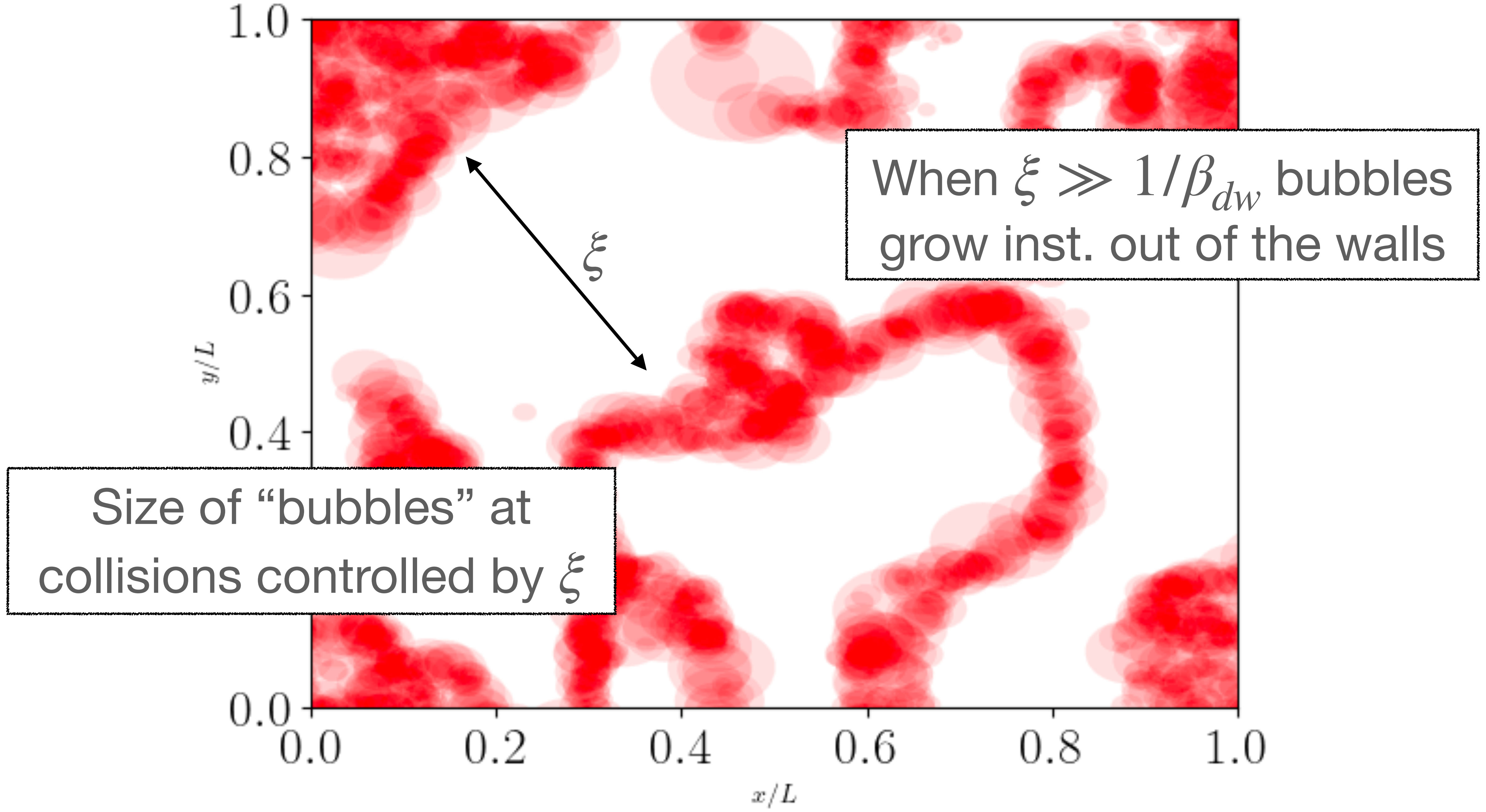


Defects as nucleation seeds

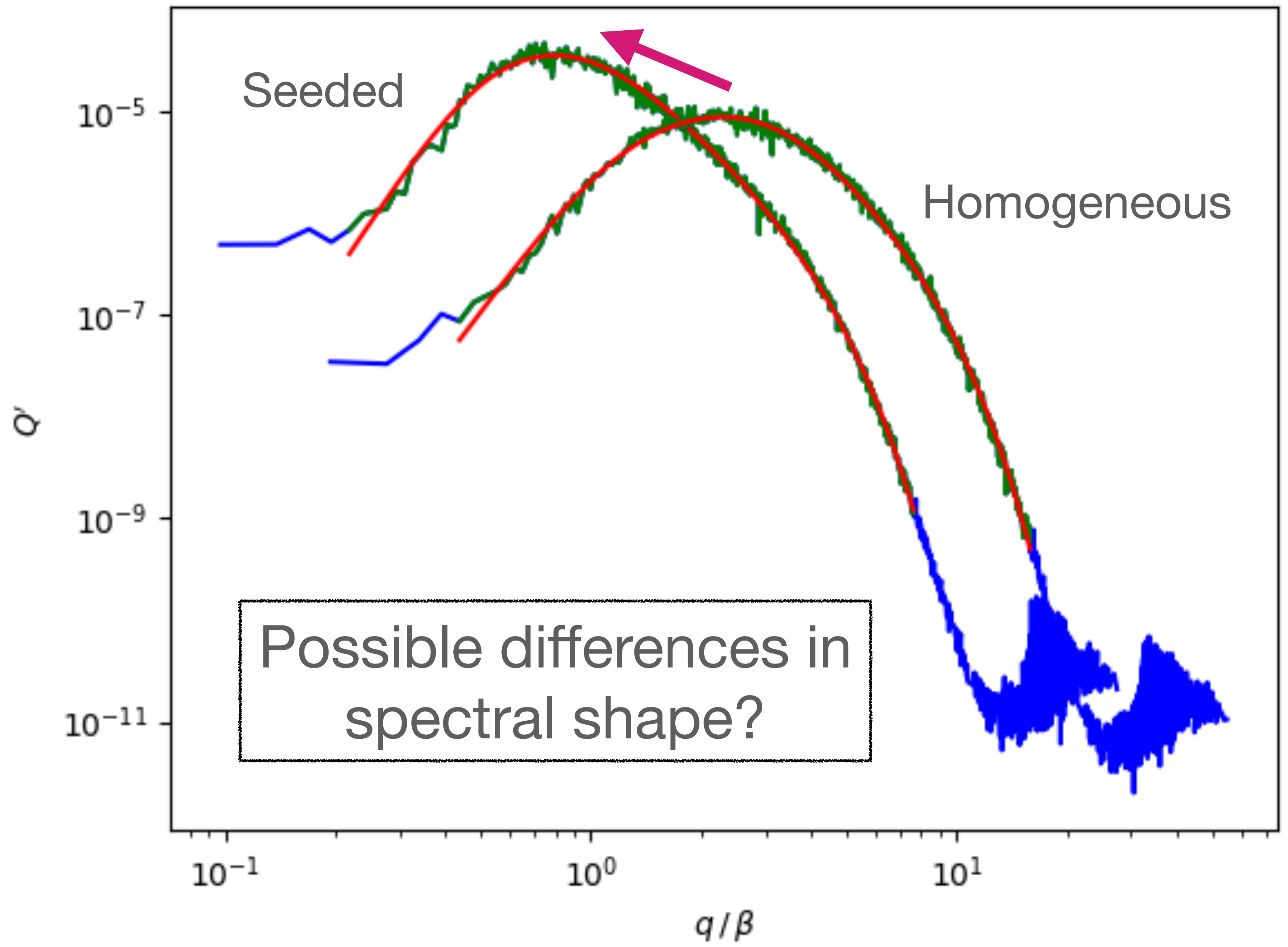
Gravitational waves

SB, Jinno, Konstandin, Rubira, Stomberg, to appear

Domain wall network mimicked by Ising model



Spectrum shifted to IR and enhanced



Defect-driven phase transition can effectively set $\beta/H_\star \sim 1$ without tuning in the **scaling regime**

