Gravitational Wave Probes of Beyond-WIMP Dark Matter

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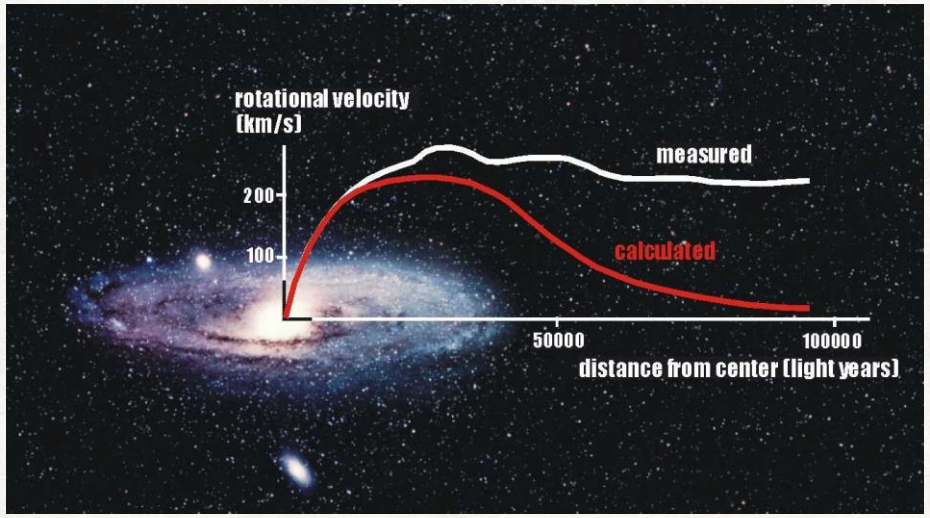
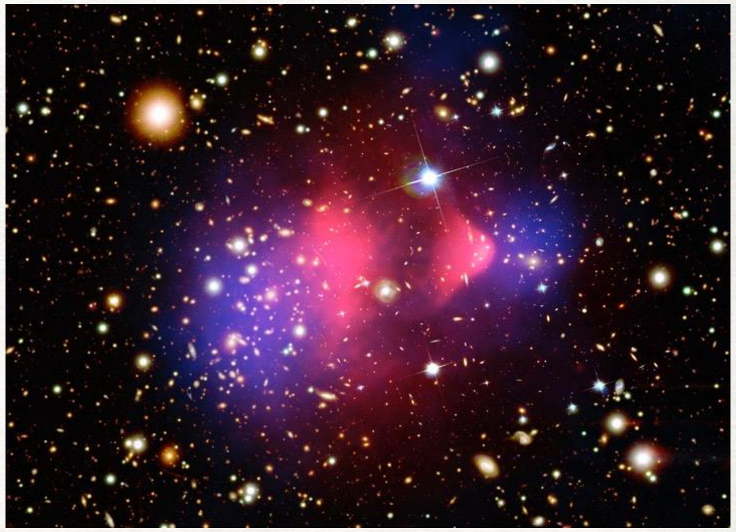
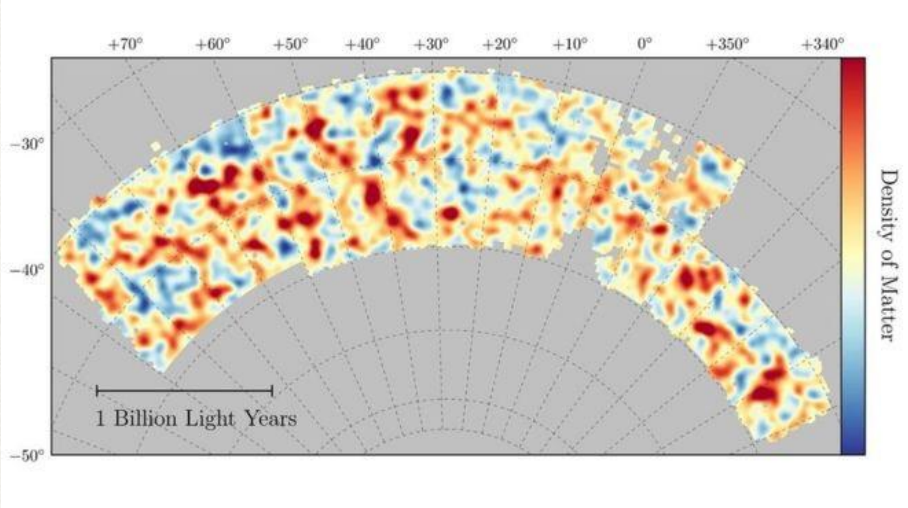
OUTLINE

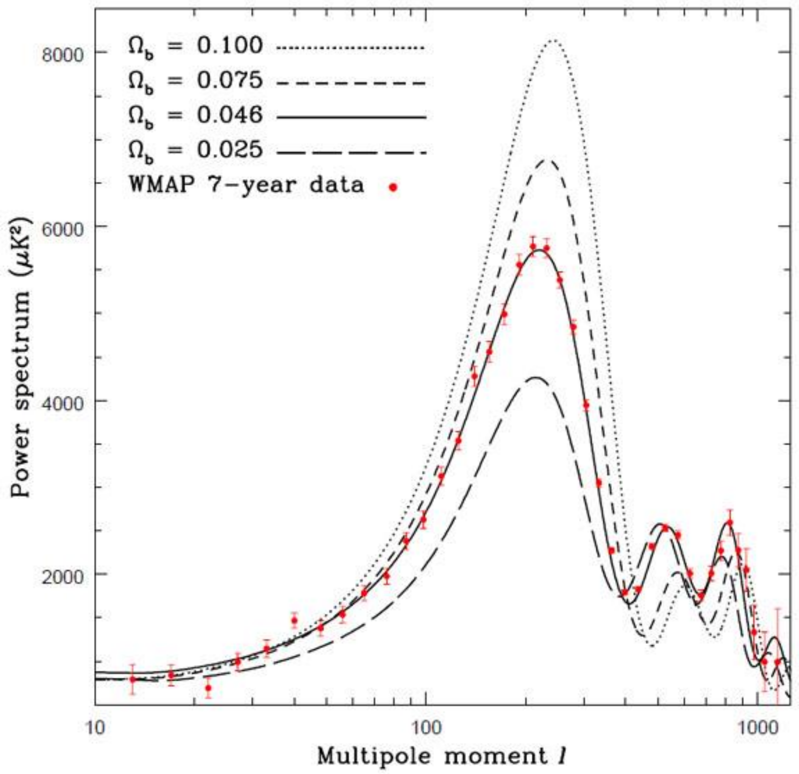
- Introduction: Dark Matter & Production Mechanisms
- Gravitational Waves From Early Universe
- Cosmological Phase Transition
- Connection to Dark Matter
- Conclusion

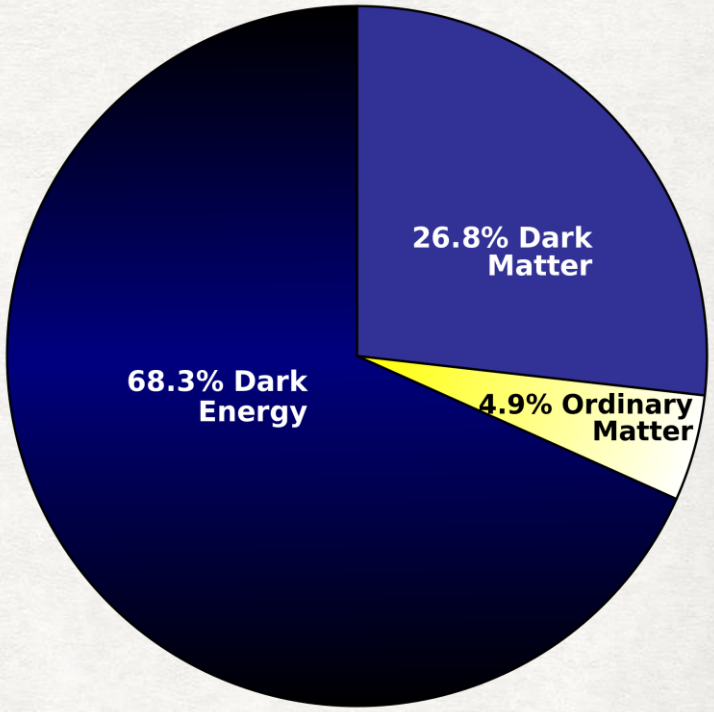
DARK MATTER: EVIDENCES

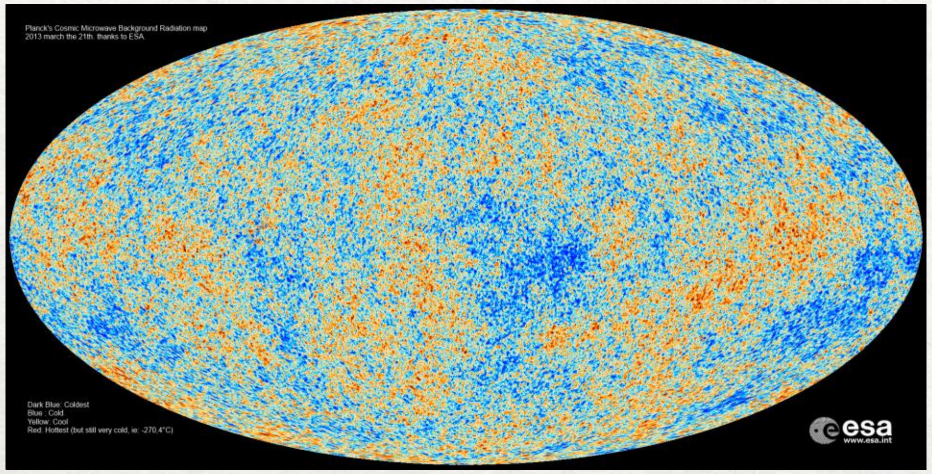






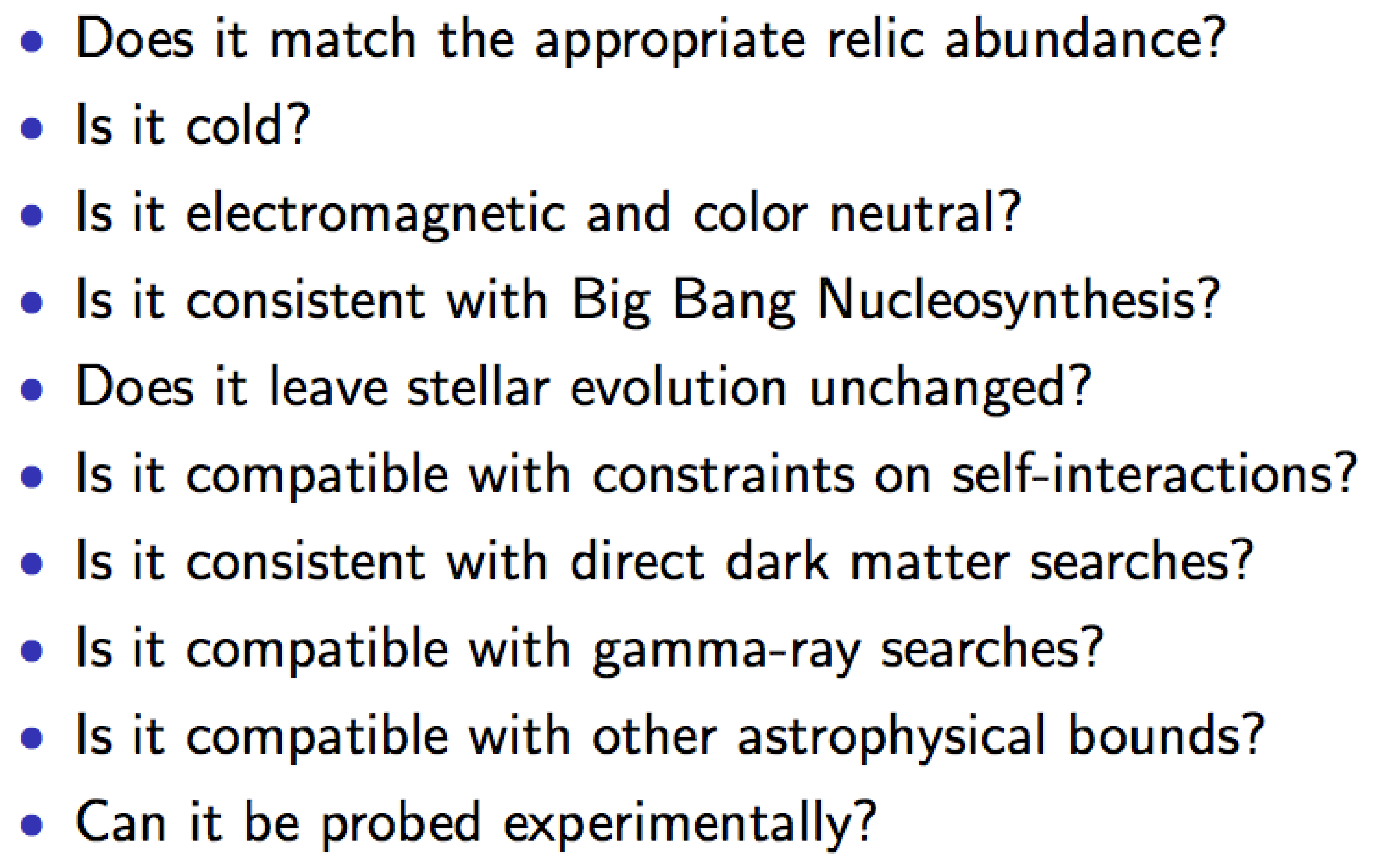






Credits:
HST, Chandra, DE Survey, WMAP, Planck

DARK MATTER: 10 POINT TEST



- Does it match the appropriate relic abundance?
- Is it cold?
- Is it electromagnetic and color neutral?
- Is it consistent with Big Bang Nucleosynthesis?
- Does it leave stellar evolution unchanged?
- Is it compatible with constraints on self-interactions?
- Is it consistent with direct dark matter searches?
- Is it compatible with gamma-ray searches?
- Is it compatible with other astrophysical bounds?
- Can it be probed experimentally?

No known particles can
satisfy these criteria!

Taoso, Bertone & Masiero JCAP 2008

DARK MATTER: WIMP MIRACLE

The abundance of DM which was in thermal equilibrium in the early Universe can be calculated by solving the Boltzmann equation.

$$\frac{dn_{\mathrm{DM}}}{dt} + 3Hn_{\mathrm{DM}} = -\langle\sigma v\rangle(n_{\mathrm{DM}}^2 - (n_{\mathrm{DM}}^{\mathrm{eq}})^2)$$

$$\Omega_{\mathrm{DM}}h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle\sigma v\rangle}$$

In terms of comoving density

$$Y \equiv \frac{n}{T^3} \sim \frac{n}{s}$$

$$x = \frac{m}{T}.$$

$$\frac{dY}{dx} = -\frac{\lambda}{x^2}\left(Y^2 - Y_{\mathrm{EQ}}^2\right),$$

$$\lambda = \frac{m^3\langle\sigma v\rangle}{H(m)}.$$

A particle having mass and interactions around the electroweak scale, can satisfy the correct relic criteria: WIMP Miracle!

$$H(T)^2 = \frac{8\pi}{3}G\rho(T)$$

$$\rho_R(T) = \frac{\pi^2}{30}g_*T^4,$$

$$s = \frac{2\pi^2}{45}g_{*s}T^3.$$

DARK MATTER: WIMP MIRACLE

Approximate analytical solution:

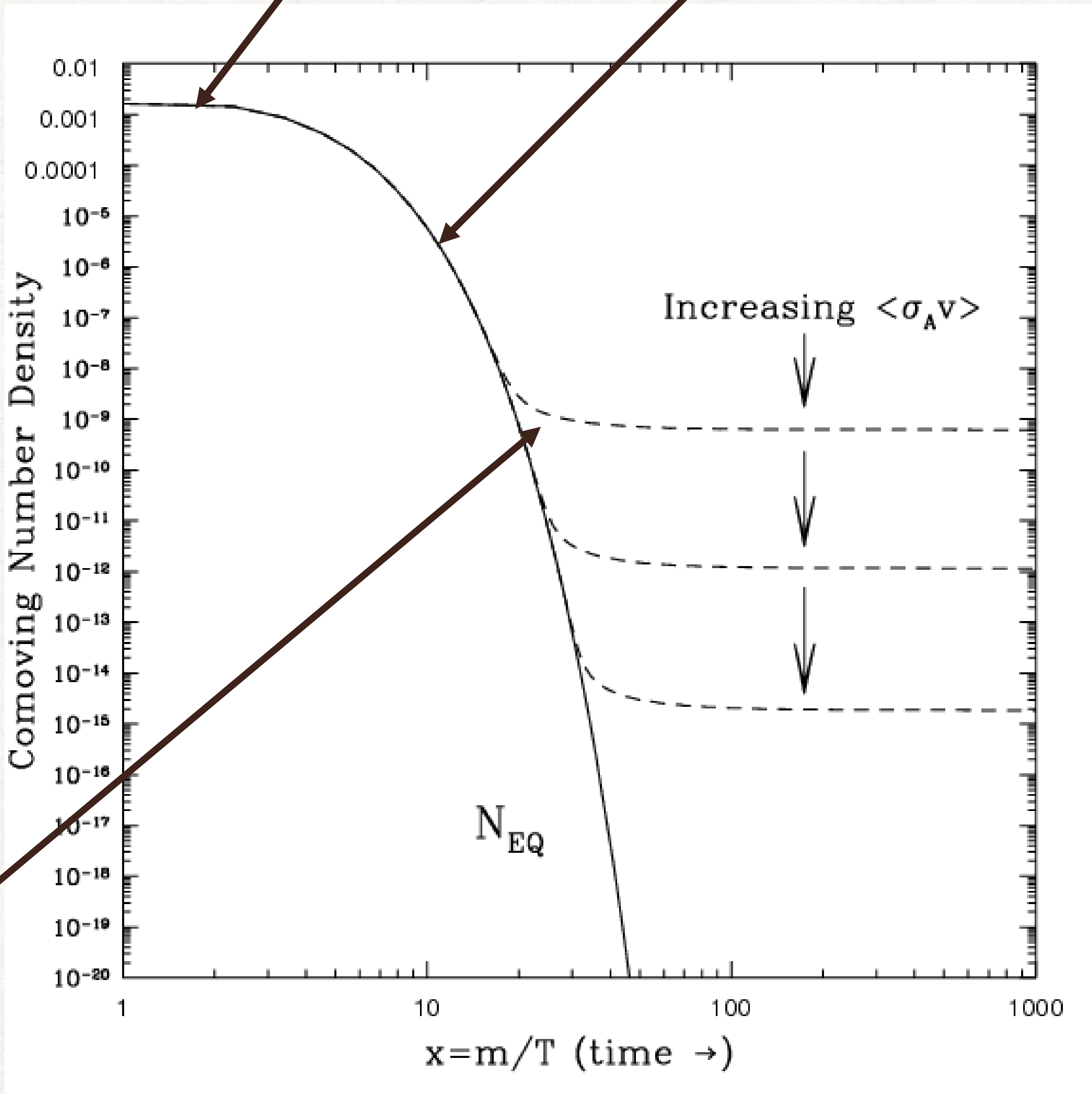
$$\Omega_{\rm DM} h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle}$$

Planck 2015, Astron. Astrophys. 2016

$$\Omega_{\rm DM} h^2 = \frac{\rho_{\rm DM}}{\rho_{\rm c}} h^2 = 0.1186 \pm 0.0020$$

Relativistic & in eqb at high T

Non-relativistic & in eqb.

