Hearing the Universe Hum with Gravitational Waves at Pulsar Timing Array:

astrophysical, cosmological and particle physics interpretations

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IMSc.-Chennai

Outline of the talk:

- Sources of Primordial Gravitational Waves
- Measurement of Stochastic GW background at Pulsar Timing Array
- Astrophysical Interpretation: supermassive black holes
- Cosmological Interpretation: strong first-order phase transition
- Primordial Blackholes from strong first order phase transition.
- Particle Physics interpretation: Axion-like particle model where PQ phase transition, three-pronged complementarity between PBH, GW and laboratory searches.

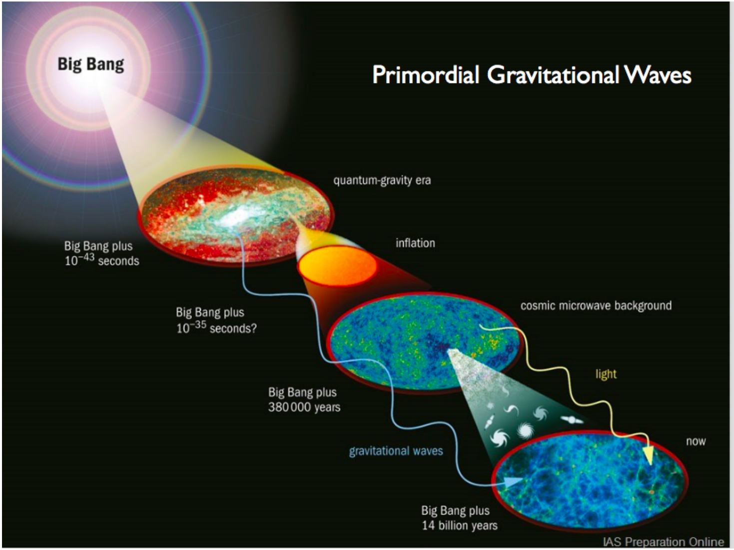
History of the Universe

Pulsar Timimg Array Collaboration

NANOGrav
Physics Frontiers Center

Disclaimer: separate analysis.

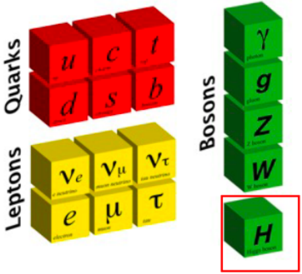
History of the Universe



History of the Universe

History of the Universe

The Standard Model.



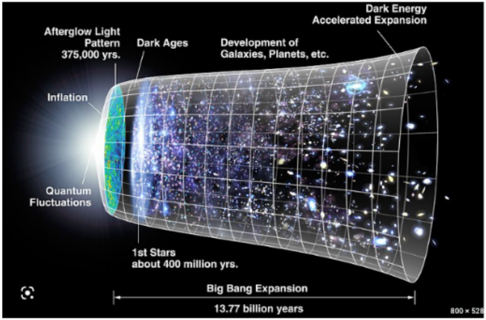
1961–1968

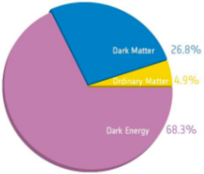
The Standard Model is very successful.

Many experimental tests. No cracks yet.

History of the Universe

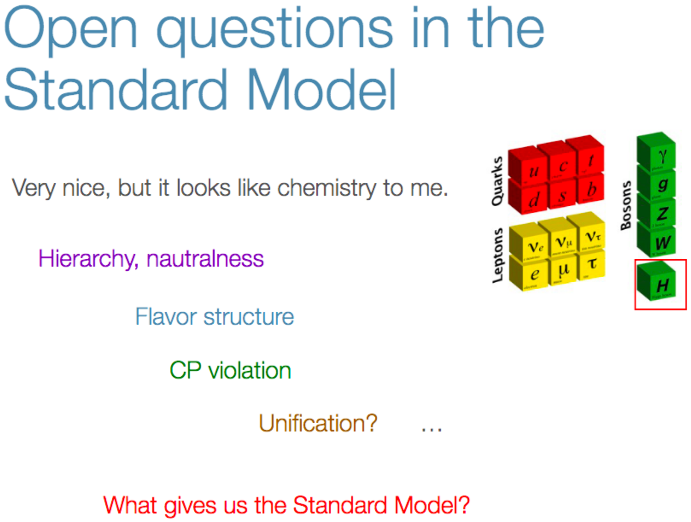
Cosmos





A standard model of cosmology.