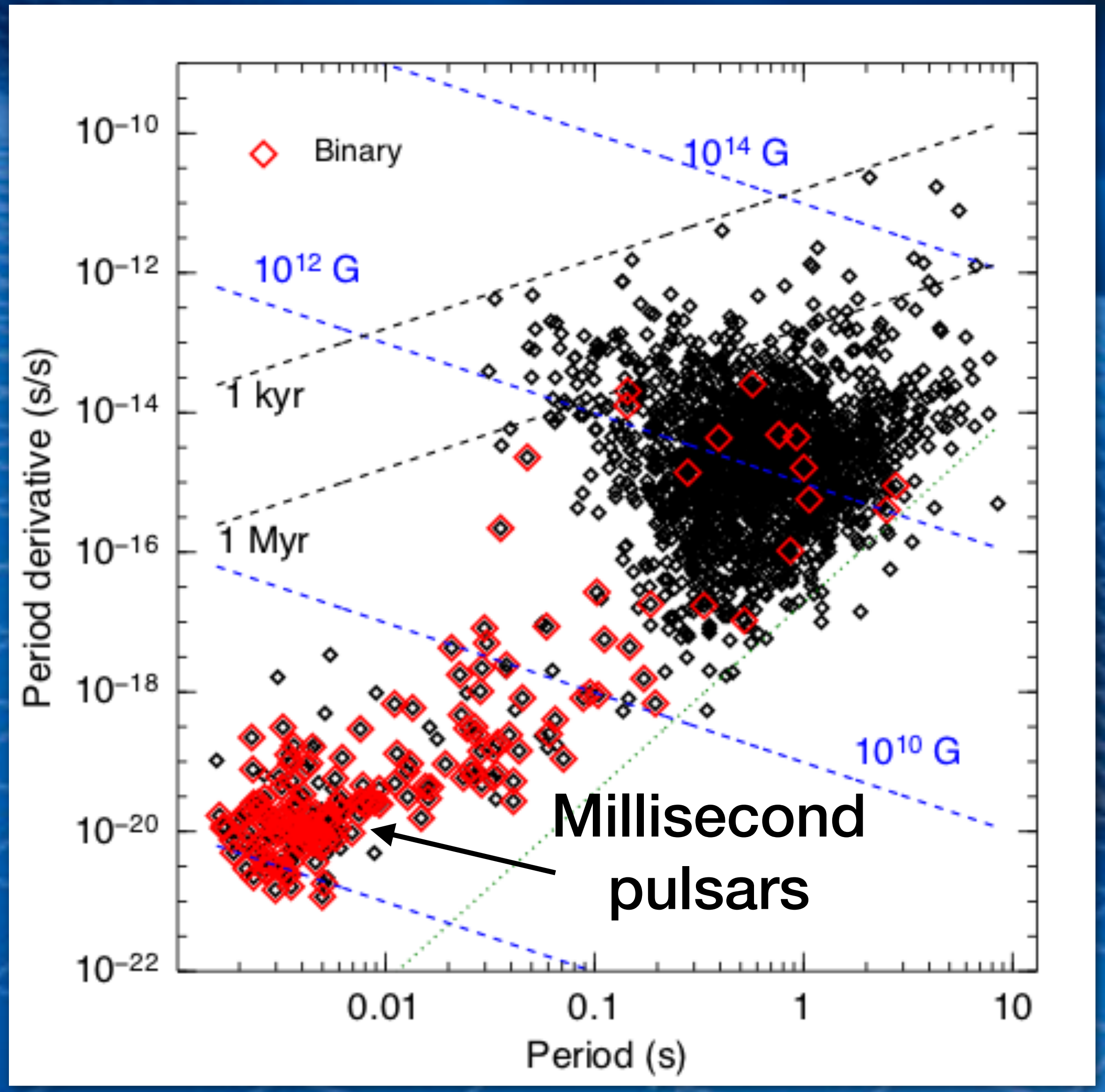
Pulsar Timing Arrays

Introduction

Neutron stars: $\mathrm{R} \sim 10\,\mathrm{km}, \quad \mathrm{B} \sim 10^{8} - 10^{15}\, G$

Great clocks: rapid rotation + large inertia = very stable

Lighthouse effect: very precise ticks when beam crosses line of sight



12.5 years, 46 pulsars
2009.04496 [astro-ph]

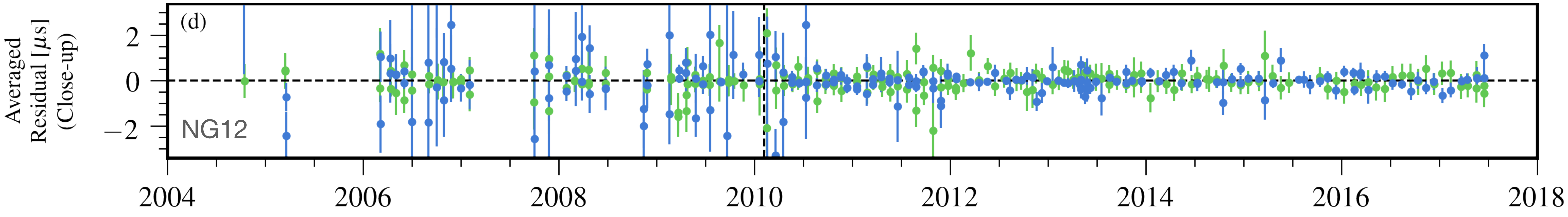
24 years, 6 pulsars
2110.13184 [astro-ph]

15 years, 26 pulsars
2107.12112 [astro-ph]

Combines 65 pulsars
2201.03980 [astro-ph]

Pulsar Timing Arrays

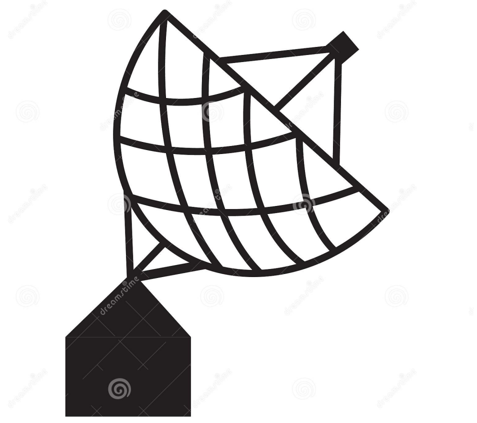
Time of arrivals (ToAs)