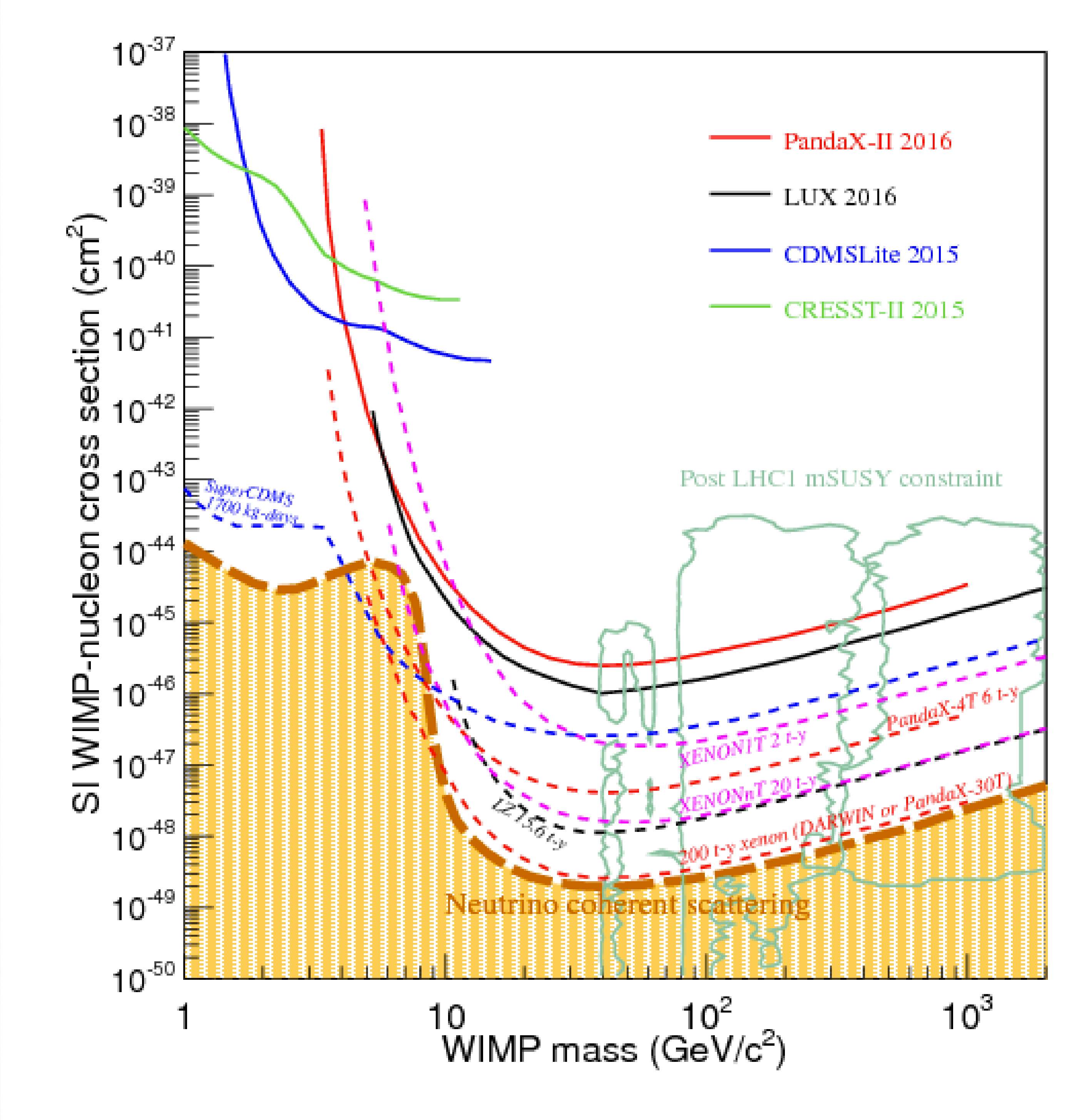


Decouples from the thermal bath when rate of interaction falls below Hubble rate of expansion: freeze-out

Arxiv: 0901.4090

DIRECT DETECTION!

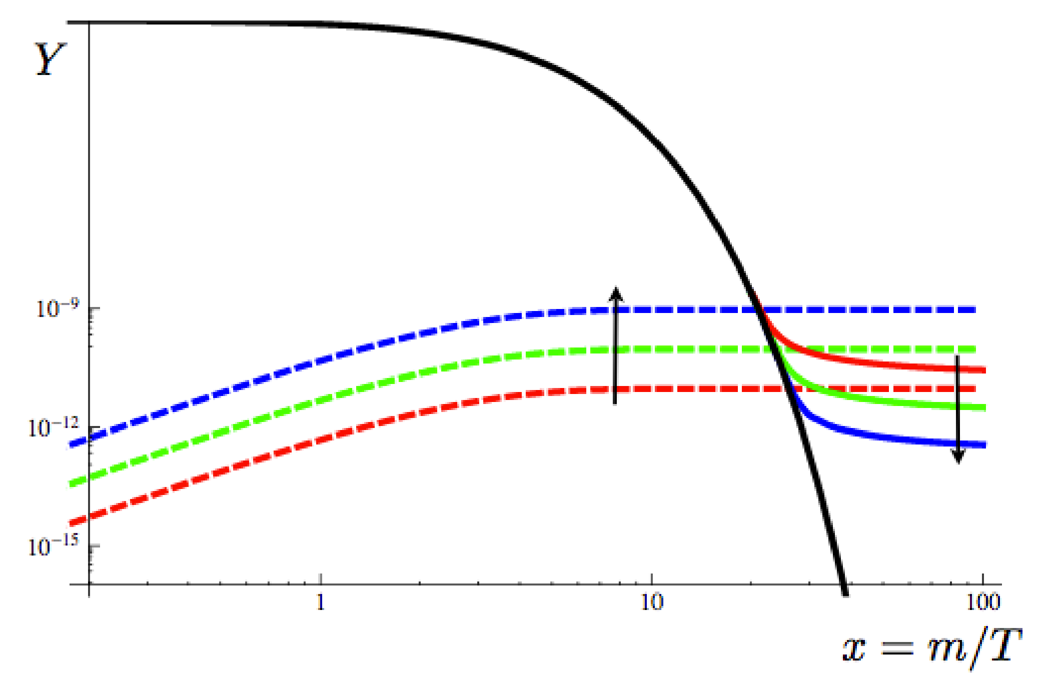
- Typical WIMP type models predict observable direct detection cross section: not seen yet.
- This motivates to explore beyond simple WIMP possibilities.

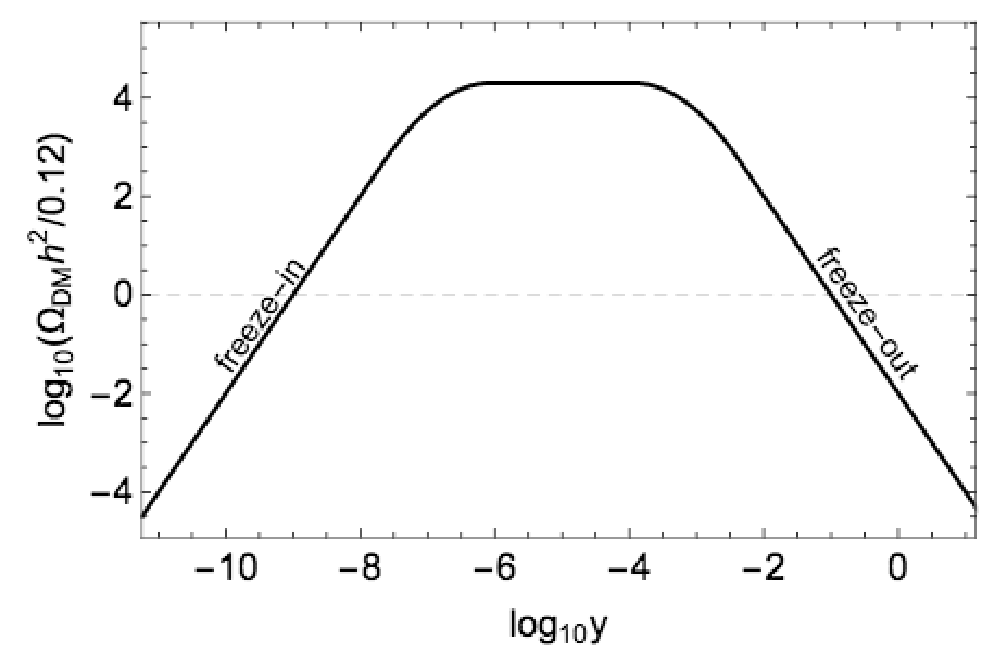


- Nature Physics 13 (2017) 212. arXiv:1709.00688

FIMP MIRACLE!

- If DM coupling to the visible sector is very small, its thermal abundance in the early Universe is negligible.
- However, it can start populating the Universe later from decay and scattering of visible sector particles: Freeze-in (L. J. Hall et al, arXiv:0911.1120).
- If same type of couplings are involved in both scattering and decay, then the latter's contribution dominates.
- Freeze-in typically requires fine tuned couplings, seeking some explanations for their dynamical origin.





Review: arXiv:1706.07442

FREEZE-IN DARK MATTER

The Boltzmann equation for a typical FIMP DM can be written as

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3\,H\,n_\chi = 2\,\Gamma_{\sigma\to\chi\chi}\frac{K_1(m_\sigma/T)}{K_2(m_\sigma/T)}n_\sigma^{\mathrm{eq}}$$

Using Maxwell-Boltzmann distribution for the mother particle, the co-moving form of the above equation is

$$\frac{x}{Y_\sigma^{\mathrm{eq}}}\frac{\mathrm{d}Y}{\mathrm{d}x} = 2\,\frac{\Gamma_{\sigma\to\chi\chi}}{H}\frac{K_1(x)}{K_2(x)}$$

$$x \equiv m_\sigma/T$$

with approximate solution

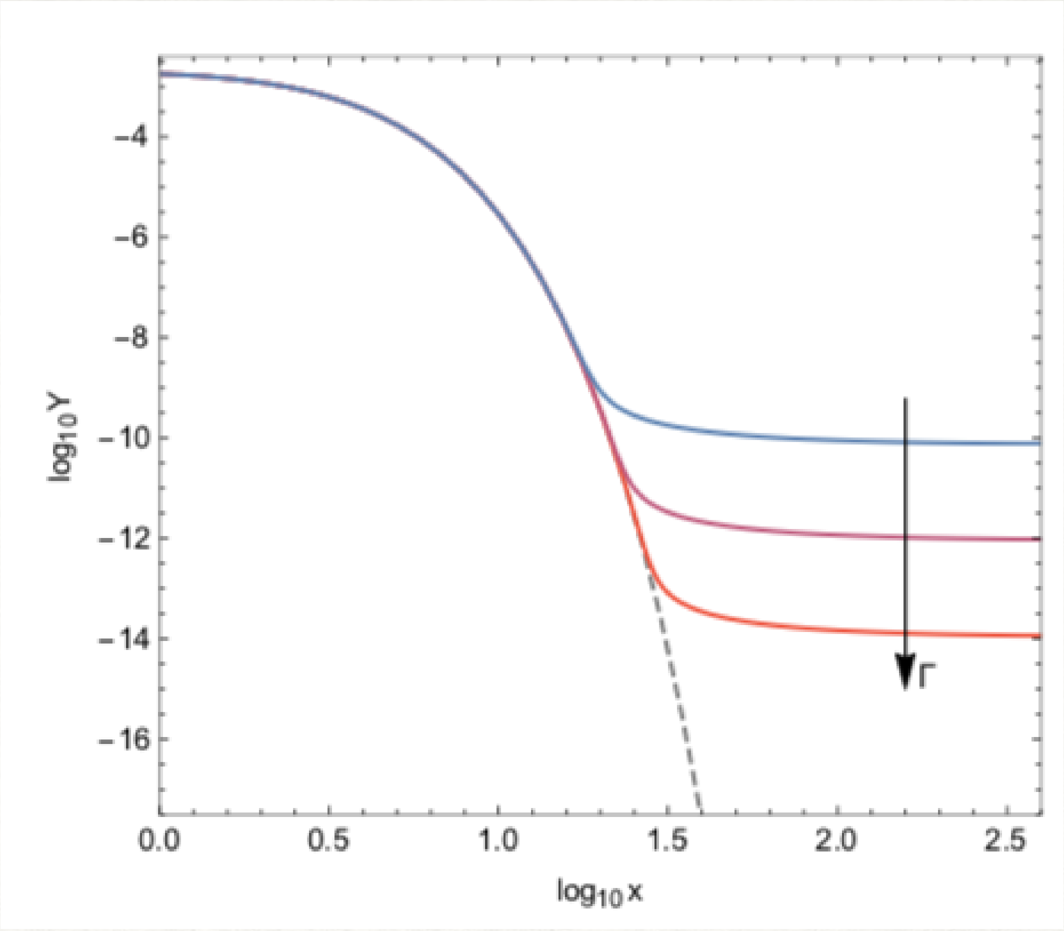
$$\Omega_\chi h^2 \simeq 4.48\times 10^8\,\frac{g_\sigma}{g_{*s}\sqrt{g_*}}\,\frac{m_\chi}{\mathrm{GeV}}\,\frac{M_{\mathrm{P}}\,\Gamma_{\sigma\to\chi\chi}}{m_\sigma^2}$$

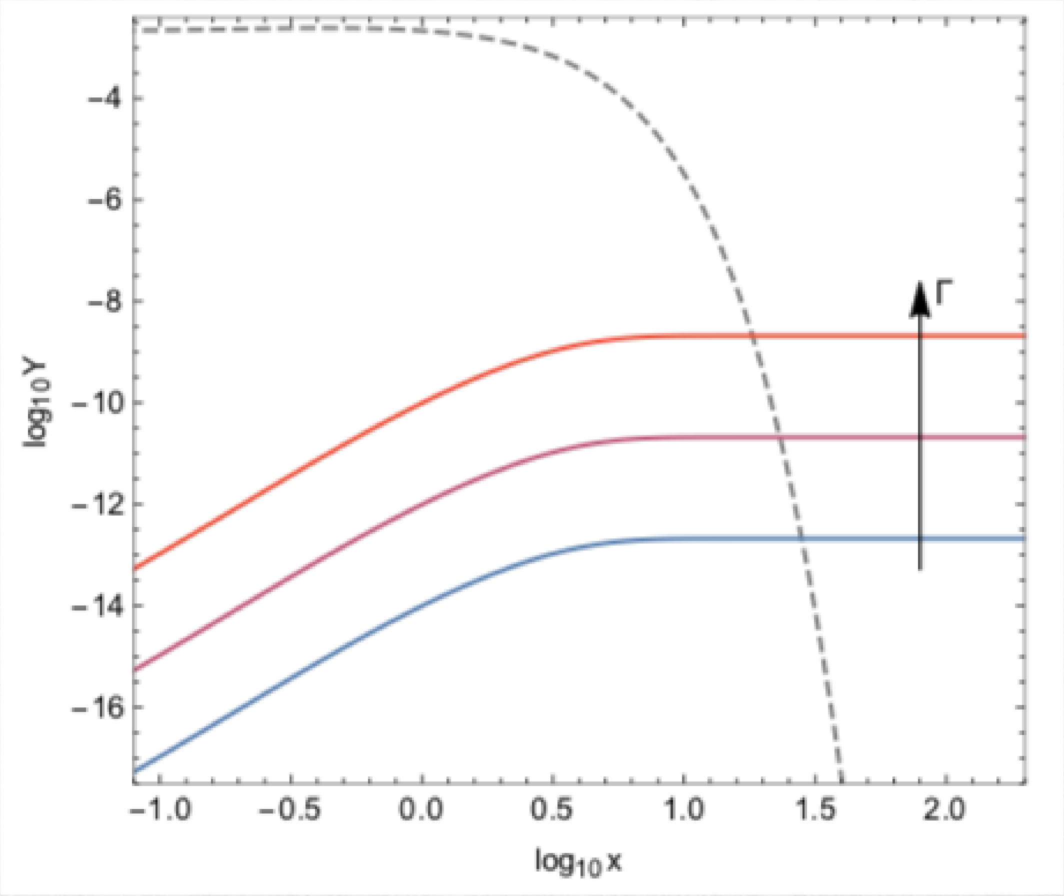
which, in order to agree with Planck 2018 bound, requires

$$y \simeq 10^{-12}\left(\frac{\Omega_\chi h^2}{0.12}\right)^{1/2}\left(\frac{g_*}{100}\right)^{3/4}\left(\frac{m_\sigma}{m_\chi}\right)^{1/2}$$

FREEZE-IN VS FREEZE-OUT

- Freeze-in (-out) yield increases (decreases) with interaction rate.
- Freeze-in (-out) does (not) depend upon initial conditions.
- Freeze-in (-out) yield gets dominated by x=m/T =2-5 (10-30).





FREEZE-OUT VS FREEZE-IN PROS & CONS

- DM in Freeze-out formalism e.g., WIMP has generic order one couplings, GeV-TeV scale masses and very good detection prospects.
- However, no such convincing WIMP signal so far. Need for a paradigm shift?
- DM in Freeze-in formalism e.g., FIMP has very feeble coupling (unnatural fine-tuning?) making it difficult to have any realistic detection prospects (except some specific indirect detection signatures).
- Non-thermal DM like FIMP may not be just another alternative, but can have deep connections to other phenomena like neutrino mass, cosmic inflation.