History of the Universe



Open questions in the Standard Model

Very nice, but it looks like chemistry to me.

Hierarchy, nautralness

Flavor structure

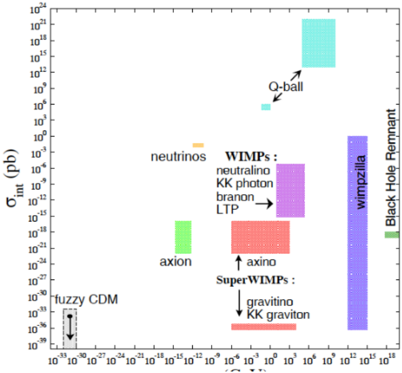
CP violation

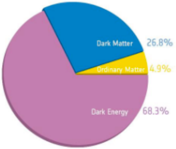
Unification? …

What gives us the Standard Model?

History of the Universe

Dark world



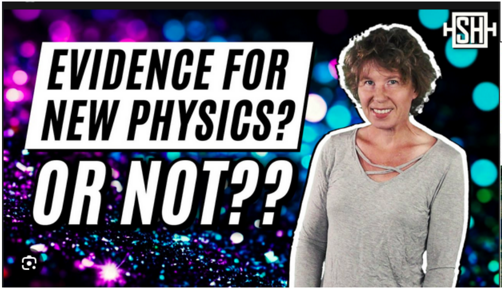


Vast gaps!

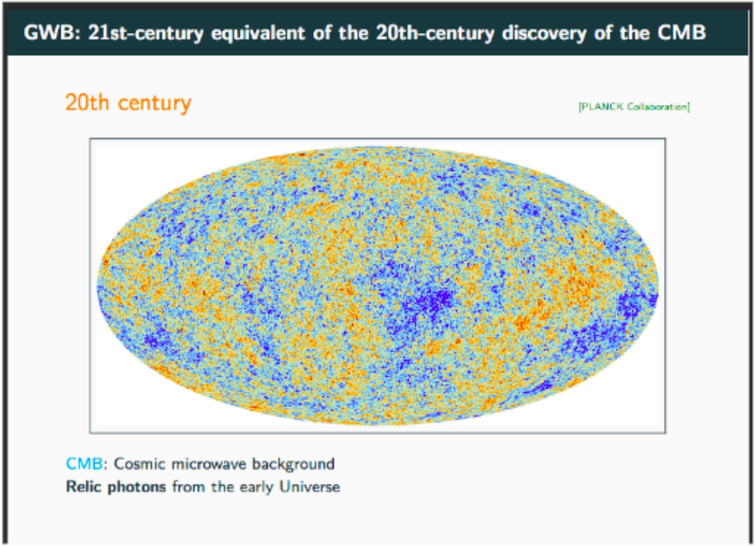
Need more lampposts!

History of the Universe

Particle physics facing critiques



History of the Universe



GWB: 21st-century equivalent of the 20th-century discovery of the CMB

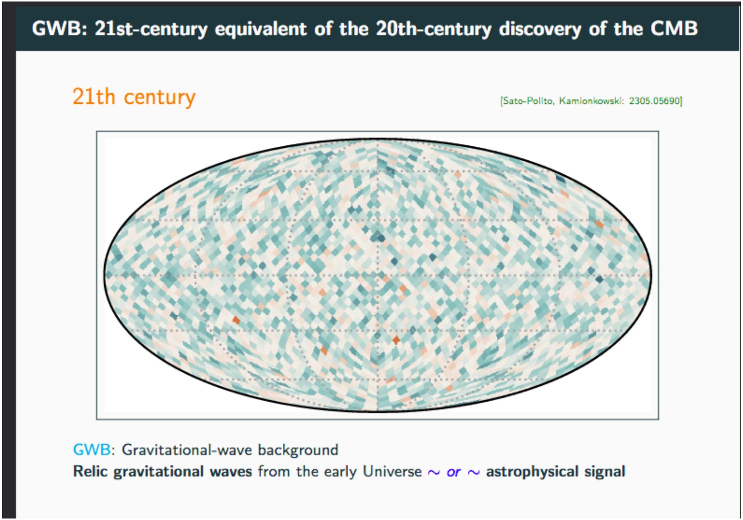
20th century

[PLANCK Collaboration]