Observe the pulsar and register the ToAs

Build a theoretical model to predict next ToAs

Time residuals:
$R = ToA|_{th} - ToA|_{obs}$



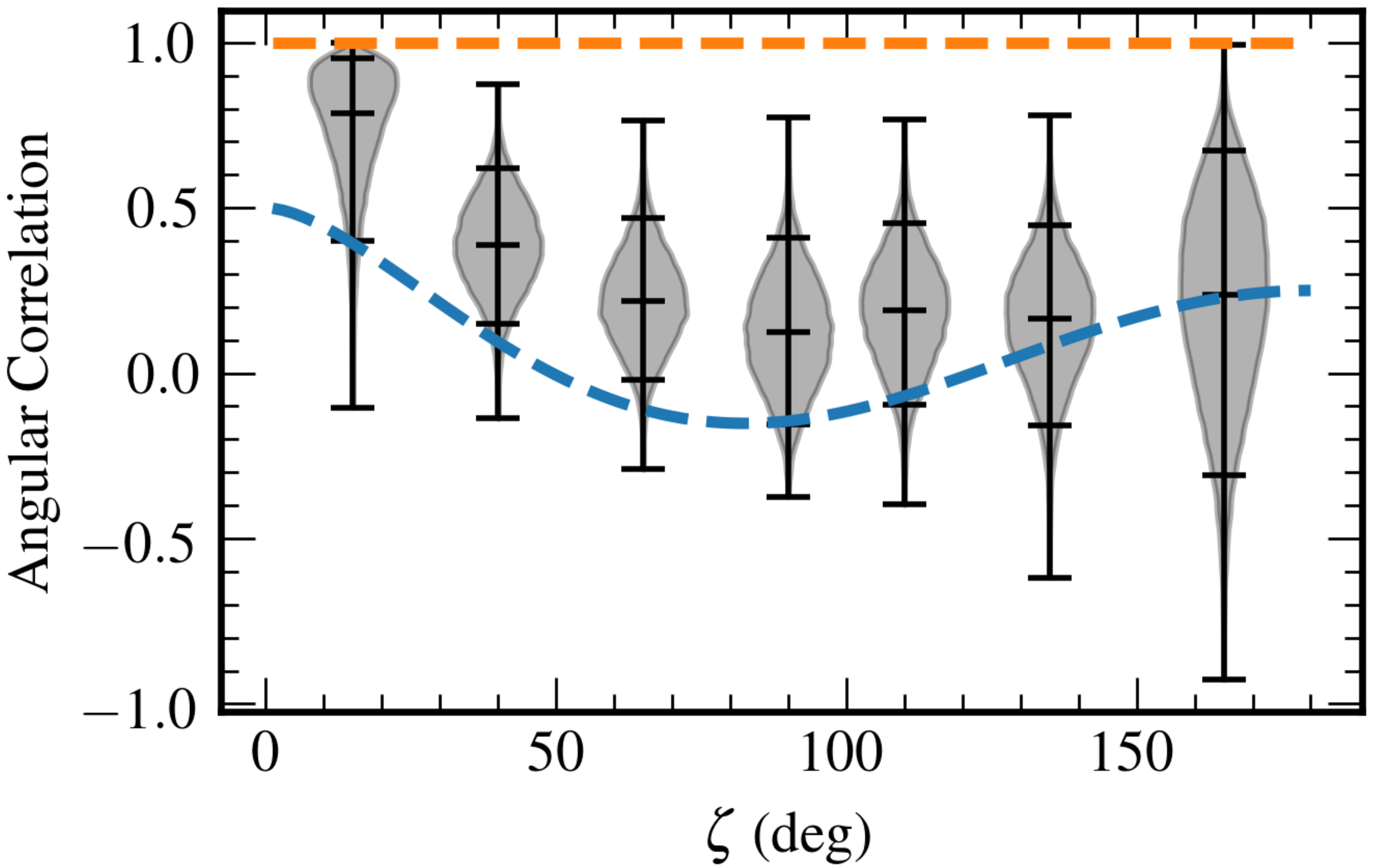
Period, period derivative, proper motion, parallax, Einstein delay, orbital decay, Shapiro delay,…

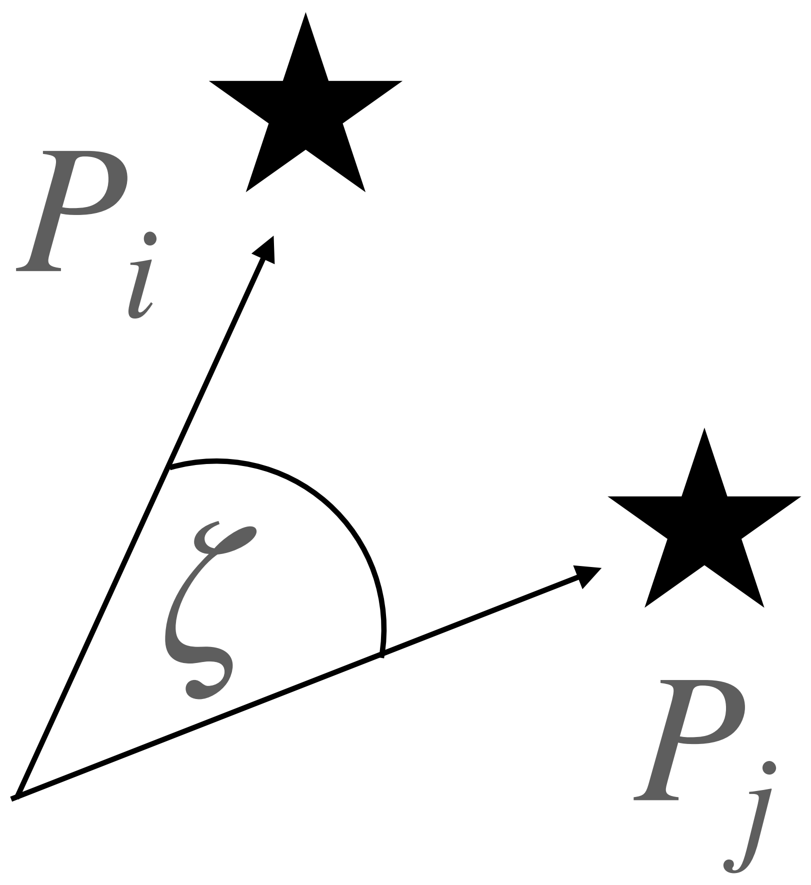
Model the noise in the data: pulsar-intrinsic + **common**

Pulsar Timing Arrays

Correlations

Evidence for a common red process among all the pulsars still not enough to claim GW detection!





Necessary to look at angular correlations:

- **Monopolar** (e.g. offset of the clock)
- **Dipolar** (e.g. misplaced solar system barycenter)
- **Quadrupolar** (prediction of **GWs**)

Pulsar Timing Arrays

Sensitivity

Narrow sensitivity band:

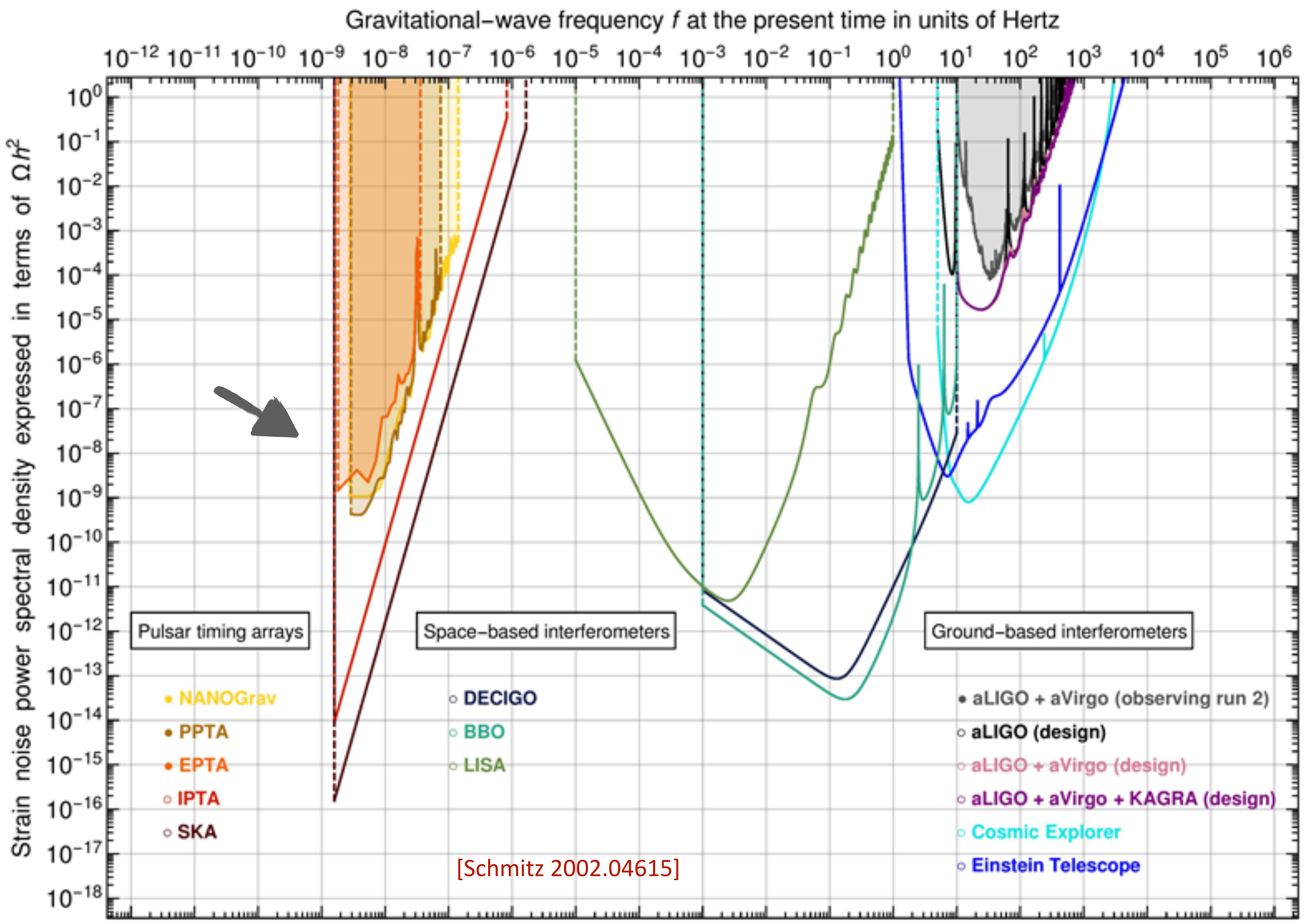
$$2\,\text{nHz} \approx (10\,\text{years})^{-1} < f < (1\,\text{month})^{-1} \approx 500\,\text{nHz}$$

Most sensitive probe in terms of GW amplitude:

$$\Omega \sim 10^{-10}$$

Relevant temperature for PTA signal (cosmological):