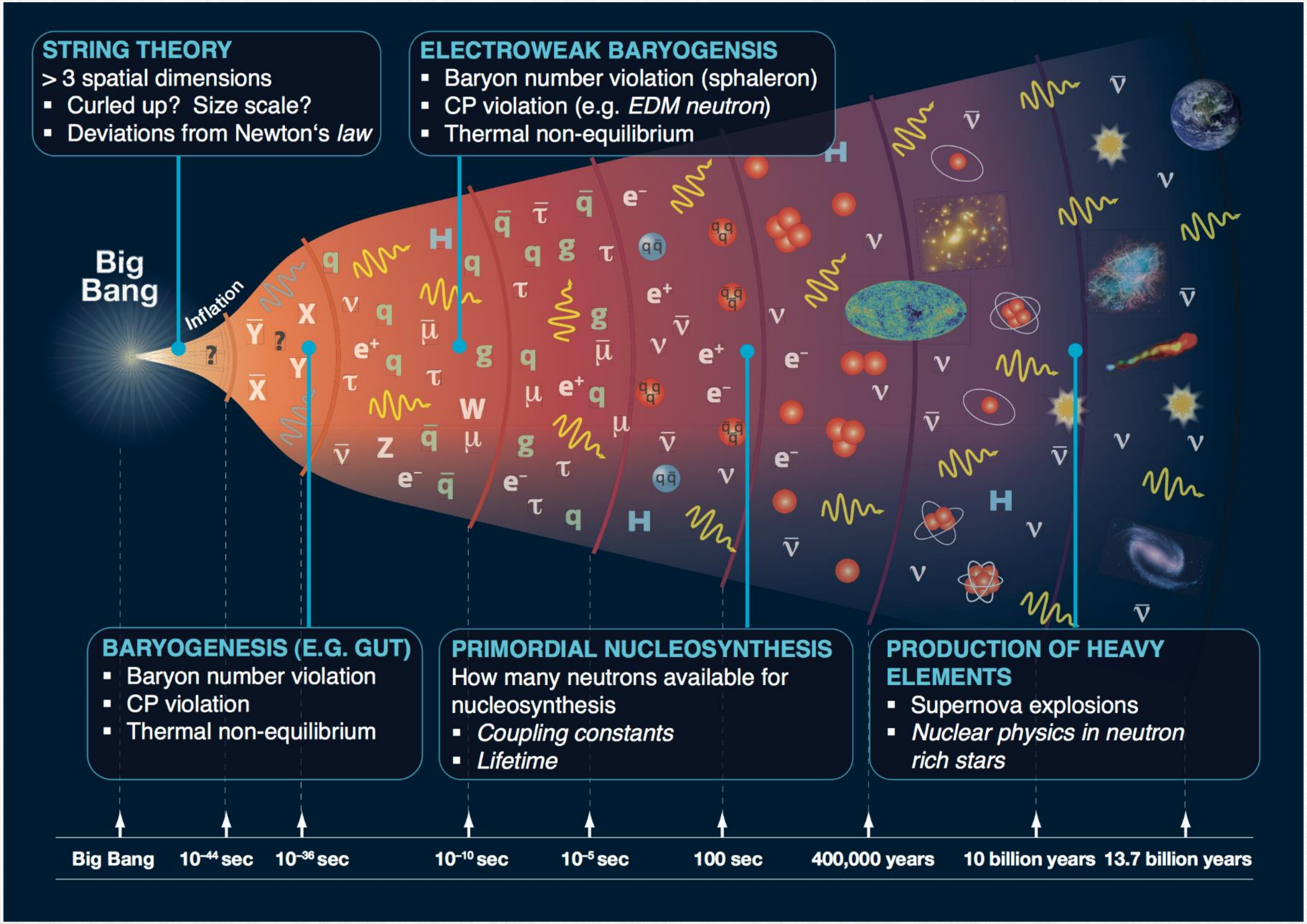
NEW WINDOWS TO PROBE DM

- Since WIMPs have not shown up and FIMPs are hard to probe at particle physics based experiments, some alternative ways of probing such scenarios may be useful.

- Stochastic gravitational wave (GW) backgrounds can offer such a possibility.

- If primordial black holes constitute DM, their mergers can also give rise to GW signals of the types LIGO-VIRGO have already observed (arxiv:1603.00464).

GW FROM EARLY UNIVERSE



STRING THEORY

> 3 spatial dimensions

- Curled up? Size scale?
- Deviations from Newton's *law*

ELECTROWEAK BARYOGENSIS

- Baryon number violation (sphaleron)
- CP violation (e.g. *EDM neutron*)
- Thermal non-equilibrium

BARYOGENESIS (E.G. GUT)

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- CP violation
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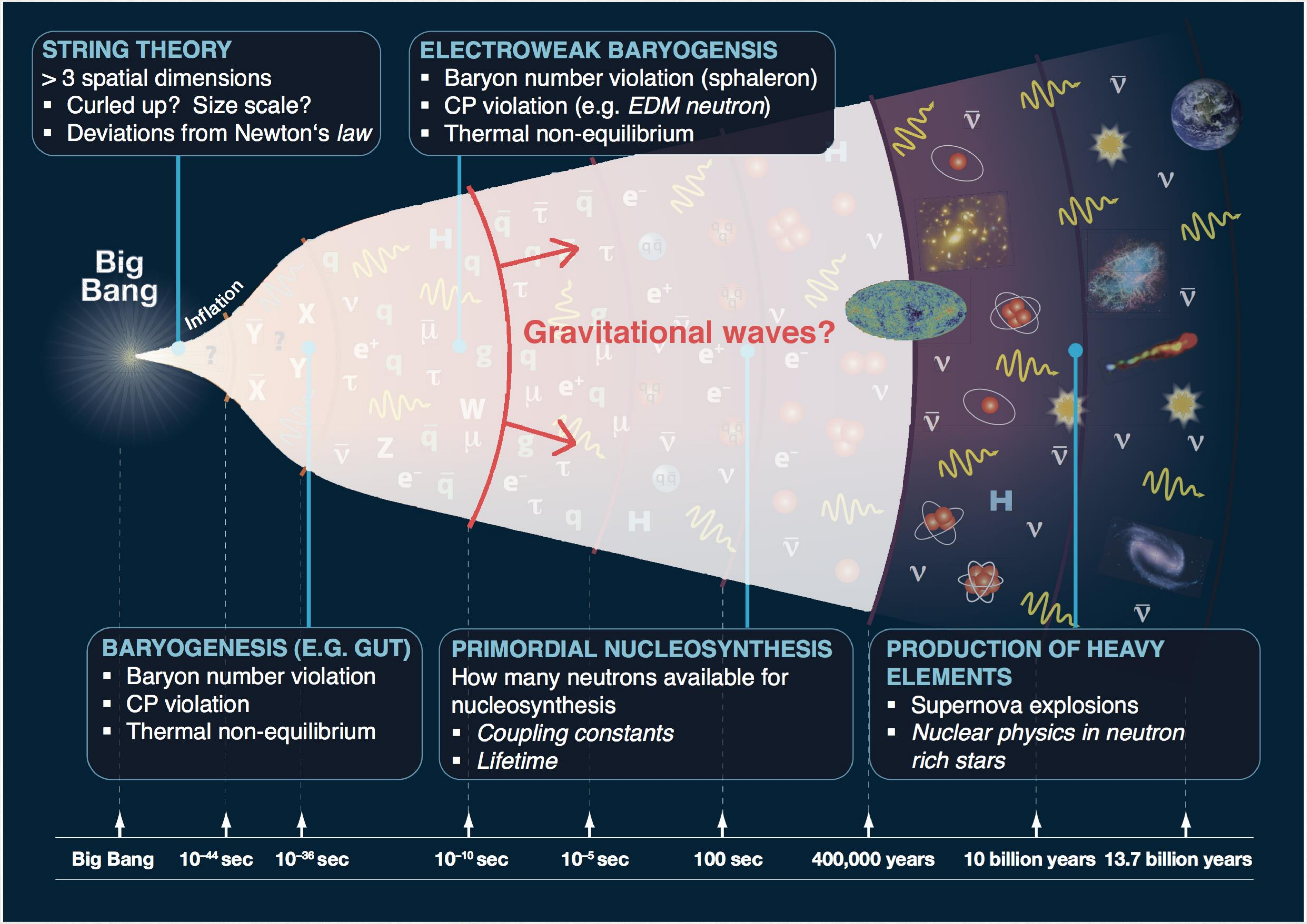
PRIMORDIAL NUCLEOSYNTHESIS

How many neutrons available for nucleosynthesis

- *Coupling constants*
- *Lifetime*

PRODUCTION OF HEAVY ELEMENTS

- Supernova explosions
- *Nuclear physics in neutron rich stars*



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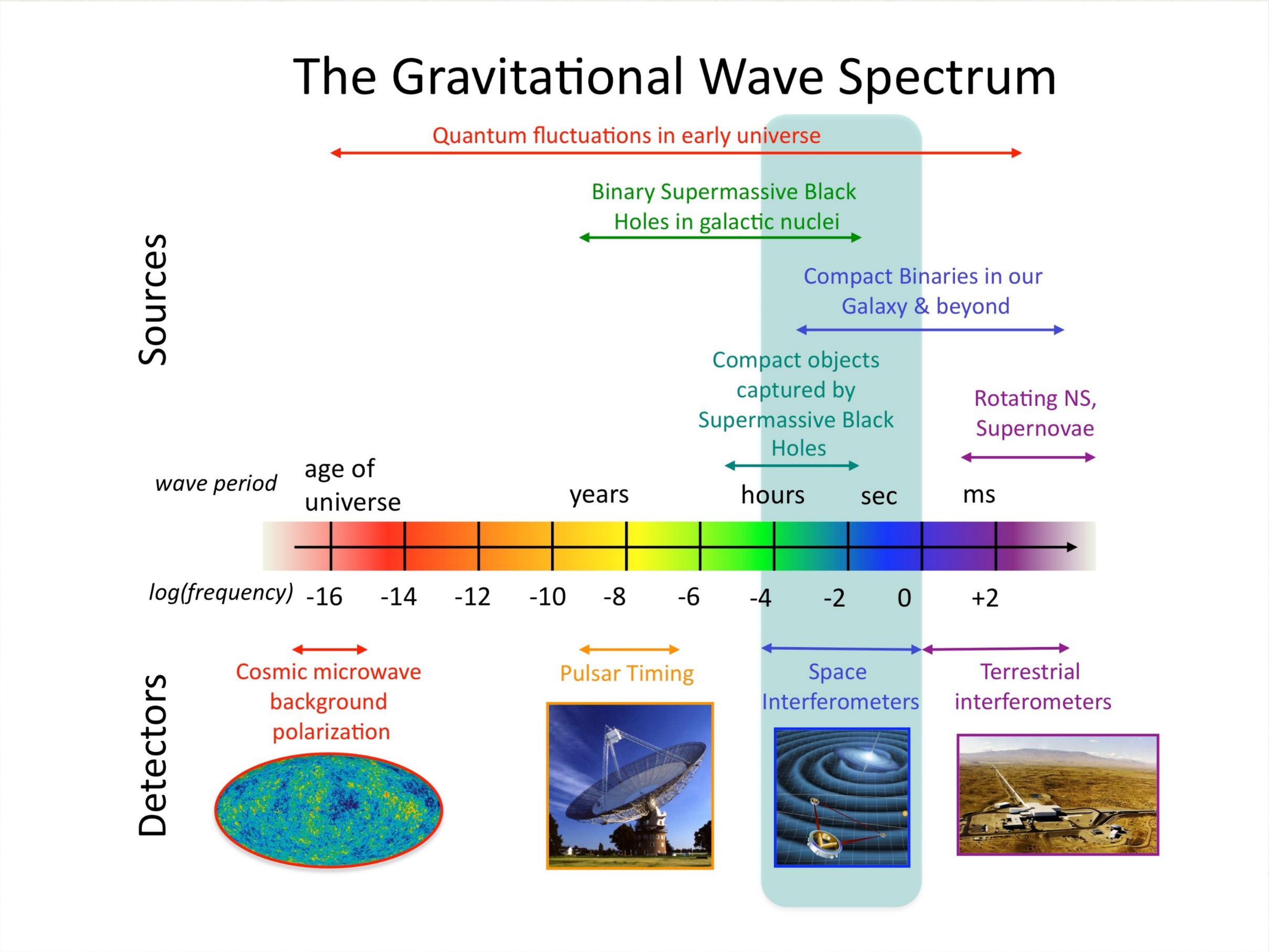
SOURCES OF PRIMORDIAL GW

- Inflation: a very rapid phase of expanding universe. Fluctuations in that inflationary phase can generate GW.

- First Order Phase Transitions (FOPT). Such transitions can be associated with certain symmetry breaking phenomena. Similar to liquid-gas transition, such transition can lead to formation of bubbles as well as turbulence, leading to GW formation.

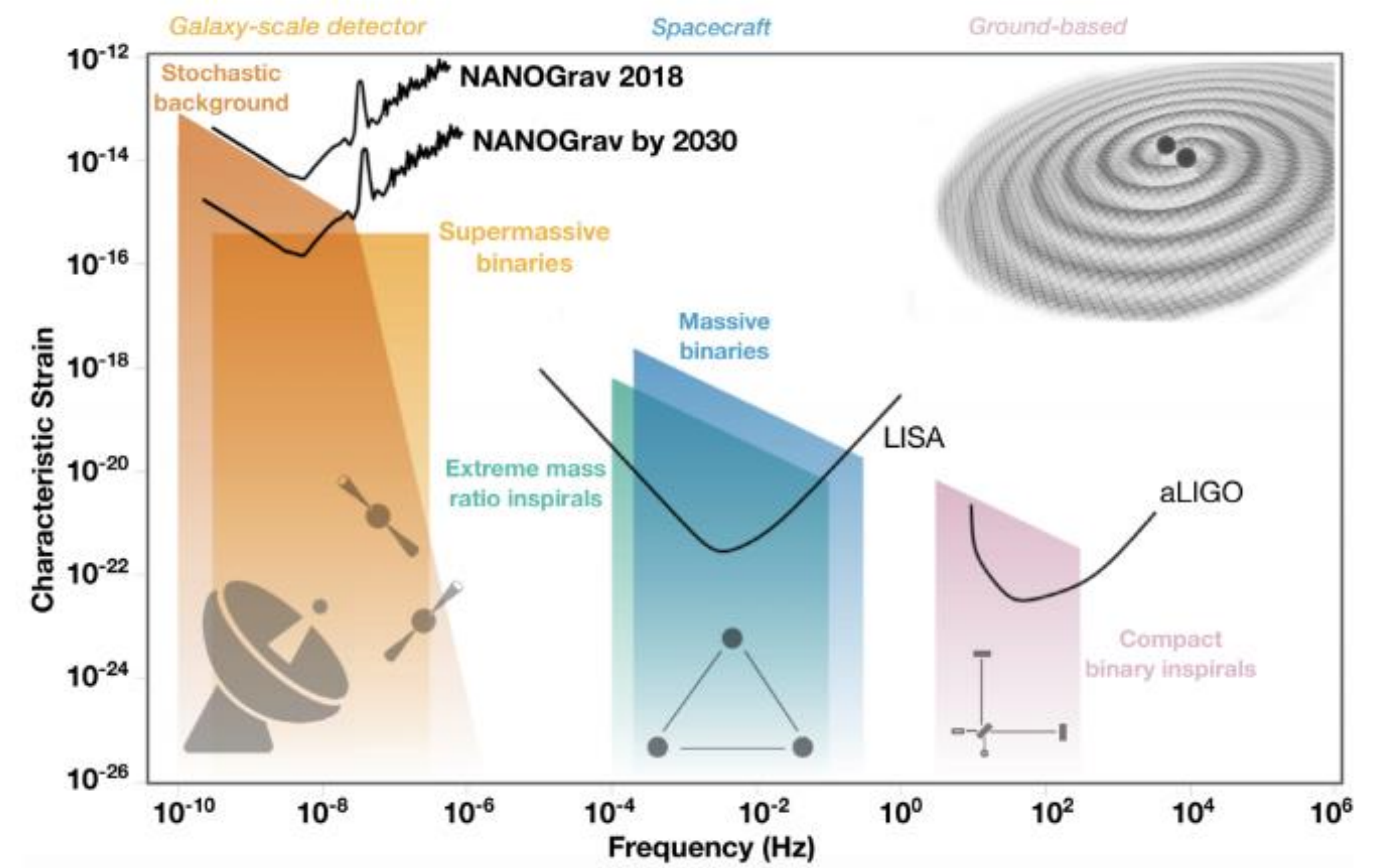
- Topological defects like cosmic strings, domain walls etc. Such defects can arise after symmetry breaking in the early Universe.



Regime of our interest

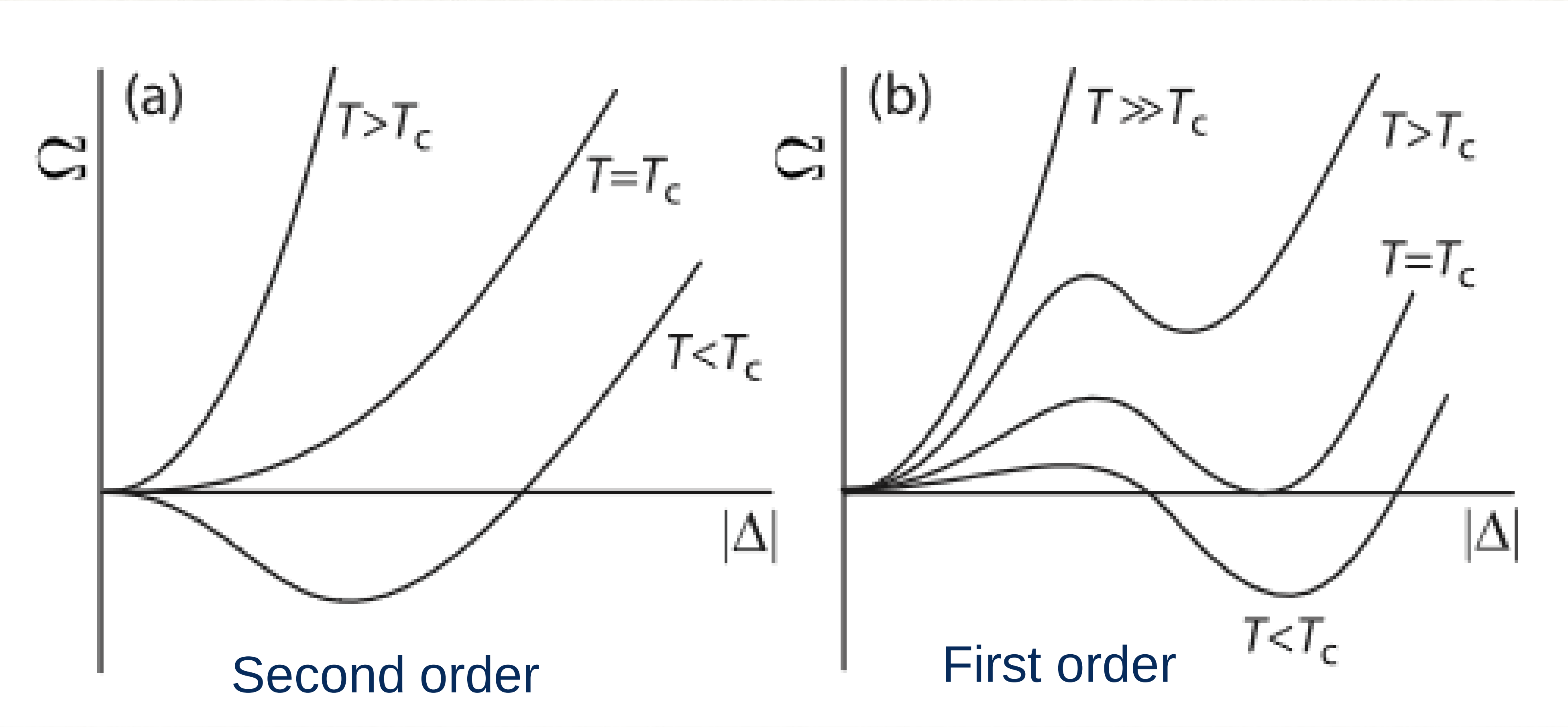
Credit: NASA

GW Sensitivity



Credit: Stephen Taylor

COSMOLOGICAL FIRST ORDER PHASE TRANSITION



Second order

First order

- Phase transition is a change of physical state of a system due to change in external conditions like temperature, pressure etc. For example, liquid-gas transition, paramagnetic to ferromagnetic transition.