CMB: Cosmic microwave background

Relic photons from the early Universe

History of the Universe



GWB: 21st-century equivalent of the 20th-century discovery of the CMB

21th century

[Sato-Polito, Kamionkowski: 2305.05690]

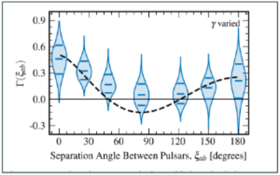
GWB: Gravitational-wave background

Relic gravitational waves from the early Universe ∼ *or* ∼ **astrophysical signal**

History of the Universe

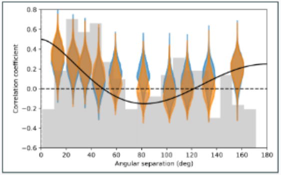
LIGO observed GW of astrohysical origin, we in PTA see stochastic GW background.

2306.16213: NANOGrav



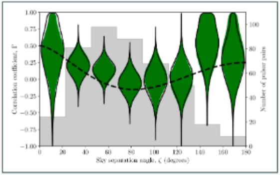
68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

2306.16214: EPTA+InPTA



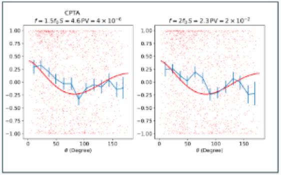
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



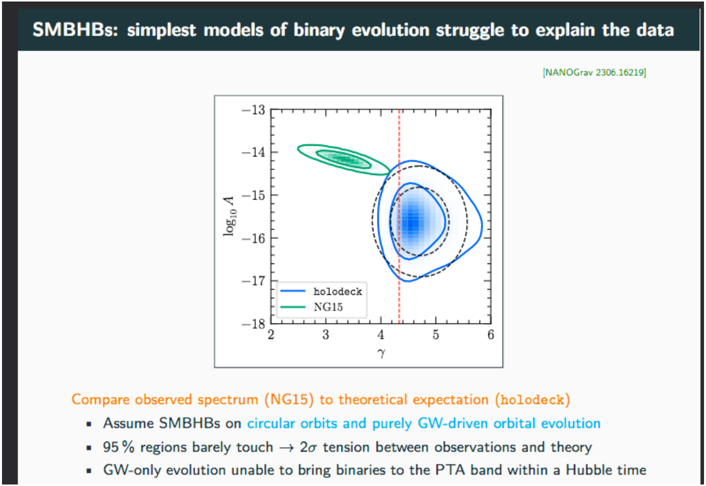
32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

2306.16216: CPTA



57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

History of the Universe



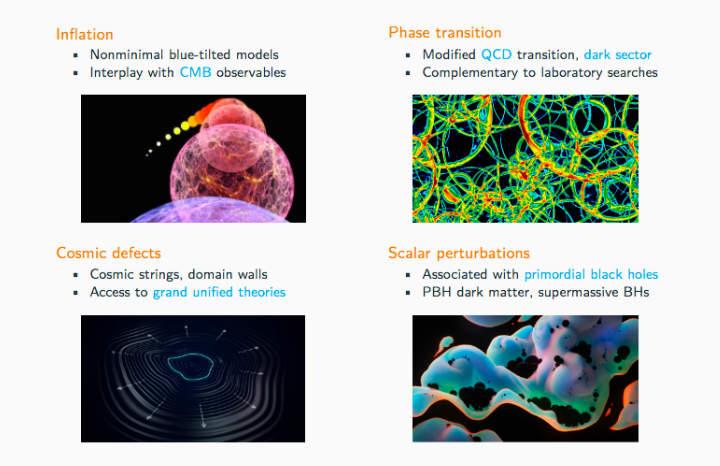
SMBHBs: simplest models of binary evolution struggle to explain the data

[NANOGrav 2306.16219]

Compare observed spectrum (NG15) to theoretical expectation (`holodeck`)