$$T_\star \simeq \text{MeV - GeV}$$

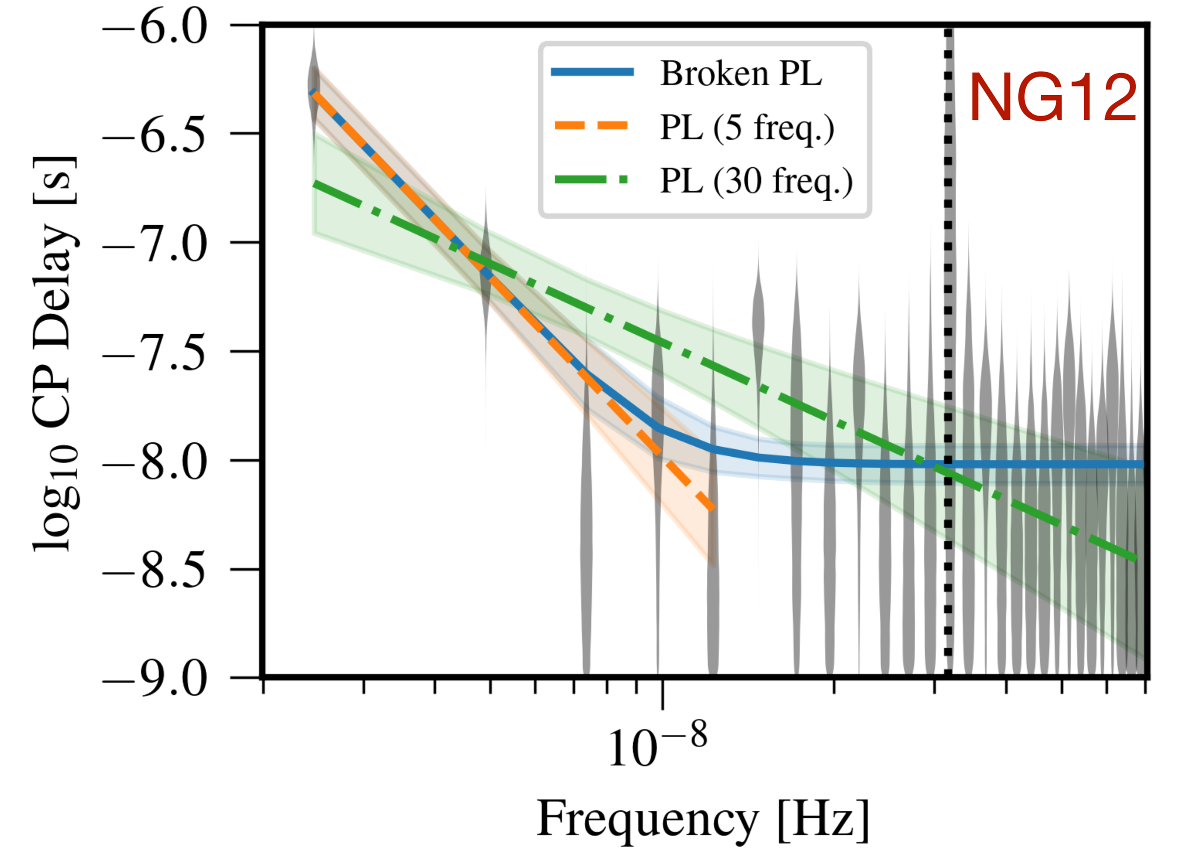


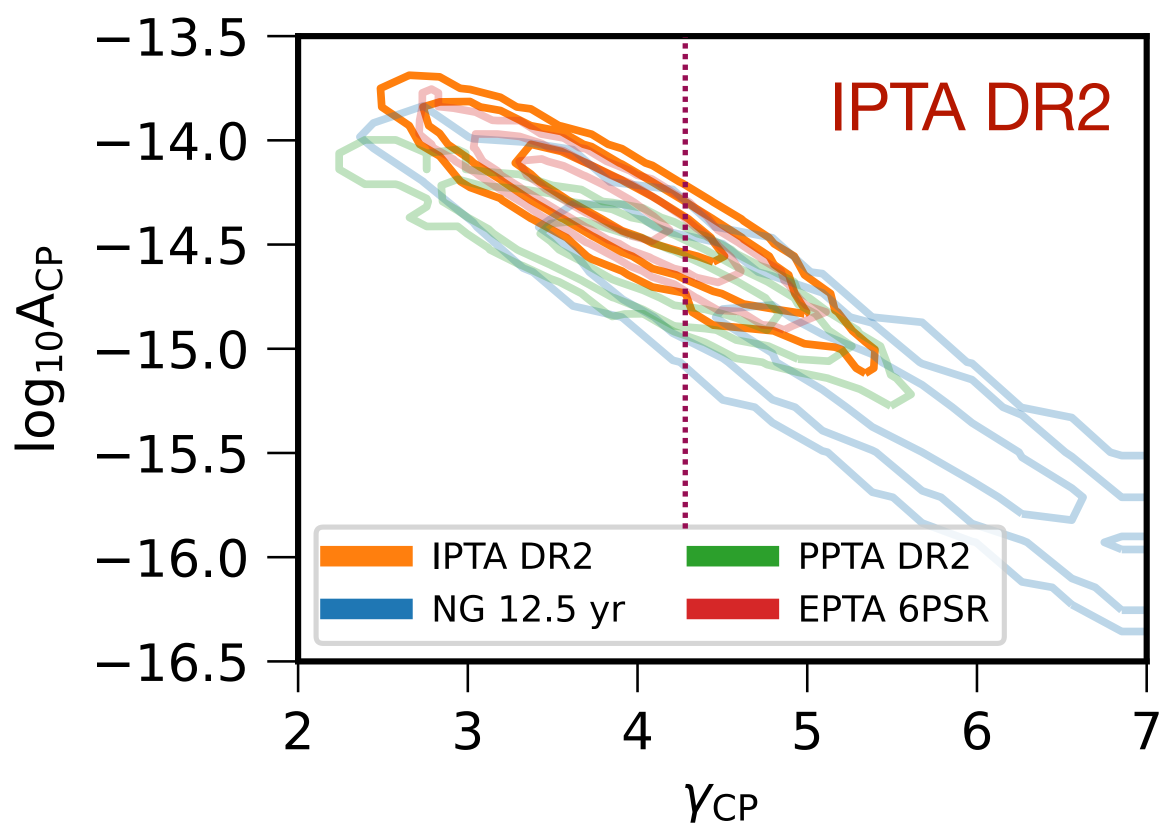
Pulsar Timing Arrays

Recent results

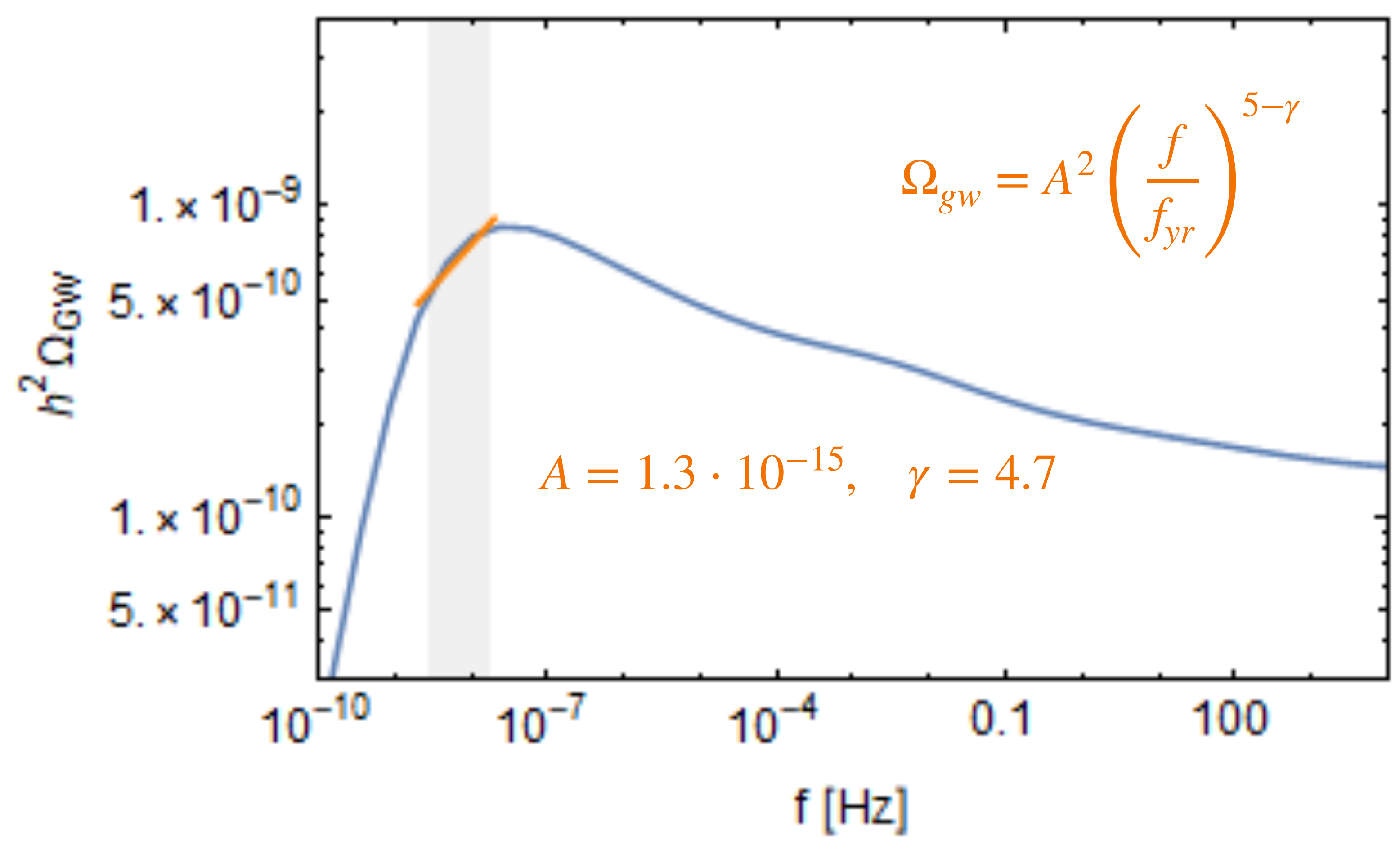
Nanograv, EPTA, PPTA and IPTA

Supermassive black hole binaries (inspiral)