- Phase transitions are described by order parameters. In cosmology, this is the vacuum expectation value of scalar fields.

COSMOLOGICAL FIRST ORDER PHASE TRANSITION

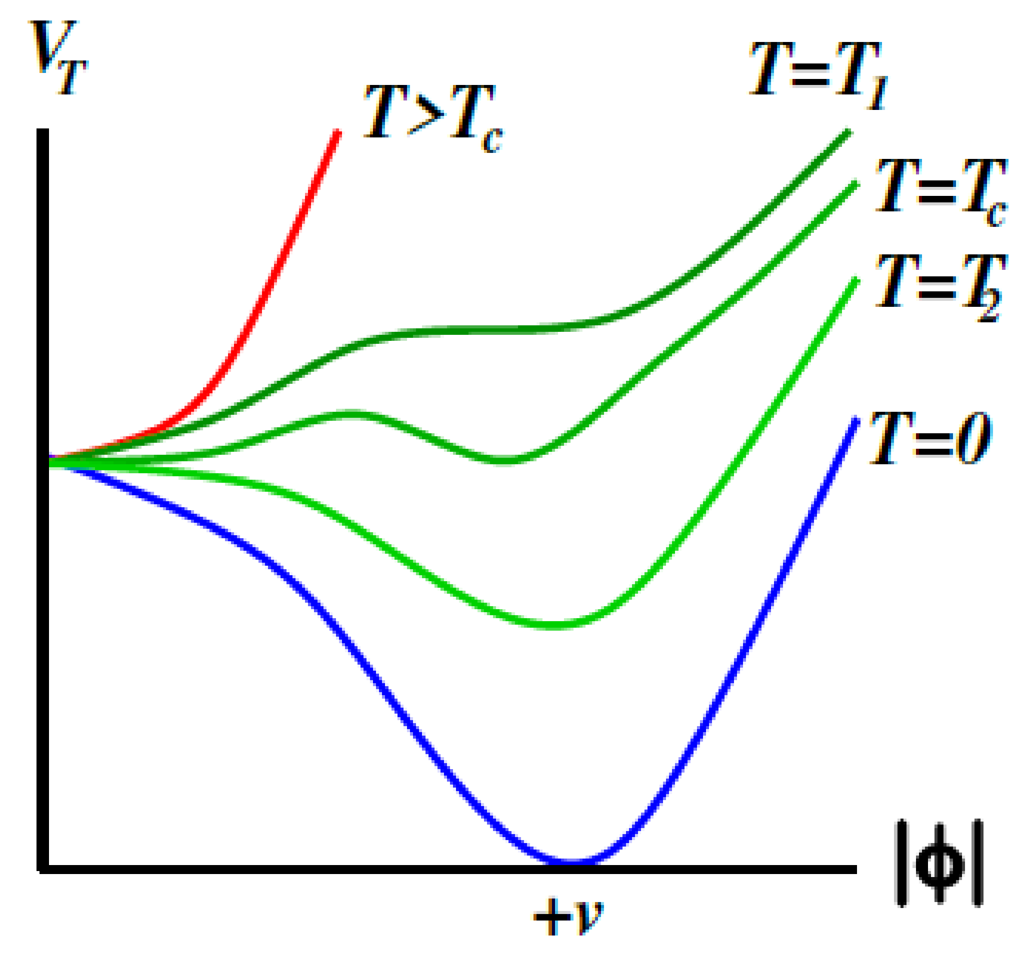
- After the discovery of the Higgs boson, we know that we live in the ground (broken symmetric) state of the potential given by

$$V_0(\phi) = \frac{\lambda}{4}\left(\phi^2 - v_{\mathrm{EW}}^2\right)^2$$

- At non-zero temperature, the above potential will receive thermal corrections

$$V_T(\phi) = \frac{D}{2}\left(T^2 - T_0^2\right)\phi^2 - \frac{A}{3}T\phi^3 + \frac{\lambda_T}{4!}\phi^4 + \ldots$$

- Depending on model parameters, the transition from symmetric to broken symmetric phase can be either 1st or 2nd order.



arXiv: 2008.09136

- Let the effective potential be

$$V_{\text{eff}}(\phi, T) \approx \frac{\mu^2 + cT^2}{2}\phi^2 - (ET + A)\phi^3 + \frac{\lambda}{4}\phi^4$$

- The cubic term is crucial to form a barrier between two minima.
- The barrier disappears at

$$T_o^2 = -\frac{\mu^2}{c} = \frac{\lambda - 3A/v}{c}v^2$$

- The critical T is

$$T_c = \frac{2}{\lambda c - 2E^2}\left[AE + \frac{\sqrt{\lambda c(2A^2 + (\lambda c - 2E^2)T_o^2)}}{2}\right]$$

- The order parameter is

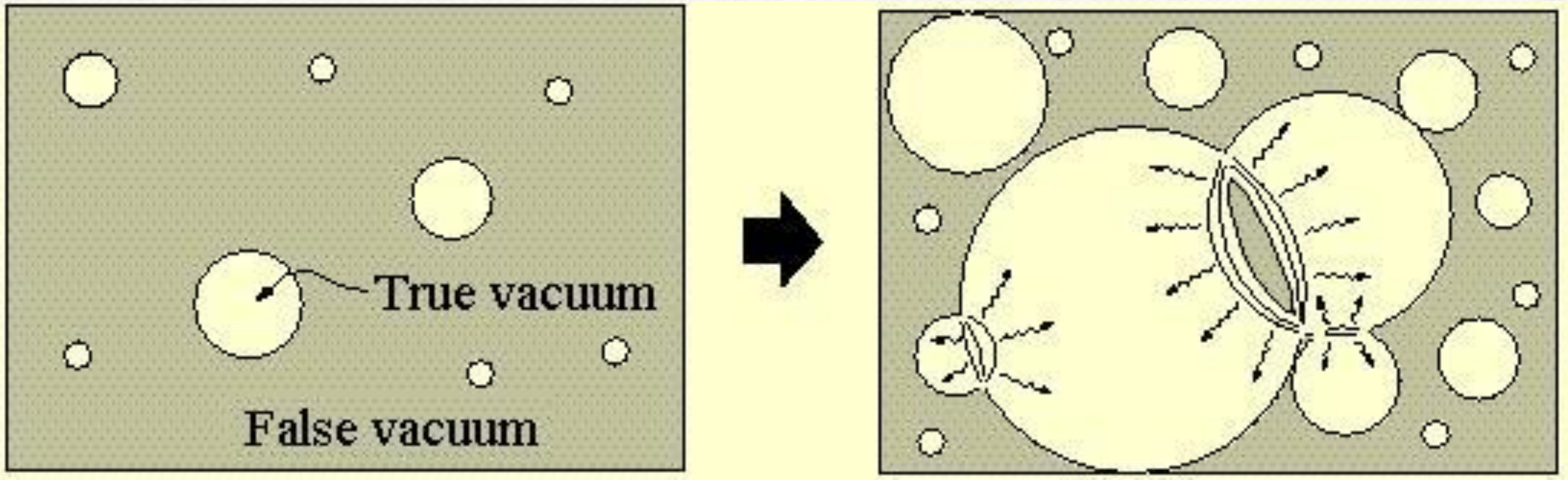
$$\frac{\phi_c}{T_c} = \frac{2(E + A/T_c)}{\lambda}$$

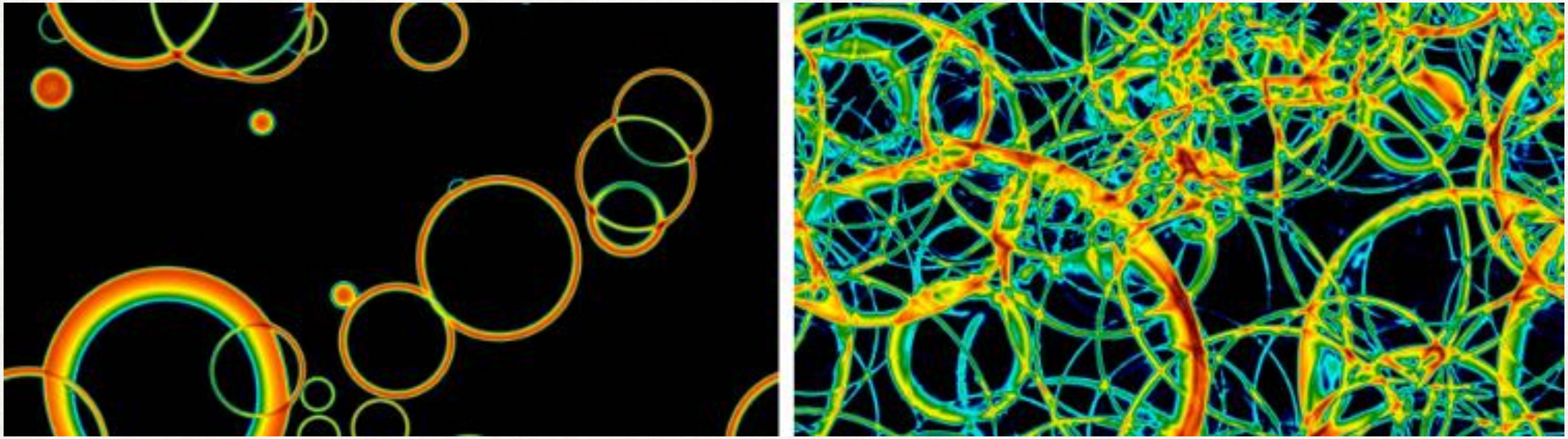
- Larger the order parameter, stronger the FOPT is.

COSMOLOGICAL FIRST ORDER PHASE TRANSITION

- If the universe undergoes a FOPT, bubbles will form (similar to boiling of water). Initially the bubbles collide and merge, producing GW.
- At later stages, after the bubbles collide and merge, the sound waves and turbulence in the plasma can source additional GW production.

COSMOLOGICAL FIRST ORDER PHASE TRANSITION





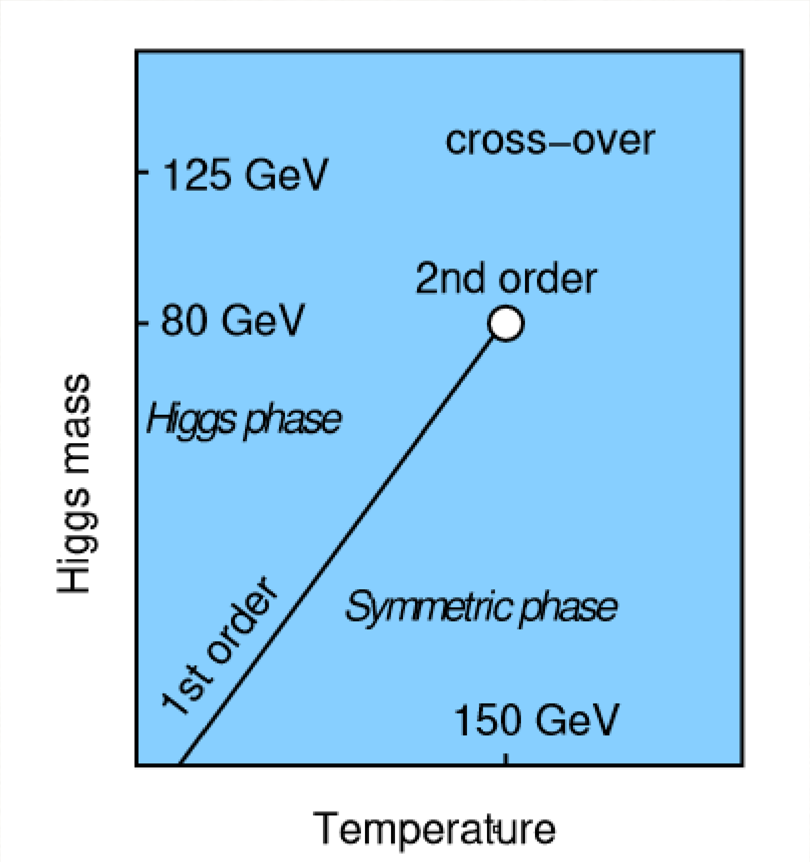
arXiv:1705.01783

FOPT WITH DM: TWO PATHWAYS

- While the electroweak phase transition (EWPT) in the SM is a second order phase transition, presence of additional particles like scalar singlet or scalar multiplet DM can lead to a first order EWPT. See, for example, arxiv:1204.4722, 2003.02276 etc. where scalar doublet DM was studied.

- While it is possible to get first order EWPT, due to various constraints on sub-TeV DM and other scalars, the GW amplitude remains very weak!

- This is because the cubic term in effective potential does not arise naturally but depends upon Higgs coupling to other fields.



arXiv: 2008.09136

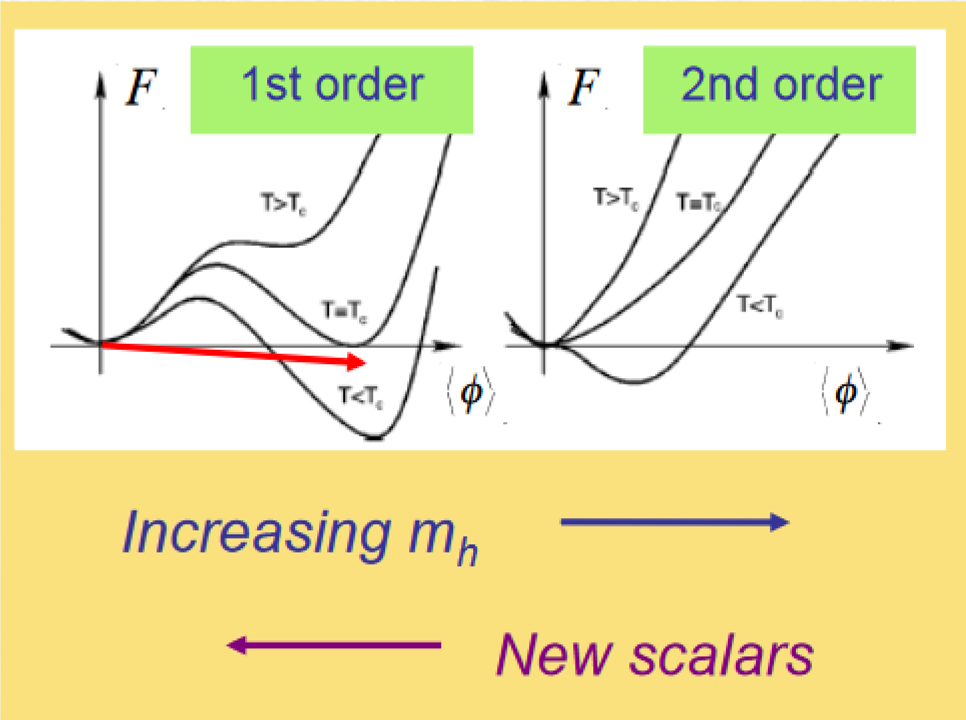
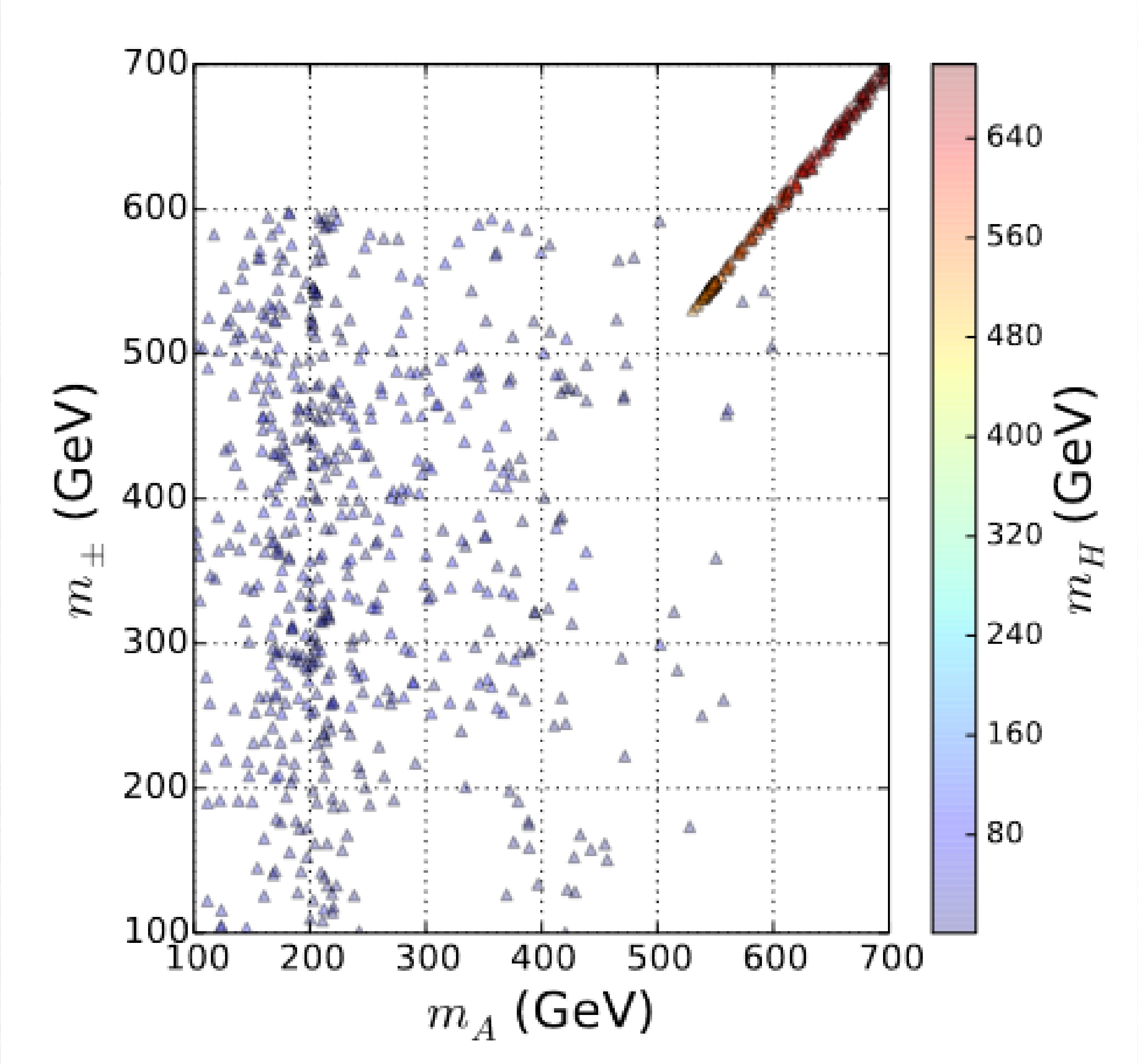
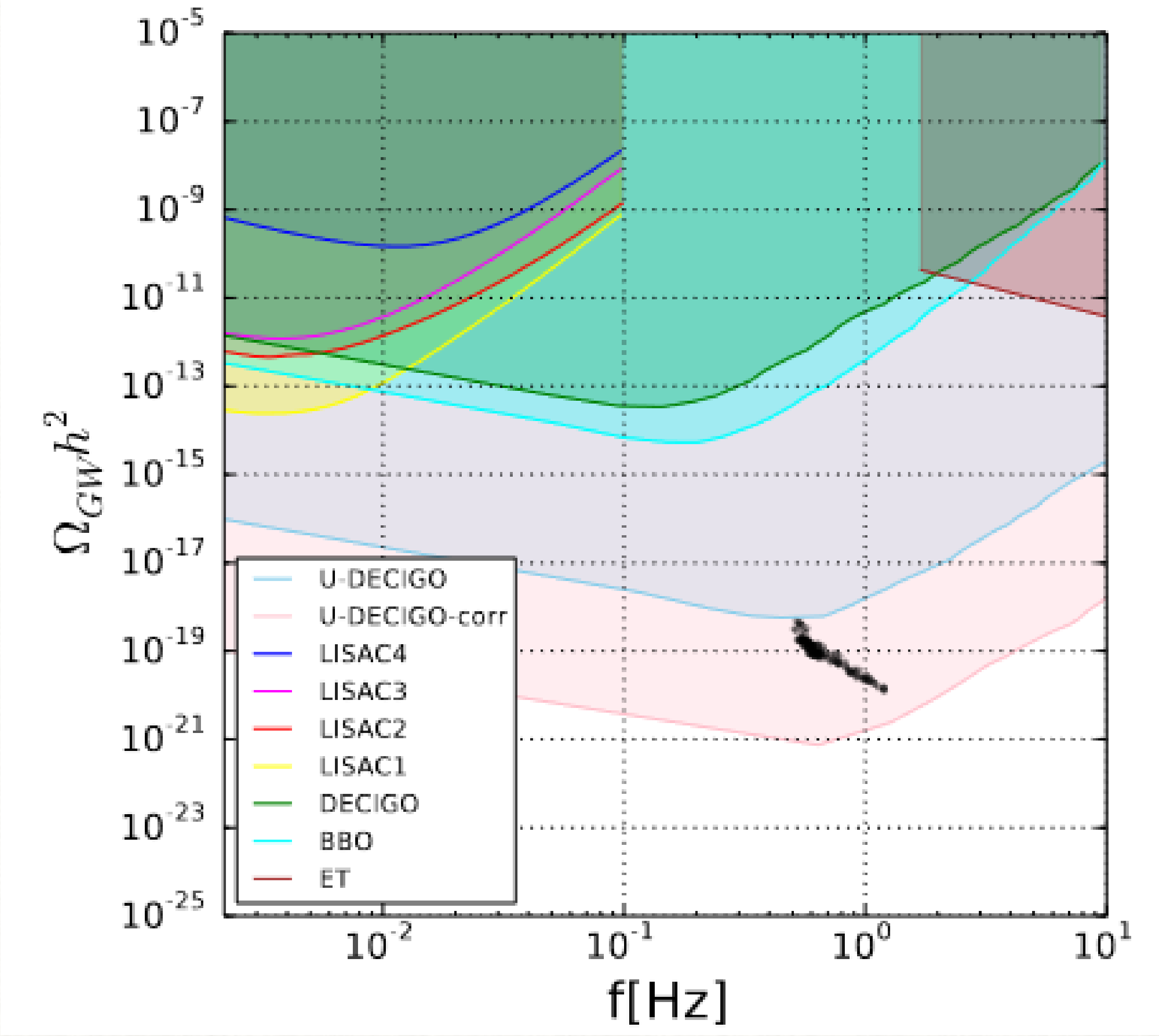