- Assume SMBHBs on circular orbits and purely GW-driven orbital evolution
- 95 % regions barely touch → 2σ tension between observations and theory
- GW-only evolution unable to bring binaries to the PTA band within a Hubble time

History of the Universe



Inflation

- Nonminimal blue-tilted models
- Interplay with CMB observables

Phase transition

- Modified QCD transition, dark sector
- Complementary to laboratory searches

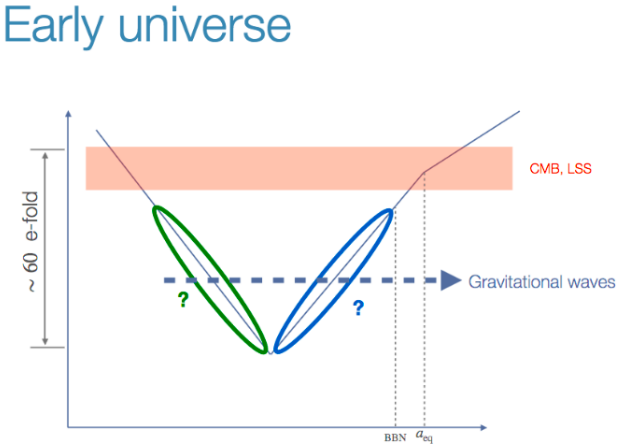
Cosmic defects

- Cosmic strings, domain walls
- Access to grand unified theories

Scalar perturbations

- Associated with primordial black holes
- PBH dark matter, supermassive BHs

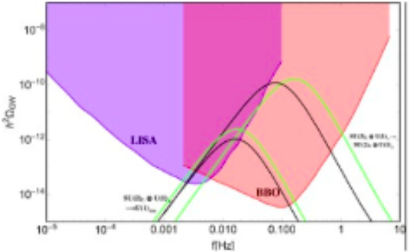
History of the Universe



Early universe

History of the Universe

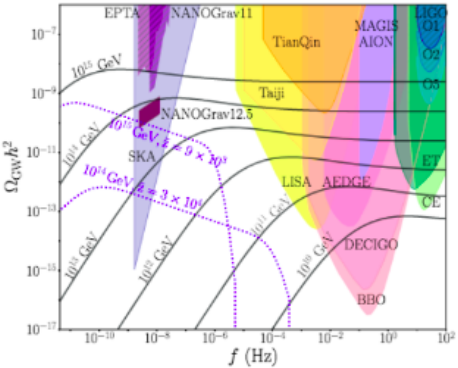
Typical GW spectrum from thermal first-order phase transition:



Huang (2018)

History of the Universe

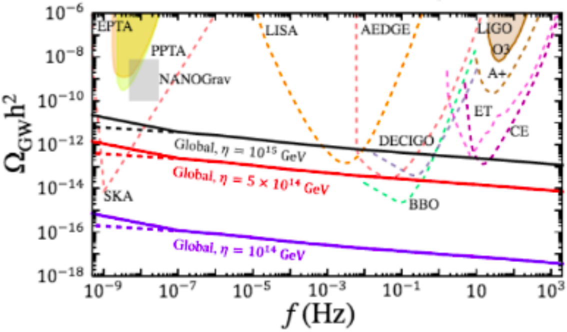
Topological defects like cosmic strings can be formed in early universe when some gauge $U(1)_X$ symmetry is broken in early universe. It give rise to scale invariant GW spectrum. Detection prospects lies on the symmetry breaking scale vev.



King (2020)

History of the Universe

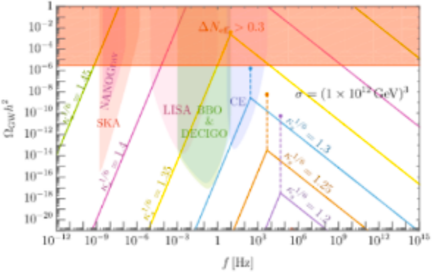
Topological defects like cosmic strings can be formed in early universe when some global $U(1)_X$ symmetry is broken in early universe. Detection prospects lies on the symmetry breaking scale vev which needs to be very high.