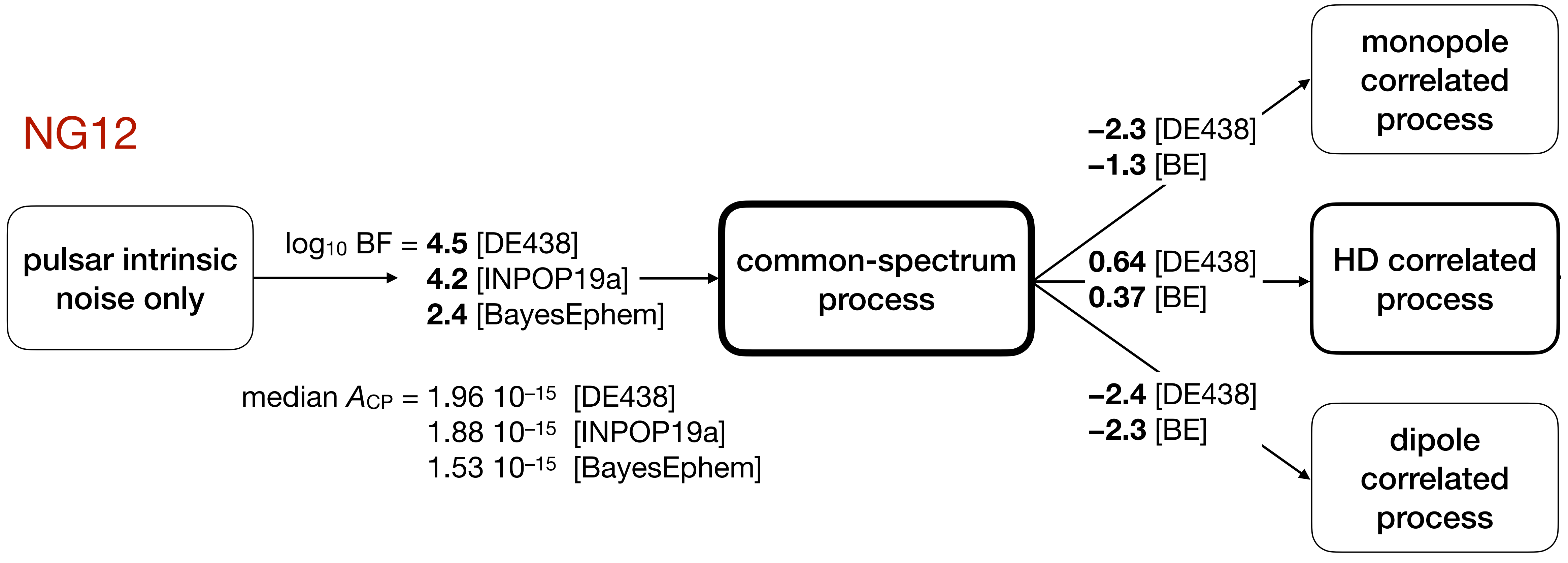


Translation to a stochastic background of GWs in terms of Ω_{gw} :



(Spectrum from cosmic strings)