Image courtesy: Michael J Ramsey-Musolf





Arxiv: 2003.02276

FOPT WITH DM: TWO PATHWAYS

- The second pathway is to decouple EWPT from FOPT: Dark sector phase transition (arxiv:1504.07263).

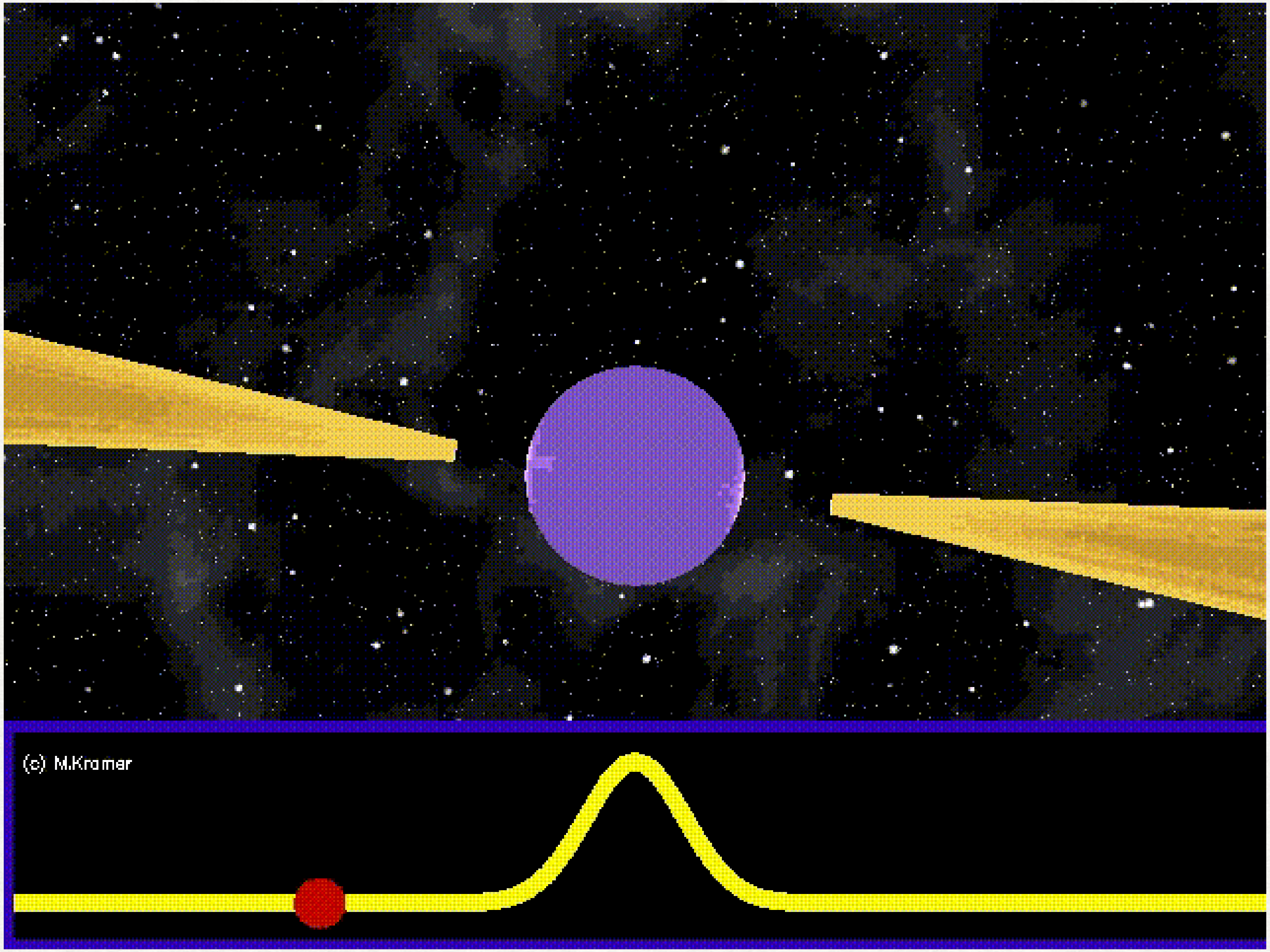
- Due to the freedom in choosing couplings/masses evading electroweak constraints, such FOPT can

(i) be very strong (like a supercooled one)

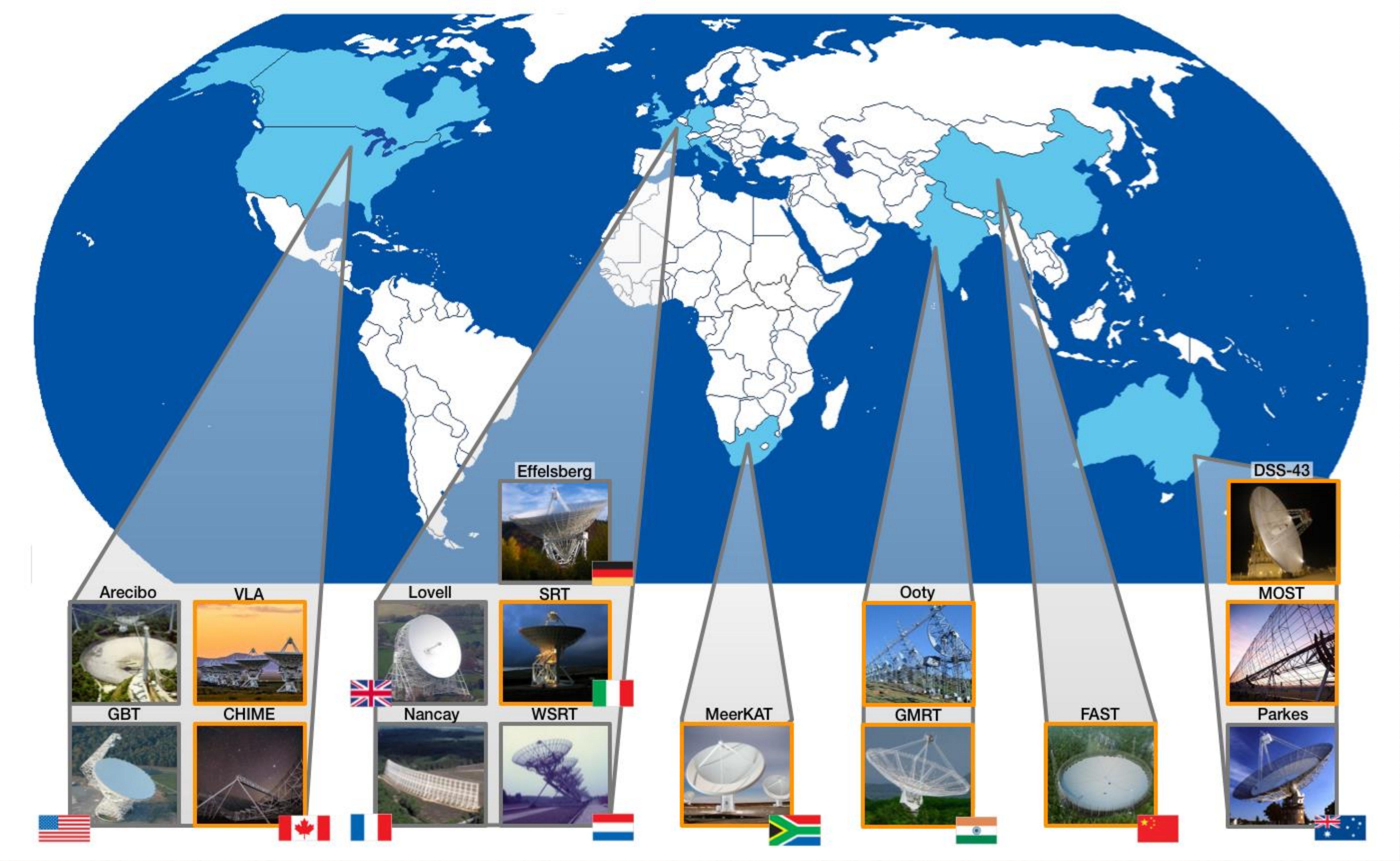
(ii) occur even below the electroweak scale

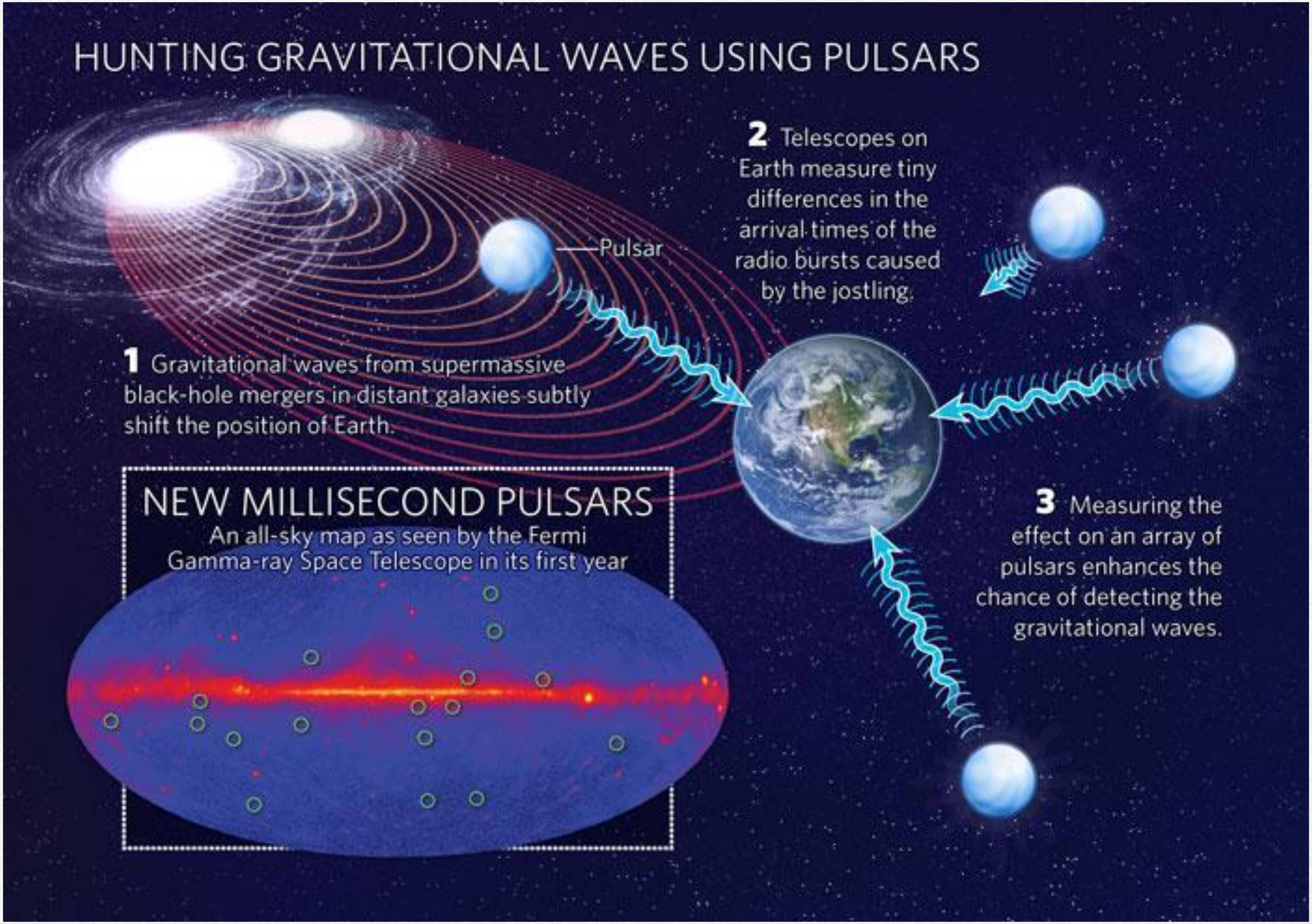
- We explore this possibility in the context of recent NANOGrav results.

PULSAR TIMING ARRAYS



IPTA TELESCOPES





HUNTING GRAVITATIONAL WAVES USING PULSARS

1 Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.

2 Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.

3 Measuring the effect on an array of pulsars enhances the chance of detecting the gravitational waves.

NEW MILLISECOND PULSARS

An all-sky map as seen by the Fermi Gamma-ray Space Telescope in its first year

Credit: NANOGrav

NANOGRAV RESULTS

- North American Nanohertz Observatory for Gravitational Waves (NANOGrav) search for GW background in 12.5 yr data finds “**Strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars**.” (ApJ Letters 905, 2 (2020))

- They analysed 45 millisecond pulsars in search of a stochastic process. However, more data are required to confirm it to be of GW origin.

- At low frequencies, the shape of the characteristic strain spectrum matches well to a power-law, with amplitude and slope consistent with supermassive black hole binaries (SMBHB).

NANOGRAV RESULTS

- A subsequent analysis by NANOGrav collaboration also found that **their data can be explained in terms of a strong FOPT taking place at sub-electroweak scale temperatures** T < 100 GeV (PRL 127, 25 (2021)).
- More recently, the Parkes Pulsar Timing Array (PPTA) data also found evidence for such common spectrum process, compatible with NANOGrav findings (arXiv:2107.12112).
- PPTA also found their data to be consistent with a cosmological first order phase transition at T ≈ 1-100 MeV (arXiv:2110.03096).
- If one takes such evidence for a stochastic process seriously, what could be the possible origins?

POSSIBLE EXPLANATIONS

- Supermassive black hole binaries (arXiv:1811.08826).
- Cosmic Strings (arXiv:2009.06555, 2009.06607).
- Primordial origin: inflation (arXiv:2009.13432).
- During formation of primordial black holes from large curvature perturbations (arXiv:2009.07832, 2009.08268).
- Cosmological first order phase transition (arXiv:2104.13930)

DARK FIRST ORDER PHASE TRANSITION

- A FOPT is possible in the standard model only for Higgs mass < 70 GeV. For 125 GeV Higgs mass, measured by the LHC, the electroweak phase transition is of second order (smooth crossover).

- A cosmological FOPT, therefore, requires new physics beyond the standard model.

- A sub-EW scale FOPT can be realized by suitable extension of the standard model (SM) where such low scale symmetry breaking occurs.

- Since new physics below the EW scale is tightly constrained from laboratory experiments, it is better not to couple SM degrees of freedom directly: **Dark sector**

Gravitational waves from a dark $U(1)_D$ phase transition in light of NANOGrav 12.5 yr data

Debasish Borah, Arnab Dasgupta, and Sin Kyu Kang
Phys. Rev. D **104**, 063501 – Published 1 September 2021

- We consider an Abelian gauge symmetry with a singlet scalar and a Dirac fermion Dark Matter.

- The singlet scalar breaks the gauge symmetry leading to dark phase transition.