Cui (2021)

History of the Universe

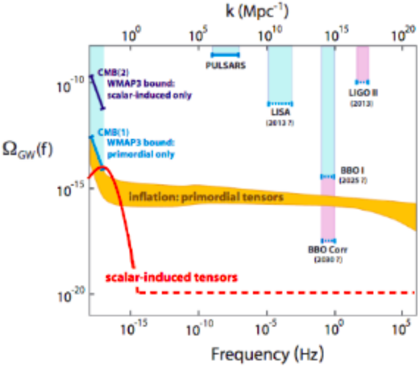
Topological defects like Domain Walls are formed when a discrete symmetry is broken and give rise to GW spectrum may look something like this (still under active research topic). Detection prospects lies of symmetry breaking scale as well as the asymmetry term in the potential, like cubic term.



Dunsky at. al. (2021)

History of the Universe

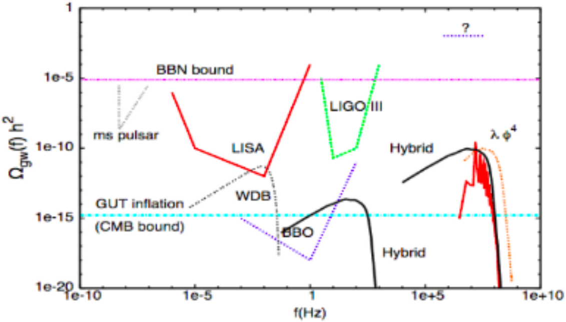
Primary Tensor Perturbations and Secondary Tensor Spectrum induced by first-order scalar perturbation via mixing. Can be tuned to generate high amplitude in high frequency regions. Acts as natural probes of particle models like Higgs inflation, axion inflation, MSSM inflation, etc.



Baumann (2007)

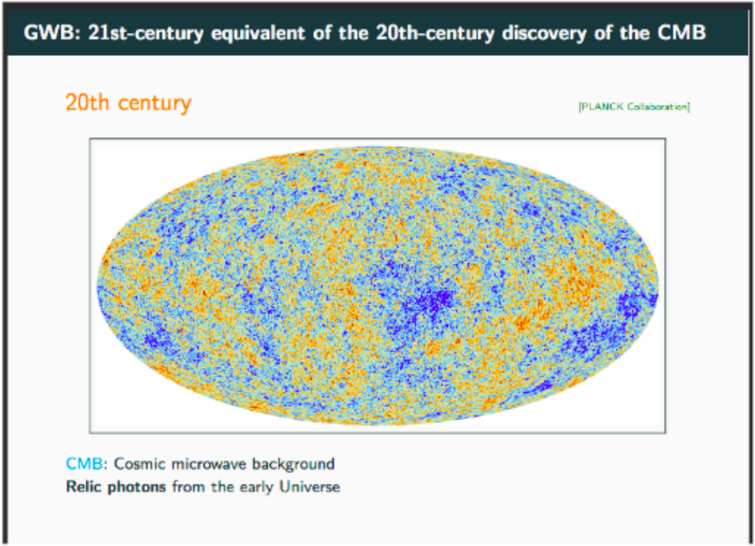
History of the Universe

Excitation of tensor perturbations during inflaton oscillating in FRW background. Back-reaction and effects of metric fluctuations. Enhancement mechanism: Bose-resonance, tachyonic growth, parametric resonance.



Figuera (2007)

History of the Universe



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[PLANCK Collaboration]

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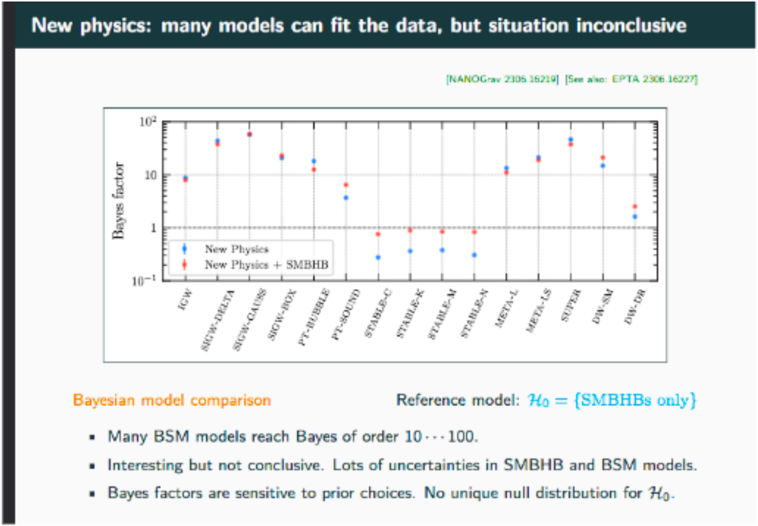
History of the Universe