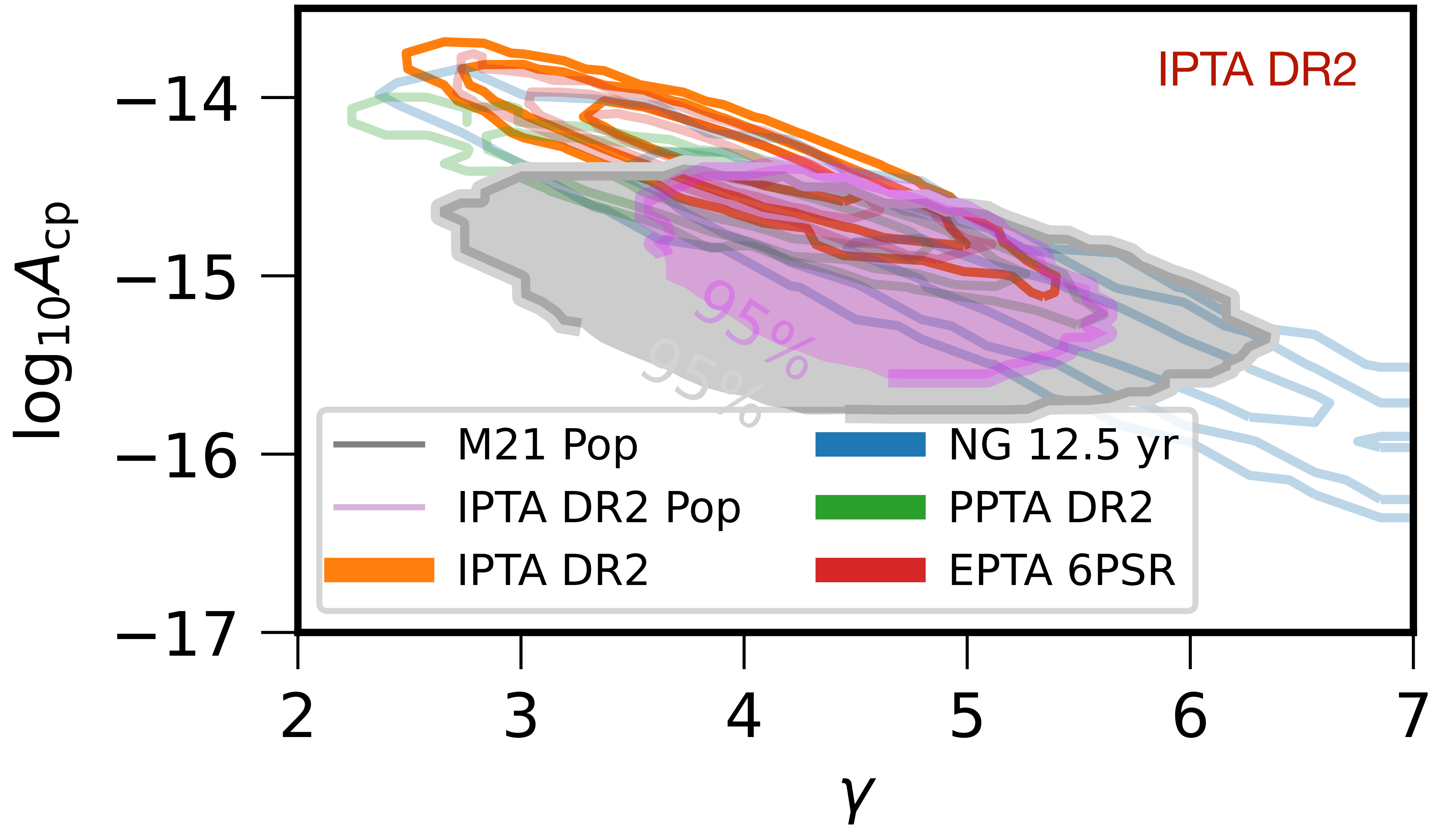
NG12



Pulsar Timing Arrays

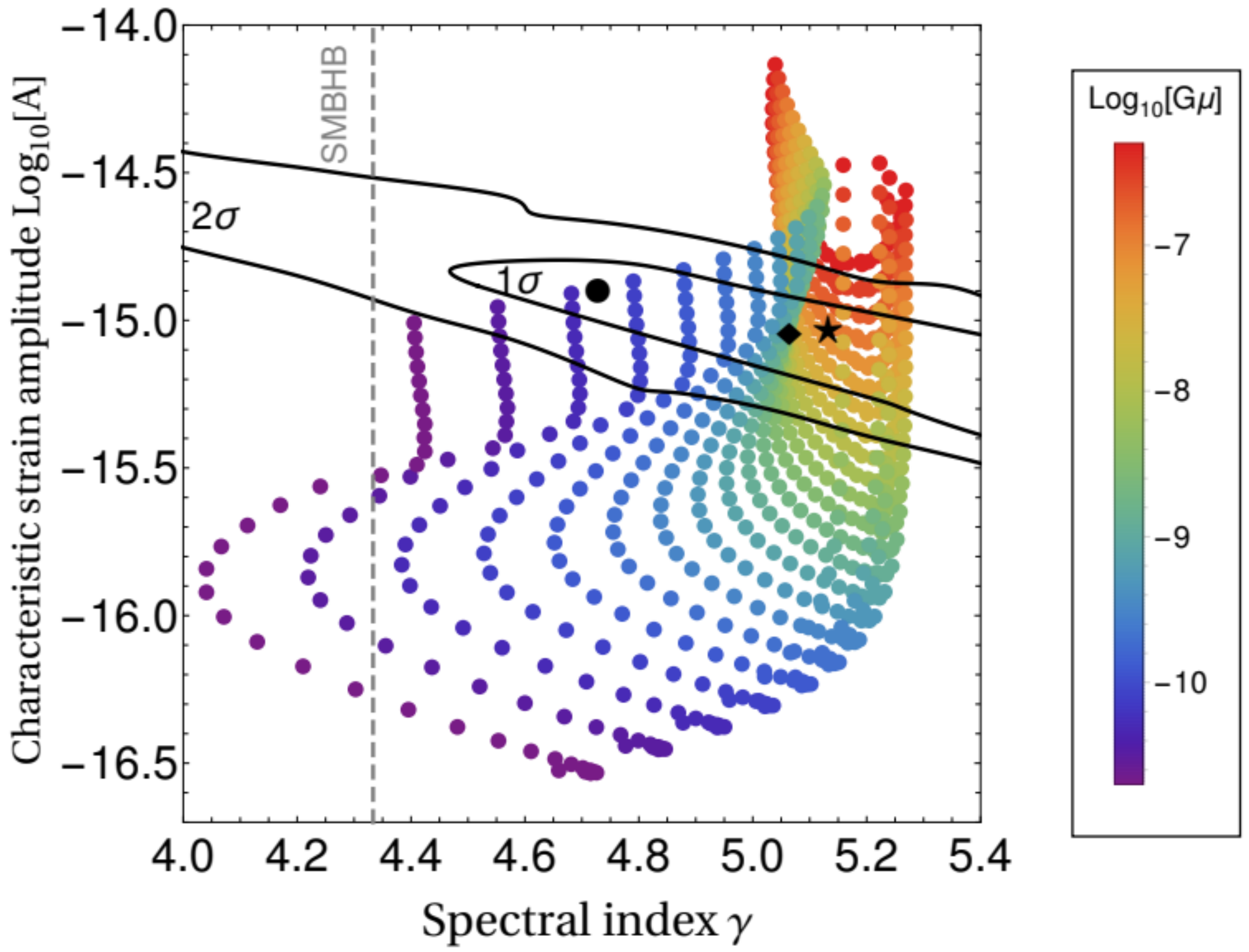
Interpretations

Astrophysical interpretation: SMBHBs $10^5 - 10^6\, M_\odot$



Grey area from simulation of SMBH population

Cosmological interpretation (1/many): cosmic strings

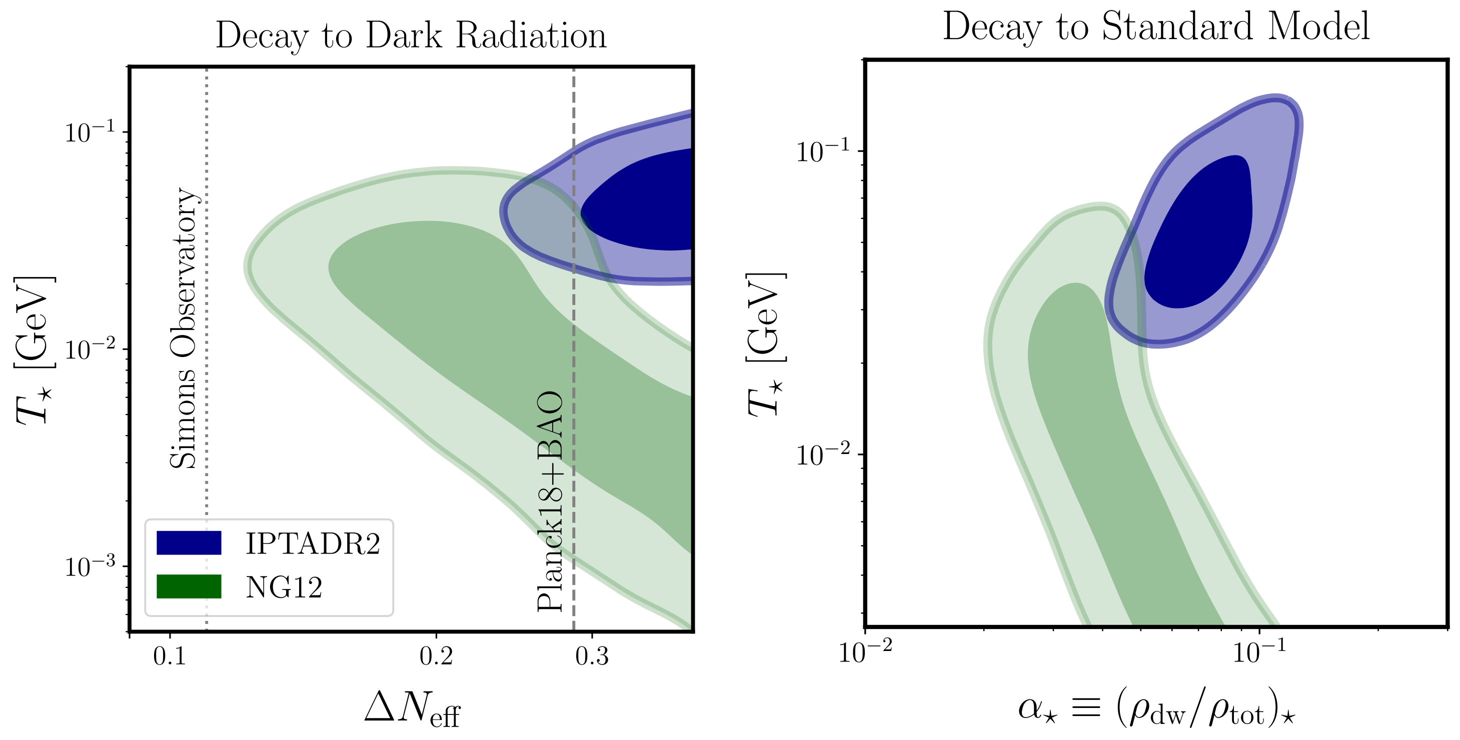


SB, Brdar, Schmitz 2009.06607 PRL

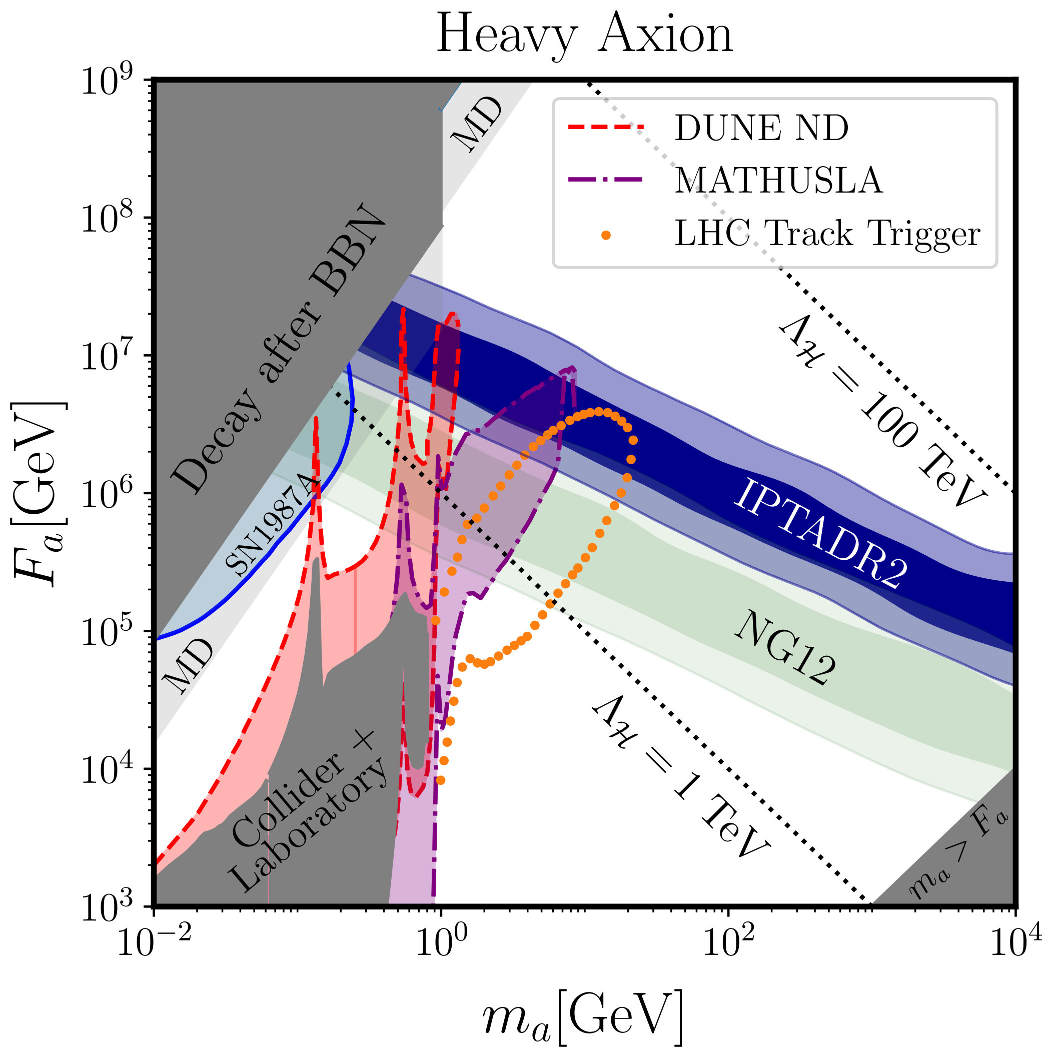
Pulsar Timing Arrays

Interpretations

Cosmological interpretation (1/many): domain walls



Figs. from Ferrera, Notari, Pujolas, Rompineve 2204.04228 JCAP



Friction with the thermal plasma?

$$\mathscr{L}_{int} \supset c_\psi \frac{1}{f_a} \partial_\mu a \, \bar{\psi} \gamma^\mu \gamma_5 \psi$$

SB, Mariotti, Rase, Sevrin, Turbang 2210.14246

Cosmological interpretation (1/many): first order transitions

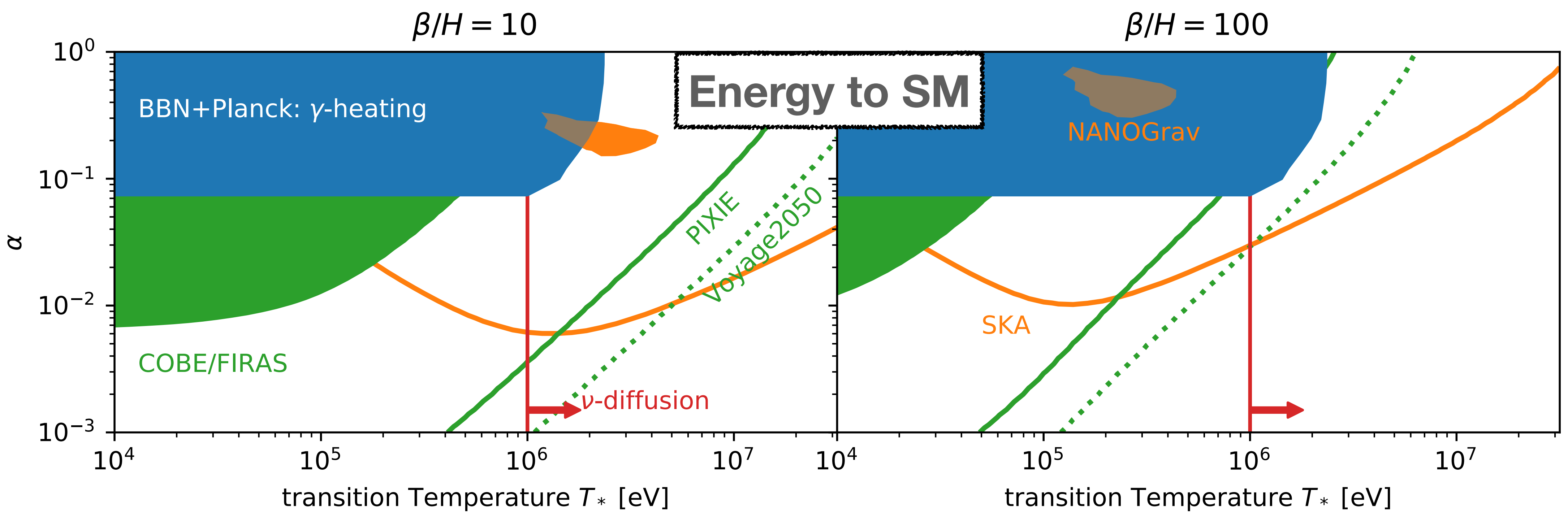


Fig. from Ramberg, Ratzinger, Schwaller 2209.14313