- The Dirac fermion charged under the symmetry can be a stable Dark Matter candidate whose relic is generated non-thermally.

$$V_{\text{tot}} = V_{\text{tree}} + V_{\text{CW}} + V_{\text{th}}$$

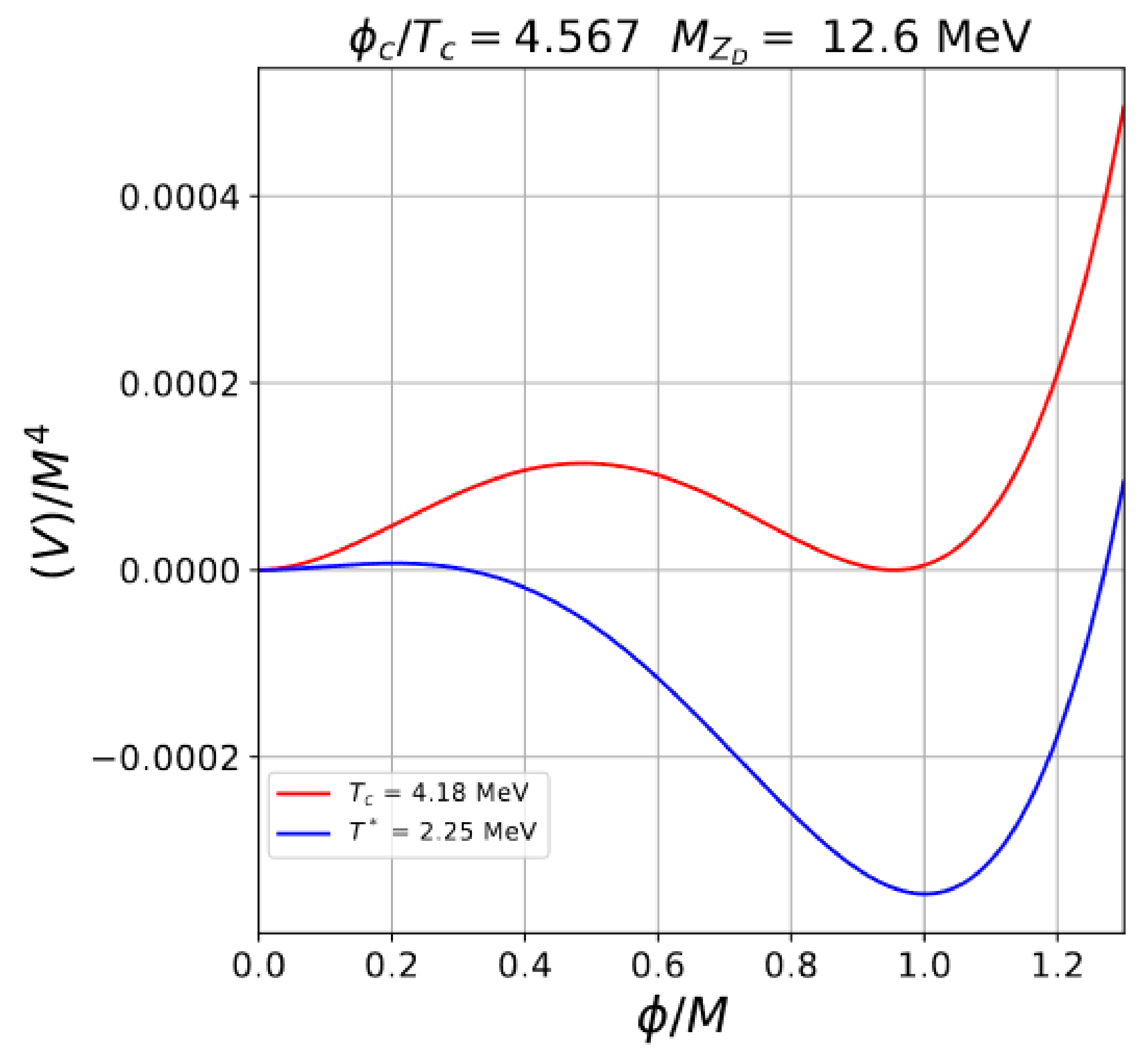
$$V_{\text{tree}} = \lambda_H (H^\dagger H)^2 + \lambda(\Phi^\dagger \Phi)^2 - \lambda^{'}(\Phi^\dagger \Phi)(H^\dagger H)$$

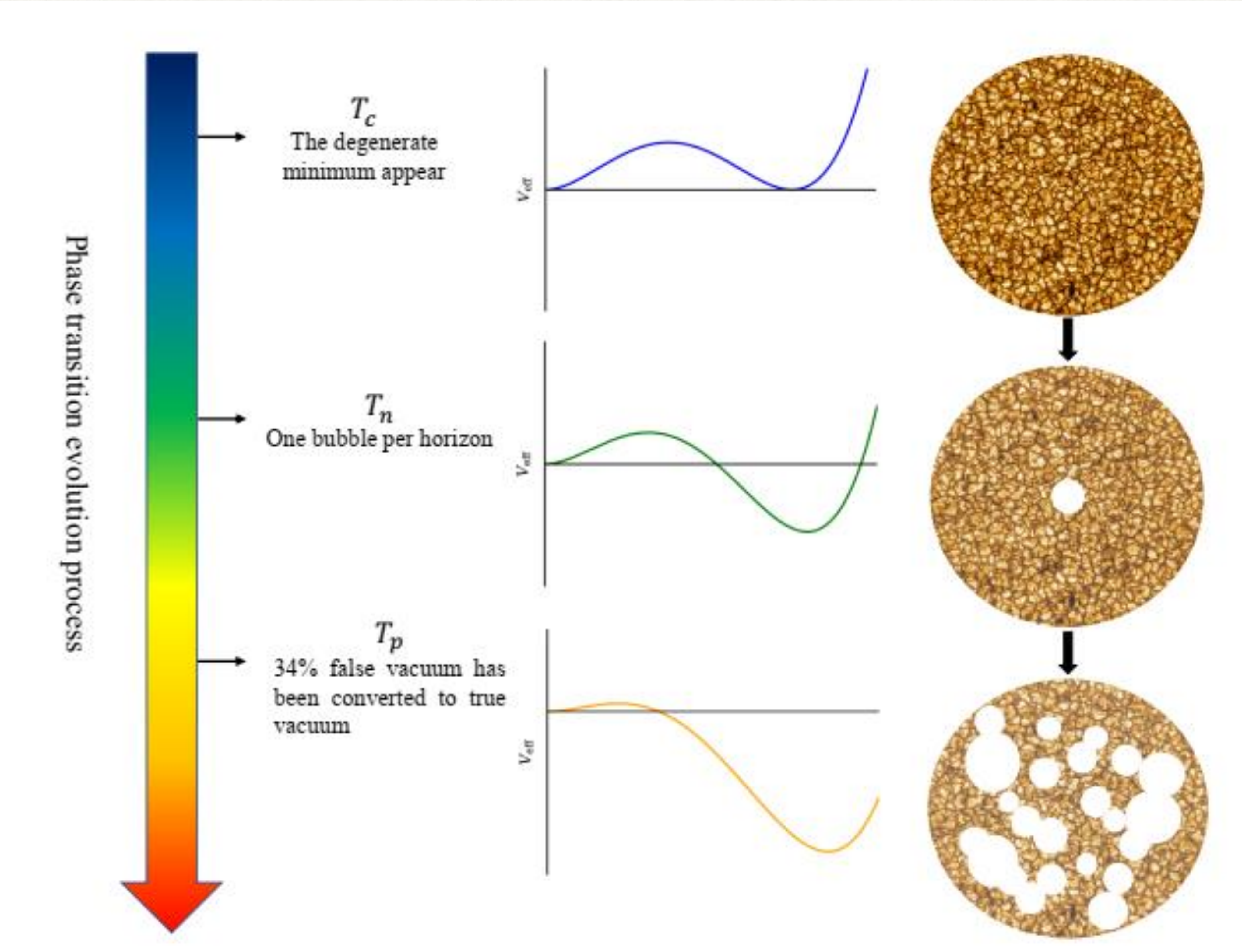
$$V_{\text{CW}} = \frac{1}{64\pi^2}\sum_i (2s_i+1) m_i^4(\phi)\left[\ln\left(\frac{m_i^4(\phi)}{\mu^2}\right) - C_i\right]$$

$$V_{\text{th}} = \sum_i \left(\frac{n_{\text{B}_\text{i}}}{2\pi^2} T^4 J_B\left[\frac{m_{\text{B}_\text{i}}}{T}\right] - \frac{n_{\text{F}_\text{i}}}{2\pi^2} J_F\left[\frac{m_{\text{F}_\text{i}}}{T}\right]\right)$$

$$J_B(x) = \int_0^\infty dz z^2 \log\left[1 - e^{-\sqrt{z^2+x^2}}\right]$$
$$J_F(x) = \int_0^\infty dz z^2 \log\left[1 + e^{-\sqrt{z^2+x^2}}\right]$$

- The FOPT proceeds via tunnelling, and the corresponding spherical symmetric field configurations called bubbles are nucleated followed by expansion and coalescence.
- The FOPT completes via percolation of growing bubbles. The corresponding percolation temperature is calculated when more than one third of the commoving volume is occupied by the true vacuum.





Arxiv: 2003.08892

GRAVITATIONAL WAVES

- A GW is a propagating mode of the transverse and traceless part of the metric perturbation, satisfying the equation

$$\ddot{h}_{ij} - \nabla^2 h_{ij} = 16\pi G T_{ij}^{\mathrm{TT}}$$

- GW can itself be a source of energy-momentum defined by

$$T_{\mu\nu}^{\mathrm{gw}} = \frac{1}{32\pi G}\langle \partial_\mu h_{ij} \partial_\nu h_{ij} \rangle$$

- The fractional energy density in GW can be found as

$$\Omega_{\mathrm{gw}} = \frac{\rho_{\mathrm{gw}}}{\rho_{\mathrm{tot}}}$$

$$\rho_{\mathrm{gw}} = \frac{1}{32\pi G}\langle \dot{h}_{ij}^2 \rangle$$

- GW spectrum is defined as

$$\frac{\mathrm{d}\Omega_{\mathrm{gw}}}{\mathrm{d}\ln f} = \frac{1}{\rho_{\mathrm{tot}}}\frac{\mathrm{d}\rho_{\mathrm{gw}}}{\mathrm{d}\ln f} = \frac{2\pi^2}{3H^2} f^3 S_h(f)$$

arXiv:1801.04268

GRAVITATIONAL WAVES

- FOPT can lead to production of stochastic GW from three different sources: bubble collision, sound wave and turbulence.

$$\Omega_{\rm GW}(f) = \Omega_\phi(f) + \Omega_{\rm sw}(f) + \Omega_{\rm turb}(f).$$

arXiv:1512.06239

- Each contribution can be parametrised as

$$h^2\Omega(f) = \mathcal{R}\,\Delta(v_w)\left(\frac{\kappa\,\alpha_*}{1+\alpha_*}\right)^p\left(\frac{H_*}{\beta}\right)^q \mathcal{S}\,(f/f_*^0)$$

Redshift

Normalisation

Spectral shape

Strength of PT:

$$\alpha_* = \frac{\epsilon_*}{\rho_{\rm rad}}$$

$$\epsilon_* = \left[\Delta V_{\rm tot} - \frac{T}{4}\frac{\partial \Delta V_{\rm tot}}{\partial T}\right]|_{T=T_*}$$

$$\Delta V_{\rm tot} \equiv V_{\rm tot}(\phi_{\rm false}, T) - V_{\rm tot}(\phi_{\rm true}, T)$$

Equivalent to the Latent heat!

GRAVITATIONAL WAVES

Duration of the PT 1/ β

Peak frequency f_*^0

Thumb rule: Fast (slow) PT at High (low) T → high (low) frequency

GWs from FOPT at electroweak scale T ~ 100 GeV in LISA (mHz) band

GWs from slow FOPT at low scale T ~ 100 MeV in PTA (nHz) band

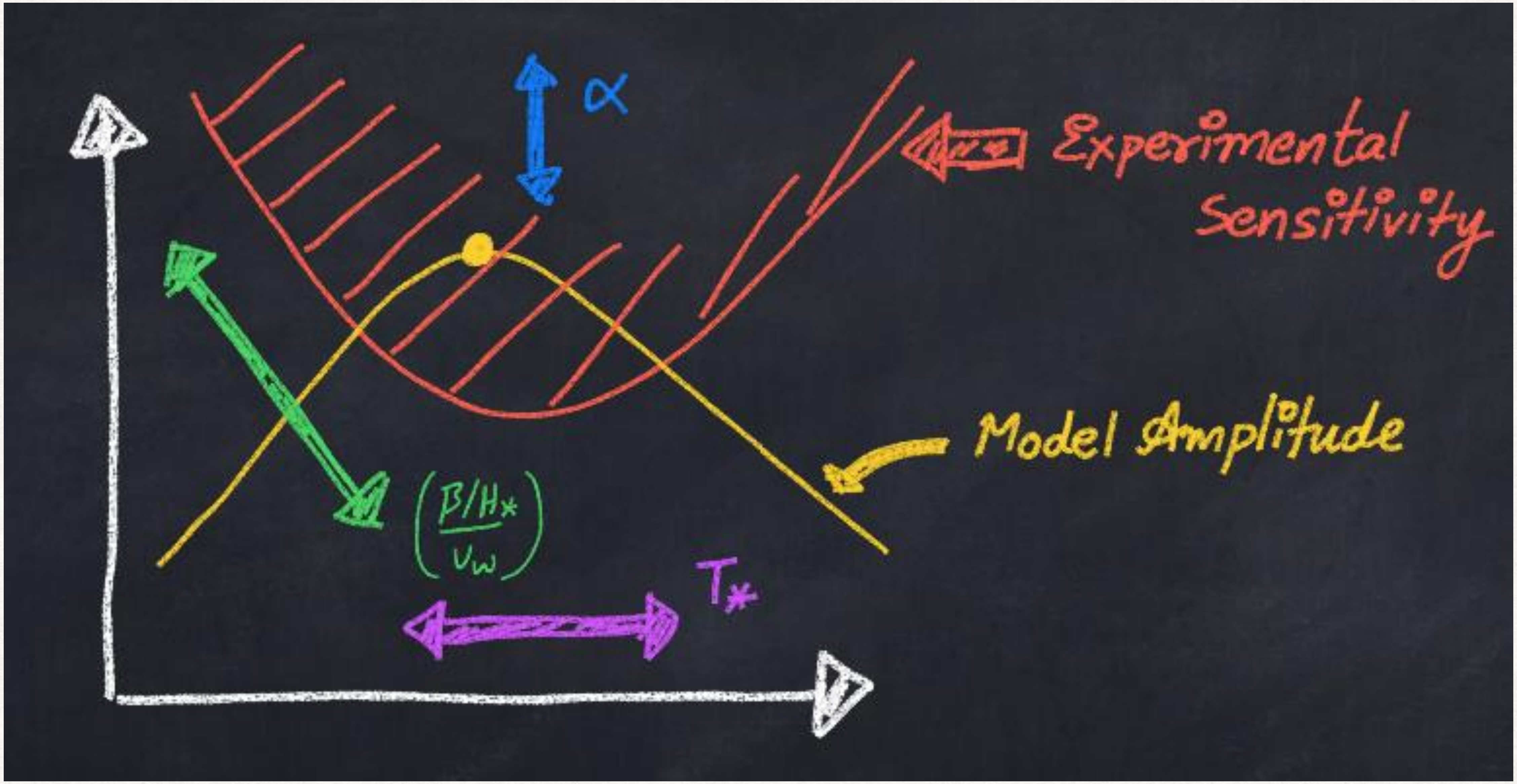
	Bubbles	Sound waves
$\Delta(v_w)$	$\frac{0.48v_w^3}{1+5.3v_w^2+5v_w^4}$	$0.513\, v_w$
κ	κ_ϕ	$\kappa_{\rm sw}$
p	2	2
q	2	1
$\mathcal{S}(x)$	$\frac{(a+b)^c}{[bx^{-a/c}+ax^{b/c}]^c}$	$x^3\left(\frac{7}{4+3x^2}\right)^{7/2}$
f_*/β	$\frac{0.35}{1+0.07v_w+0.69v_w^4}$	$\frac{0.536}{v_w}$

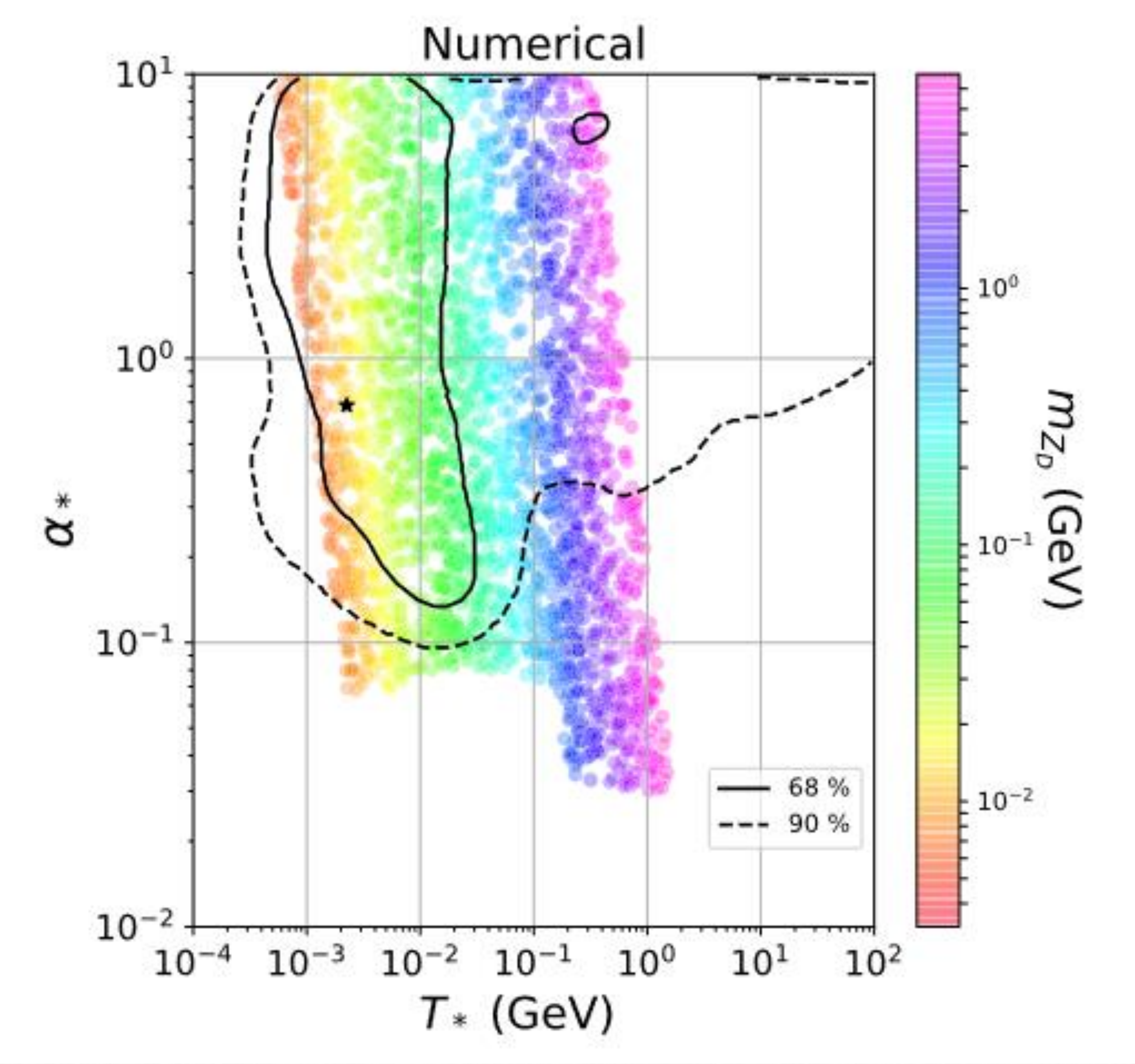
$$\mathcal{R} \simeq 7.69 \times 10^{-5} g_*^{-1/3}$$

$$f_*^0 \simeq 1.13 \times 10^{-10}\mathrm{Hz}\left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{\mathrm{H}_*}\right)\left(\frac{T_*}{\mathrm{MeV}}\right)\left(\frac{g_*}{10}\right)^{1/6}$$

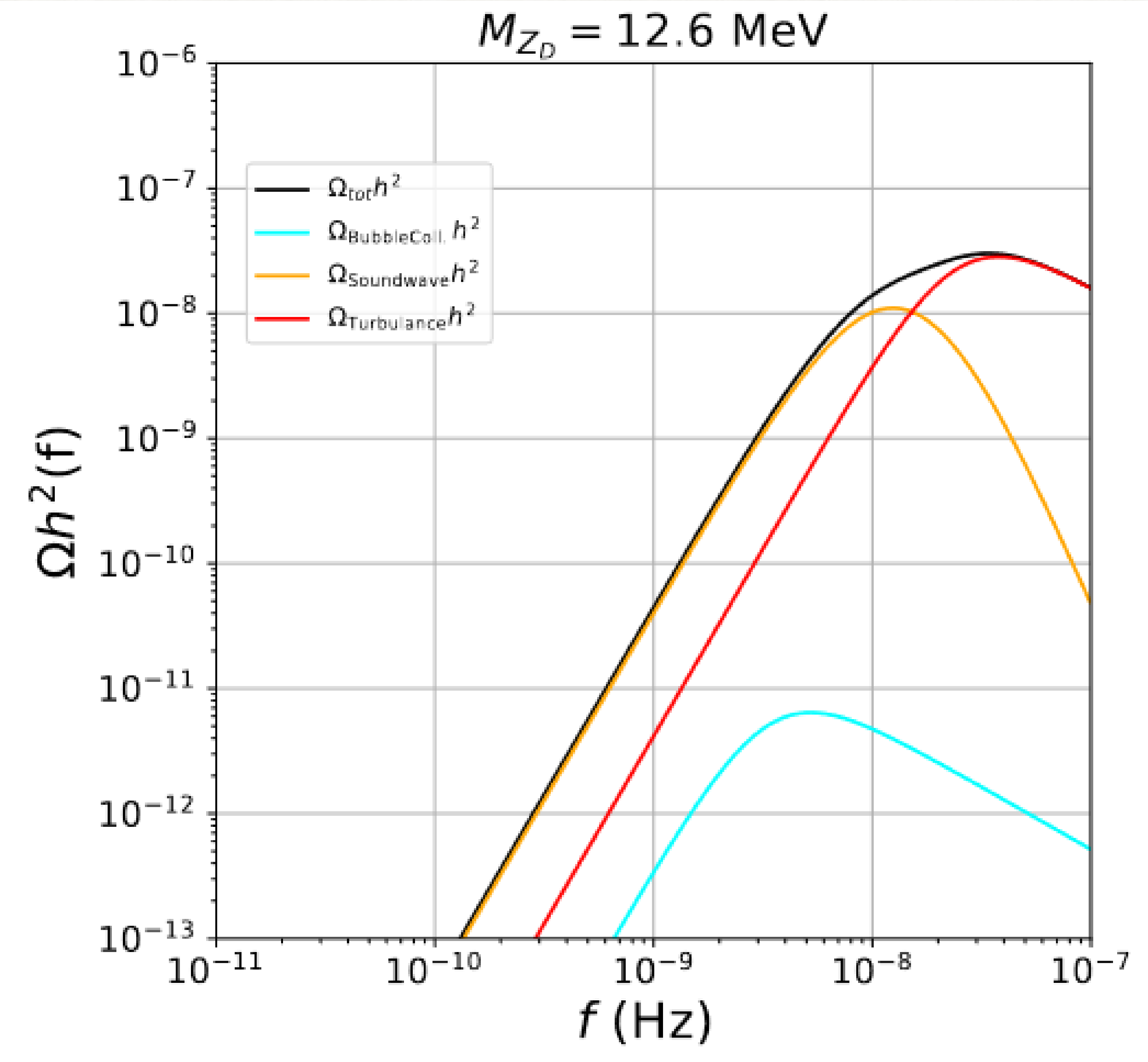
arXiv:2104.13930

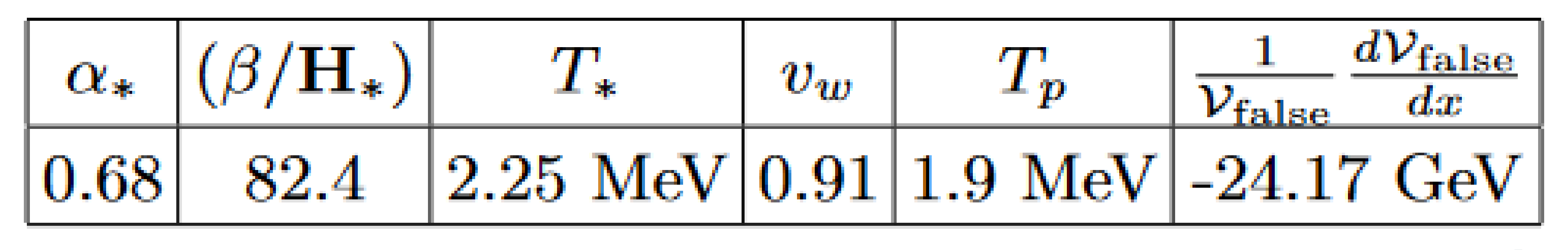
TYPICAL GW SPECTRUM FROM FOPT





DB, A Dasgupta, S K Kang, arXiv:2105.01007



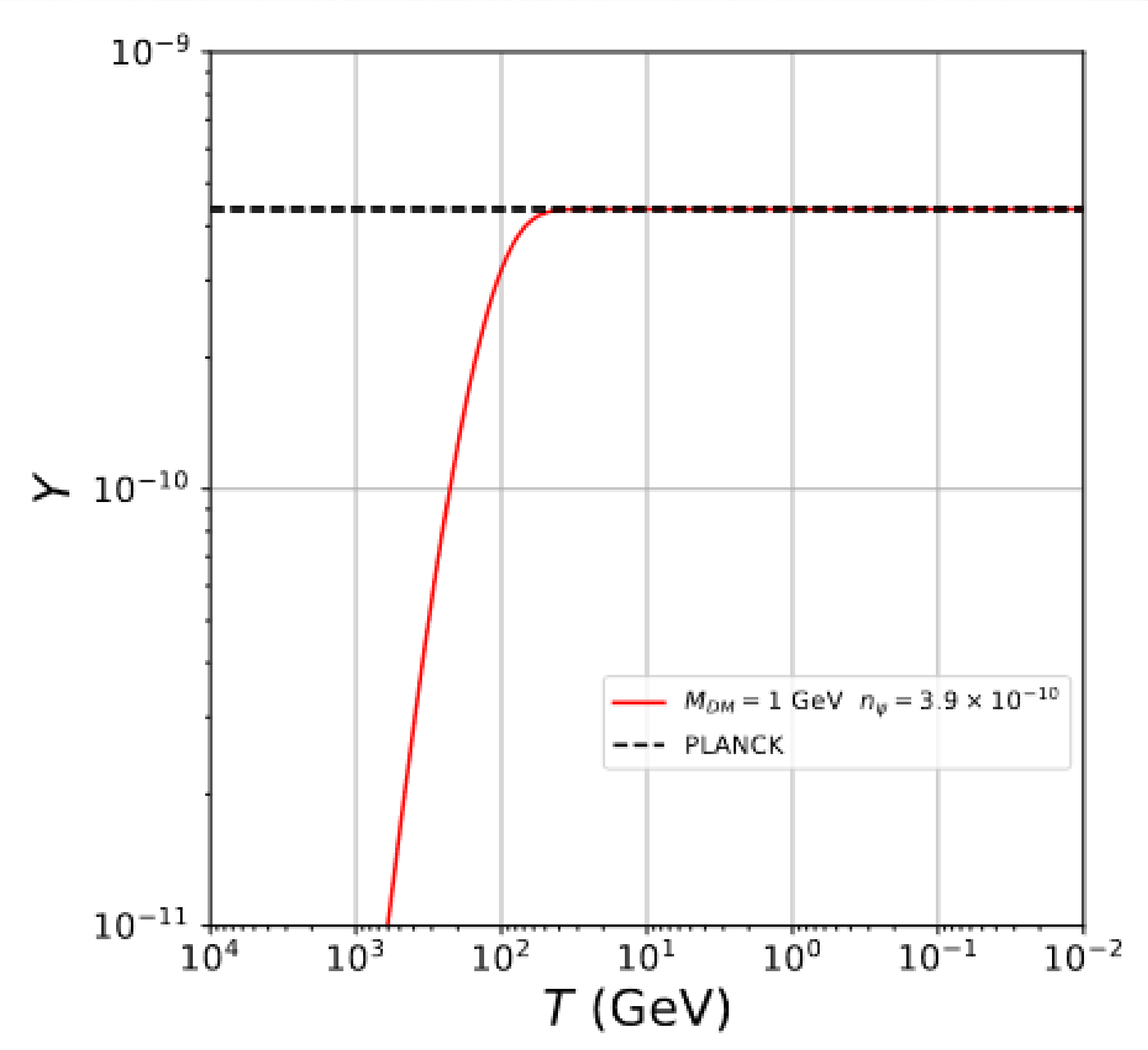


α_*	$(\beta/\mathbf{H}_*)$	T_*	v_w	T_p	$\frac{1}{\mathcal{V}_{\rm false}}\frac{d\mathcal{V}_{\rm false}}{dx}$
0.68	82.4	2.25 MeV	0.91	1.9 MeV	-24.17 GeV

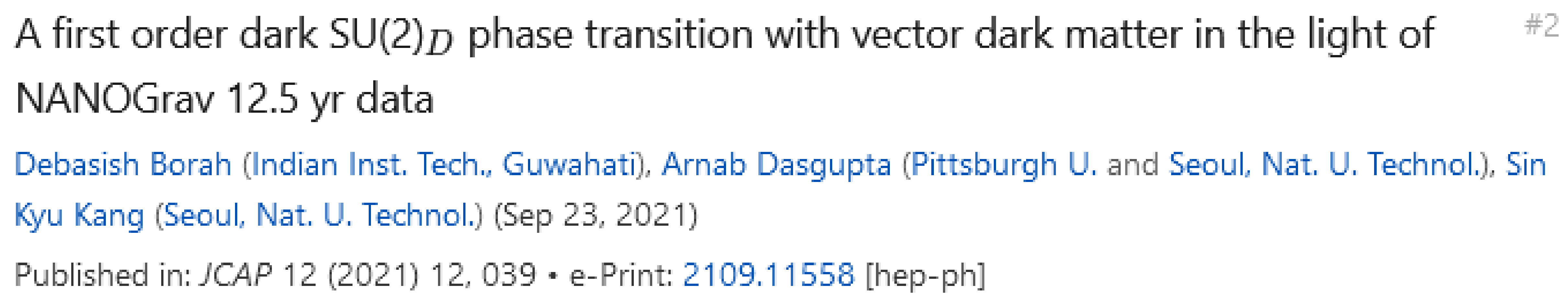
DB, A Dasgupta, S K Kang, arXiv:2105.01007

CONNECTION TO DARK MATTER

- Production of DM can happen either thermally or non-thermally.
- In our setup, we consider non-thermal production of Dirac fermion DM.
- The feeble interaction between visible and dark sector occurs due to tiny kinetic mixing between dark U(1) with the SM counterpart.



DB, A Dasgupta, S K Kang, arXiv:2105.01007



A first order dark SU(2)$_D$ phase transition with vector dark matter in the light of NANOGrav 12.5 yr data

#2

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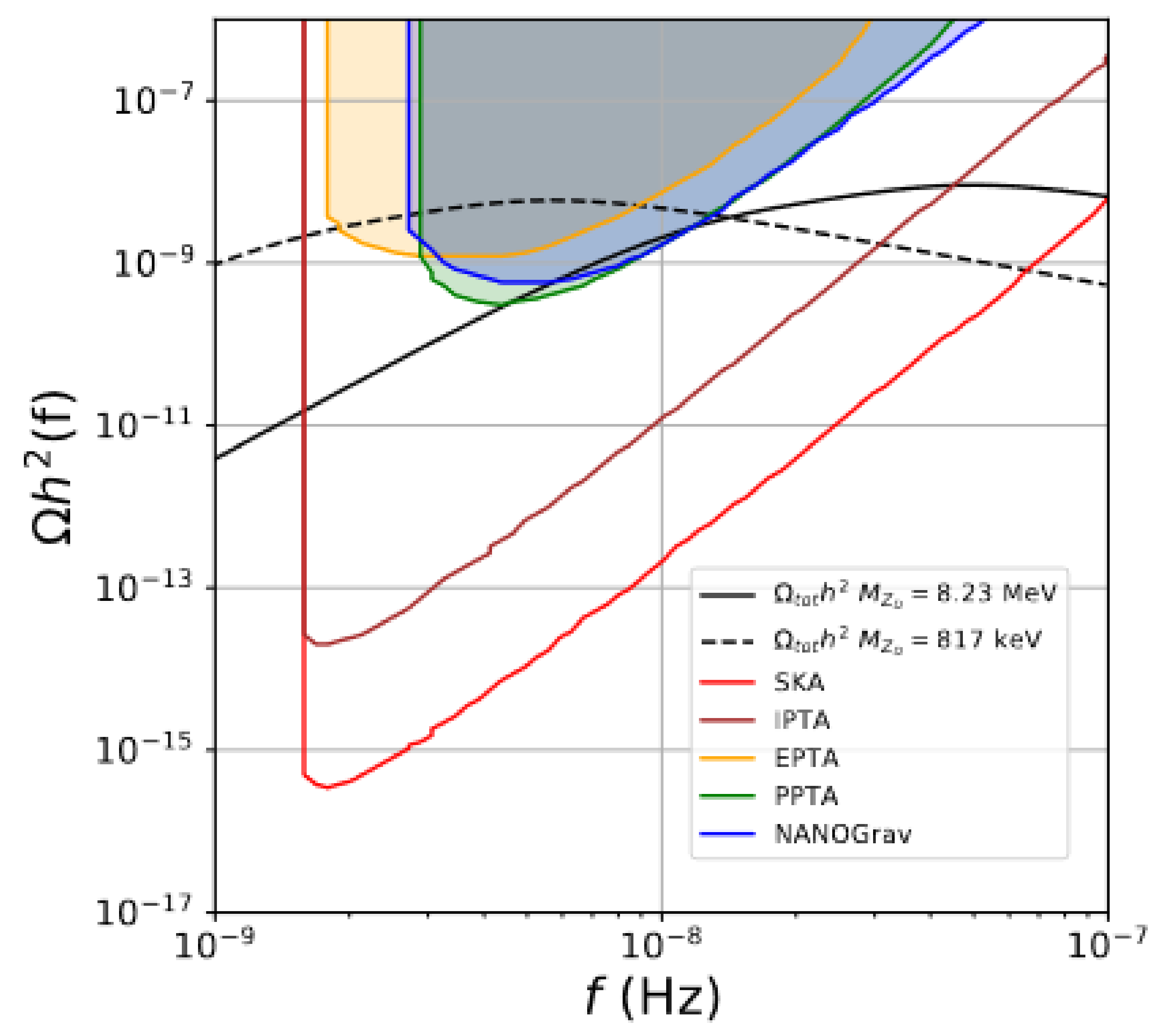
- We also consider a non-Abelian dark gauge symmetry breaking as a source of FOPT in the early universe.
- The massive vector boson, a consequence of the phase transition, can act as a dark matter candidate by itself.

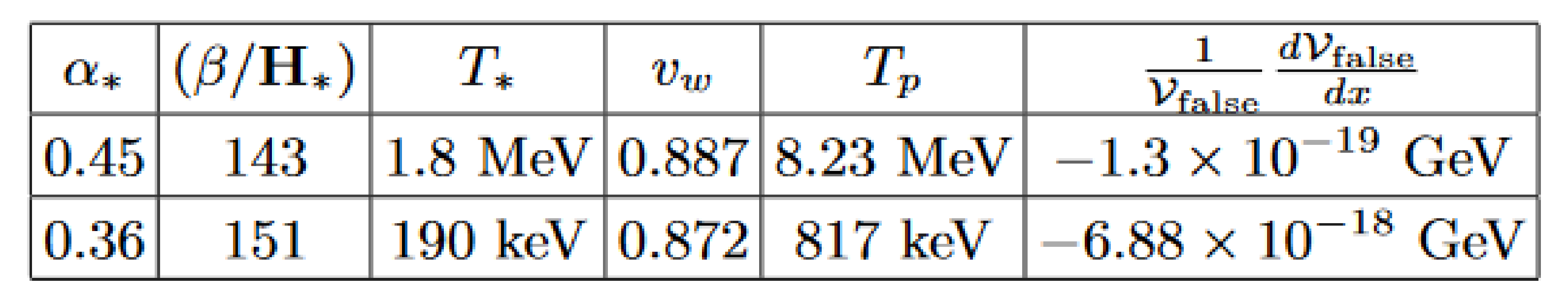
$$V_{\text{tree}} = \lambda_1 (H^\dagger H)^2 + \lambda_2 (\Phi^\dagger \Phi)(H^\dagger H) + \lambda_3 (\Phi^\dagger \Phi)^2$$

$$\mathcal{L}_{\text{kin}} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{1}{4} (F_D)_{\mu\nu} (F_D)^{\mu\nu}$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} G_2 + iG_3 \\ M + \phi + iG_1 \end{pmatrix}$$

- We show that the model can explain NANOGrav data while being within the sensitivities of other experiments.
- Future data should be able to confirm or rule out these possibilities.
- Similar to the earlier work, DM can be generated non-thermally via Higgs portal interactions.





α_*	$(\beta/\mathbf{H}_*)$	T_*	v_w	T_p	$\frac{1}{\mathcal{V}_{\text{false}}}\frac{d\mathcal{V}_{\text{false}}}{dx}$
0.45	143	1.8 MeV	0.887	8.23 MeV	-1.3×10^{-19} GeV
0.36	151	190 keV	0.872	817 keV	-6.88×10^{-18} GeV

DB, A Dasgupta, S K Kang, arXiv:2109.11558

PROBING DM WITH GW FROM COSMIC STRINGS

- We consider a scenario where DM is of WIMP type but has weaker interaction rates with the visible sector than a typical WIMP.
- This can be naturally realized if DM interacts with the SM via a heavy mediator: say a superheavy U(1) vector boson.
- Spontaneous breaking of U(1) can produce cosmic strings (arxiv: 1909.00819) which can emit GW with a characteristic spectrum.
- There have been some recent proposals to probe Superheavy DM which acquire mass from a high scale U(1) symmetry breaking using GW spectrum emitted from cosmic strings (see, for example, arxiv: 2107.13112).
- However, the characteristic GW spectrum from cosmic strings can arise without DM too: need some stronger connection!