Energy injection happens at very low temperatures: subject to cosmo constraints.

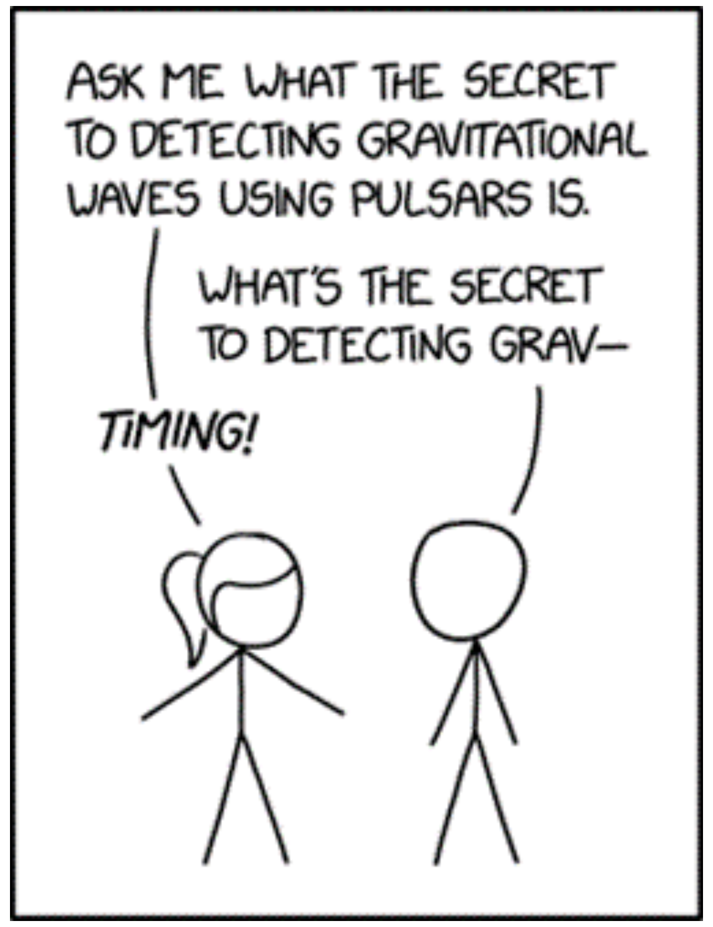
A **seeded phase transition** can help as the **temperature** can be somewhat **larger** by having $\beta/H \sim 1$ effectively.

Summary

Cosmological phase transitions offer exciting phenomenology in terms of a **stochastic background of gravitational waves** due to the dynamics associated to **topological defects**, **bubble nucleation**, and the **non-trivial interplay** for **impurity—driven phase transitions**.

Detection of gravitational waves probes uncharted energy scales for **fundamental physics**. Within the promising program for the next decades, **Pulsar Timing Arrays** are on the verge of finding **first evidence of a stochastic background**.

Together with astrophysical sources, several cosmological interpretations are possible, each of them coming with challenges and virtues: lively arena for **new physics** searches and **BSM.**



Thank you!