- We consider a gauged B-L model with three right handed neutrinos (RHN) required for anomaly cancellation and one Dirac fermion as DM candidate.

$$\mathcal{L}_{\rm DM} = i\overline{\chi}\not{D}(q_\chi)\chi - m_\chi\overline{\chi}\chi.$$

$$\not{D}(q_\chi)\,\chi = \gamma^\mu\left(\partial_\mu + i g_{BL}\, q_\chi\, Z_{BL_\mu}\right)\chi$$

- For superheavy B-L gauge boson, DM can not annihilate much via B-L mediated processes and hence gets overproduced. One of the RHN can release entropy via late decay into leptons, bringing the DM abundance within observed limit (Scherrer & Turner 1985).

- Such late entropy release can cause distortions in GW spectral shapes generated by cosmic strings.

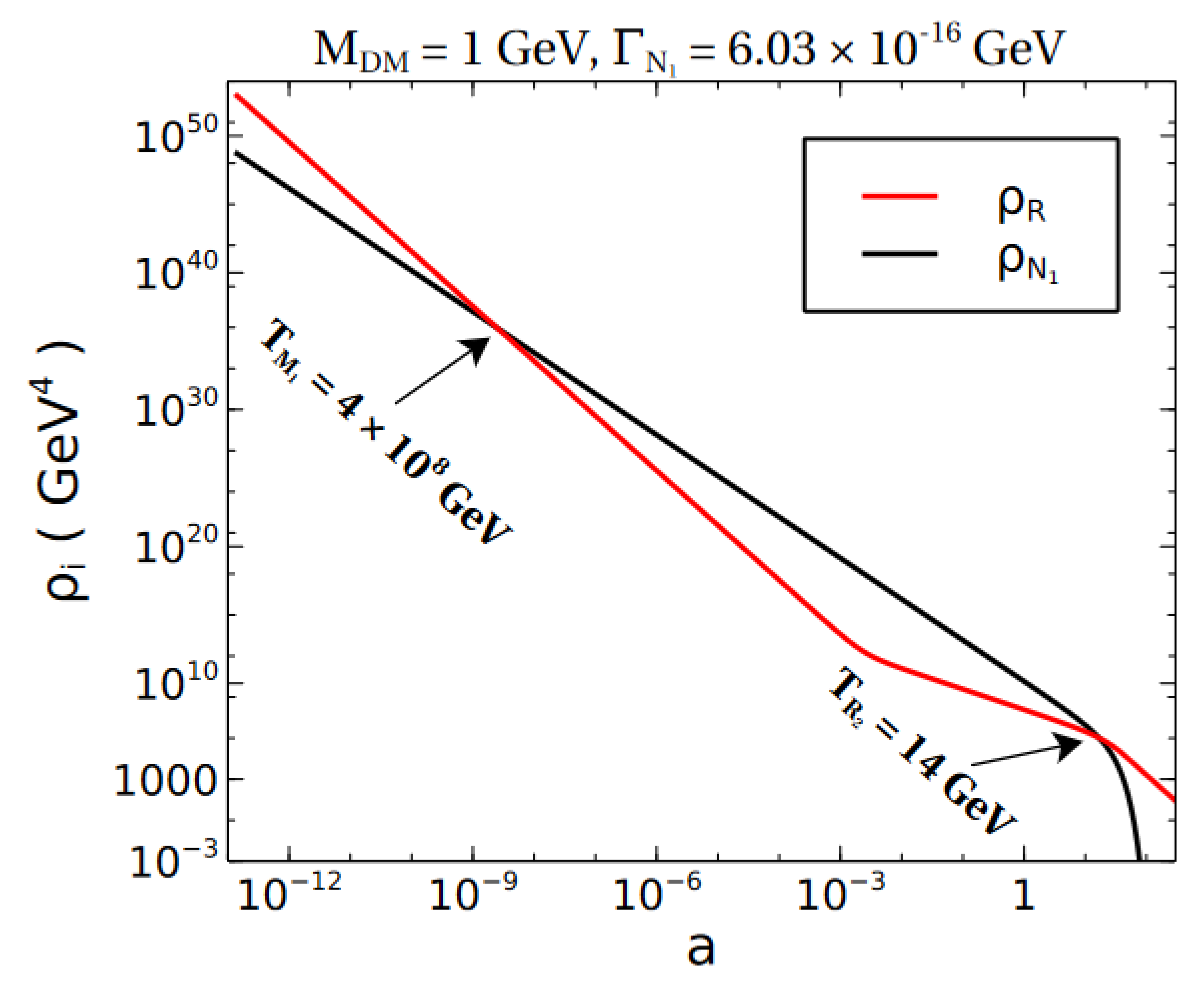
- Decay of heavier RHN can generate baryon asymmetry via leptogenesis and also non-zero neutrino masses.

- Need to solve coupled Boltzmann equations for DM relic:

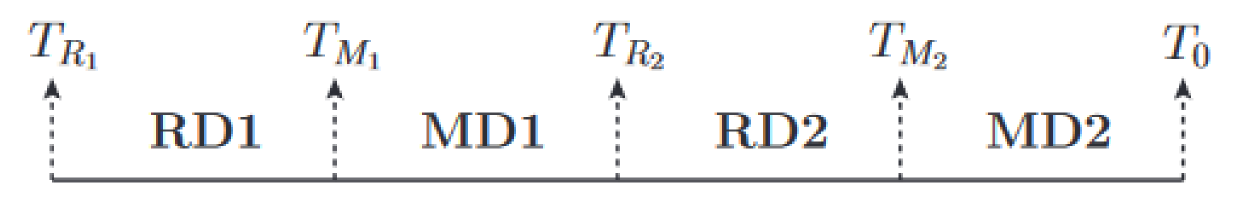
$$\frac{dE_\chi}{da} = \frac{\langle\sigma v\rangle_\chi}{Ha^4}\left((E_\chi^{\rm eq})^2 - E_\chi^2\right) ,$$

$$\frac{dE_{N_1}}{da} = \frac{\langle\sigma v\rangle_{N_1}}{Ha^4}\left((E_{N_1}^{\rm eq})^2 - E_{N_1}^2\right) - \frac{\Gamma_{N_1}}{Ha}E_{N_1} ,$$

$$\frac{dT}{da} = \left(1+\frac{T}{3g_{*s}}\frac{dg_{*s}}{dT}\right)^{-1}\left[-\frac{T}{a}+\frac{\Gamma_{N_1}M_{N_1}}{3H\ s\ a^4}E_{N_1}\right]$$

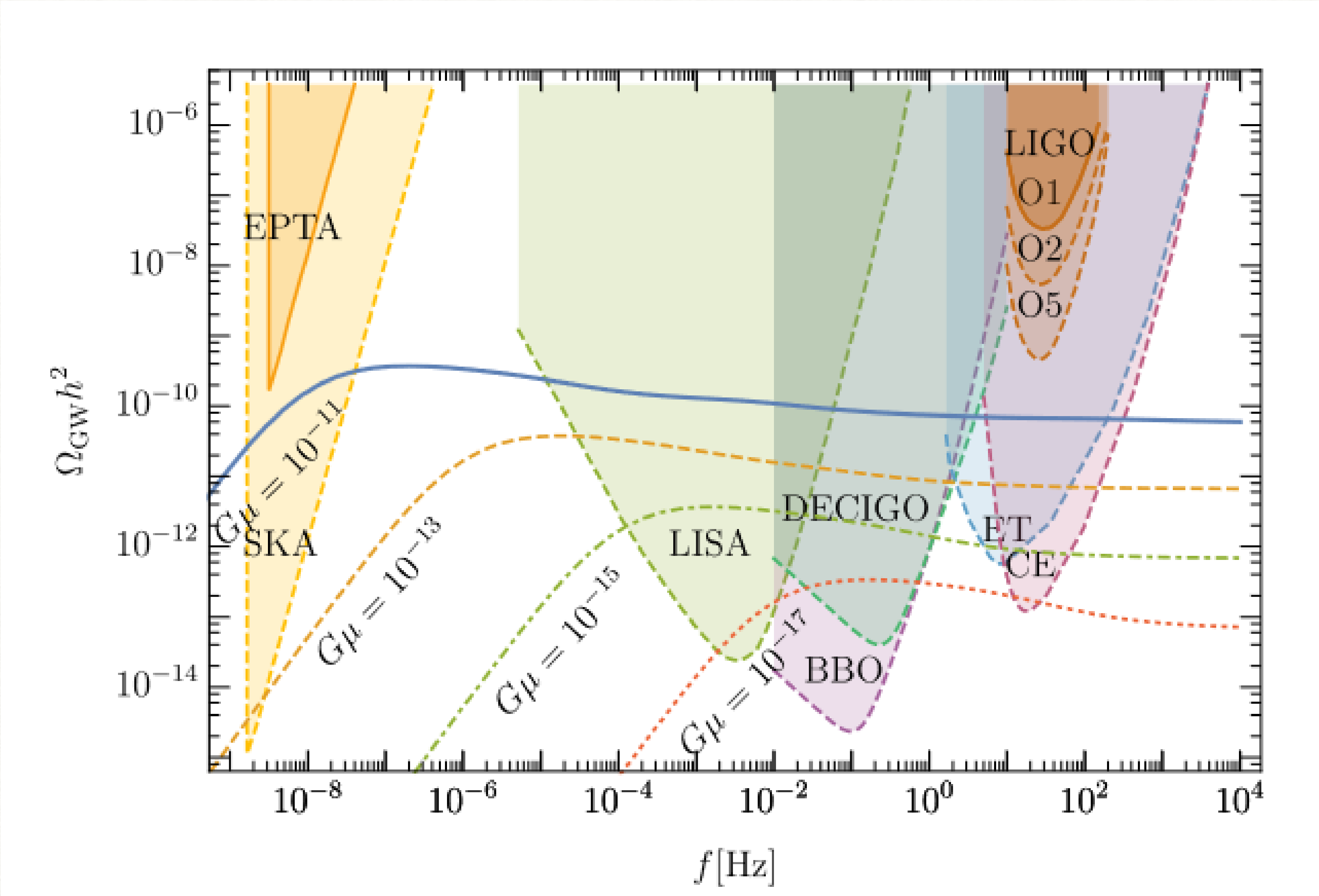


- Naturally leads to non-standard cosmological history with early matter domination due to long-lived diluter.



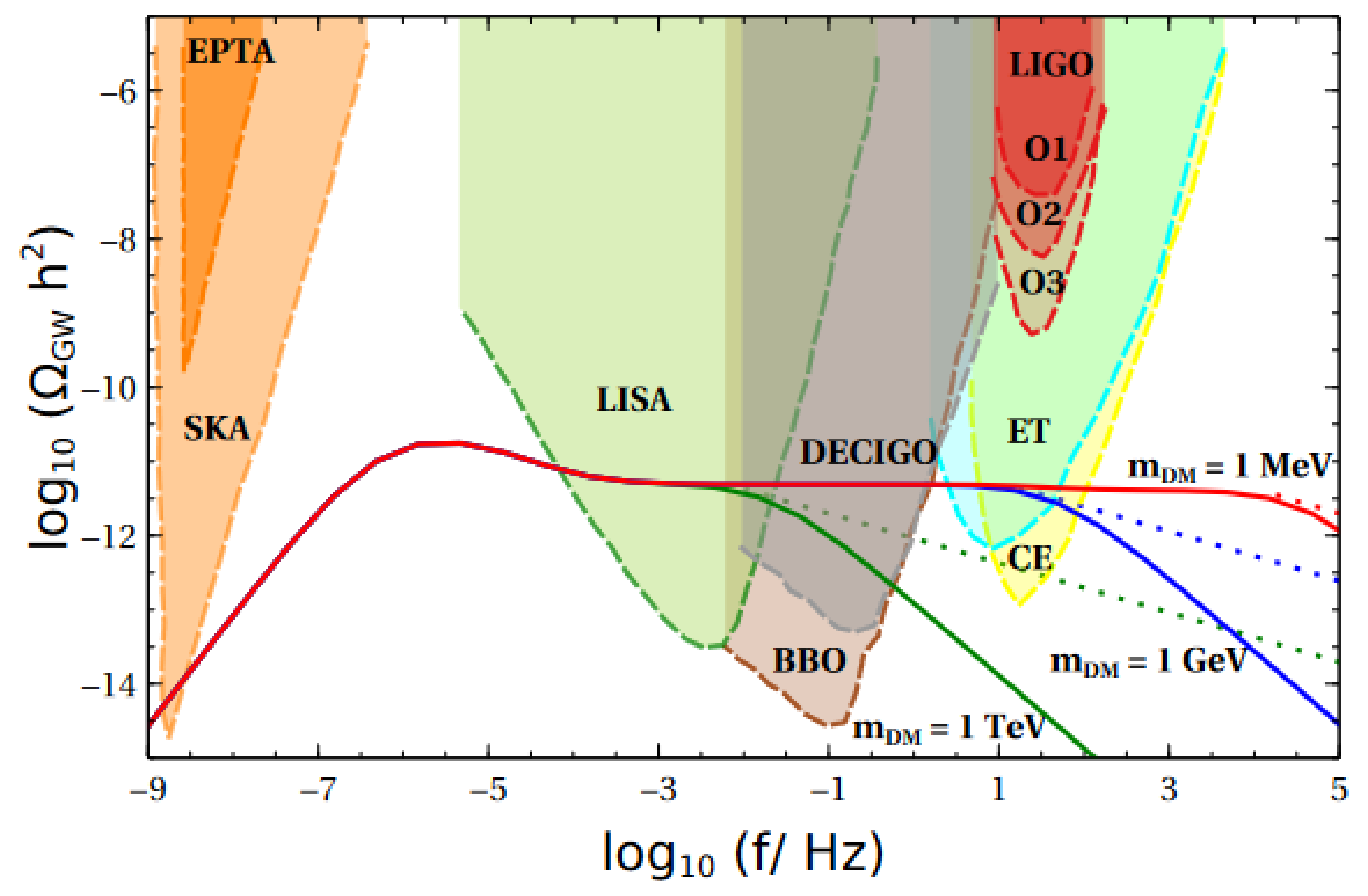
CHARACTERISTIC GW SPECTRUM

$$\Omega_{GW}^{(k=1)}(f) = \frac{128\pi G\mu}{9\zeta(\delta)} \frac{A_r}{\epsilon_r} \Omega_r \left[(1+\epsilon_r)^{3/2} - 1\right]$$



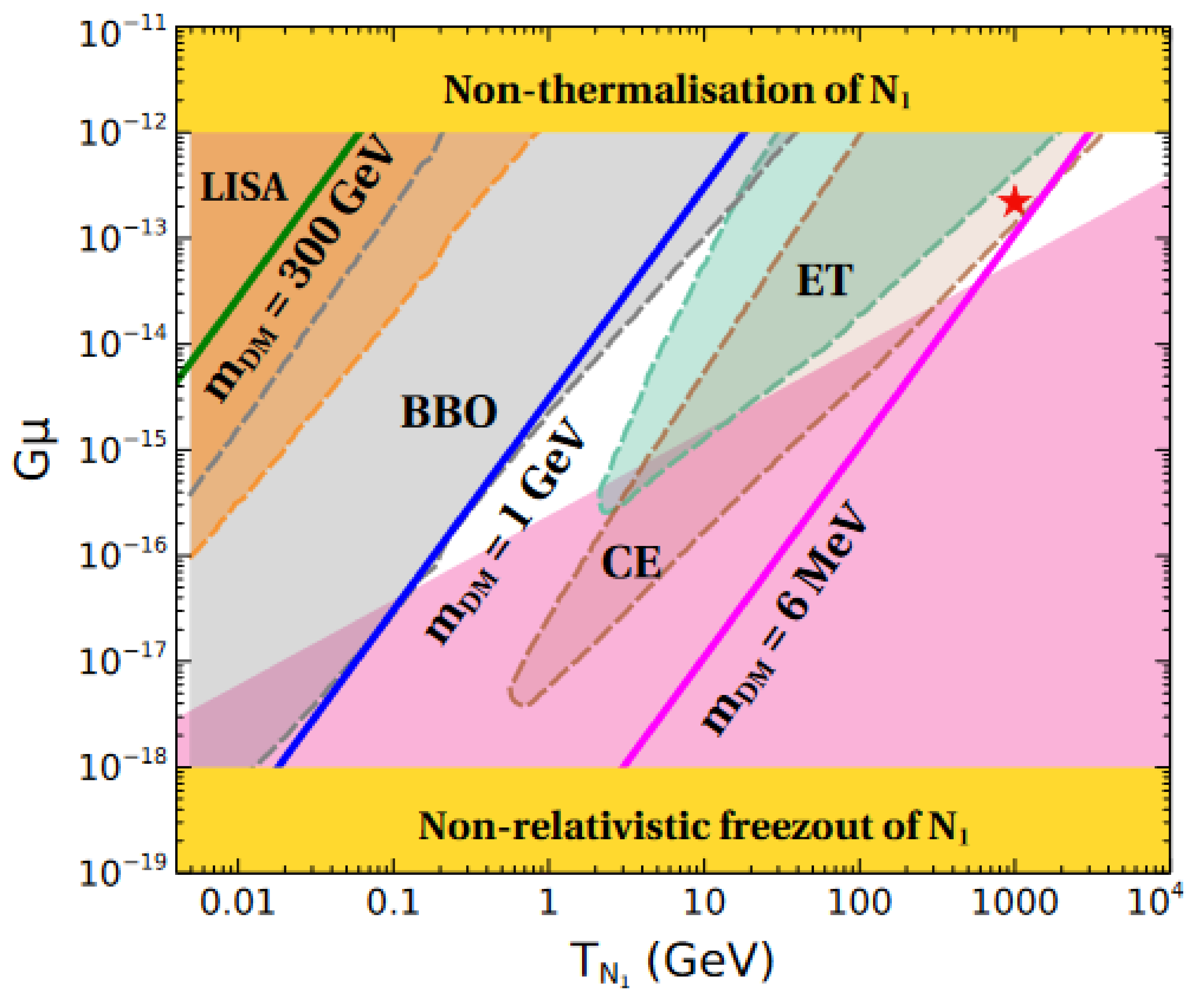
Arxiv: 1808.08968

GW SPECTRUM WITH DM



$$f_\Delta = \sqrt{\frac{8}{\alpha\Gamma G\mu}}t_\Delta^{-1/2}t_0^{-2/3}t_{\rm eq}^{1/6}$$

Arxiv: 2202.xxxxx



Arxiv: 2202.xxxxx

SUMMARY

- Dark Matter scenarios beyond the thermal WIMP paradigm have limited detection aspects at direct search experiments: GW can offer complementary probes.
- Light DM in low scale dark sector models can be responsible for sub-EW scale first order phase transition. GW produced from such phase transition can be probed at PTA based experiments like NANOGrav, PPTA etc.
- DM of a wide mass range having interaction rate below typical WIMPs can also be probed via GW spectral shapes if DM interacts with SM via superheavy U(1) gauge bosons.
- Many more exciting possibilities to be explored in this direction!

Thank you