New physics: many models can fit the data, but situation inconclusive

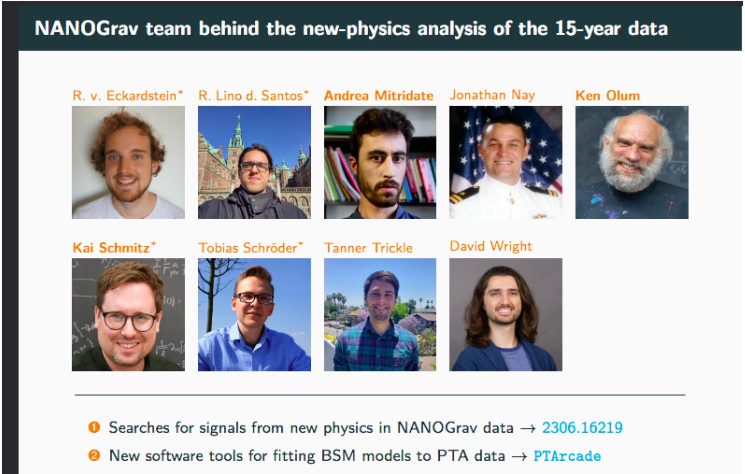
[NANOGrav 2306.16219] [See also: EPTA 2306.16227]

Bayesian model comparison

Reference model: $\mathcal{H}_0 = \{\text{SMBHBs only}\}$

- Many BSM models reach Bayes of order $10 \cdots 100$.
- Interesting but not conclusive. Lots of uncertainties in SMBHB and BSM models.
- Bayes factors are sensitive to prior choices. No unique null distribution for $\mathcal{H}_0$.

History of the Universe



NANOGrav team behind the new-physics analysis of the 15-year data

R. v. Eckardstein* · R. Lino d. Santos* · **Andrea Mitridate** · Jonathan Nay · **Ken Olum**

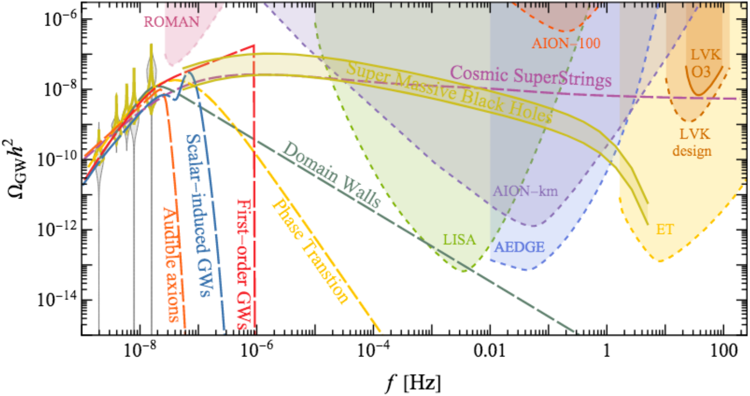
Kai Schmitz* · Tobias Schröder* · Tanner Trickle · David Wright

❶ Searches for signals from new physics in NANOGrav data → 2306.16219

❷ New software tools for fitting BSM models to PTA data → `PTArcade`

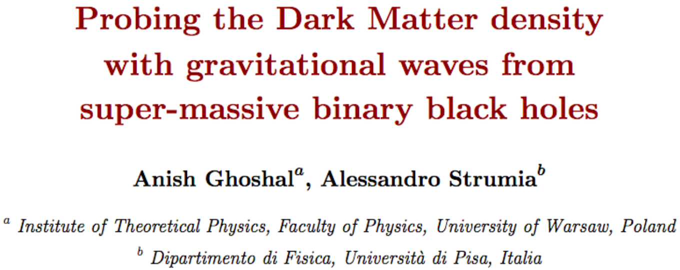
History of the Universe

Several sources of SGWB of cosmic origin:



Ellis (2023)

History of the Universe



Probing the Dark Matter density with gravitational waves from super-massive binary black holes

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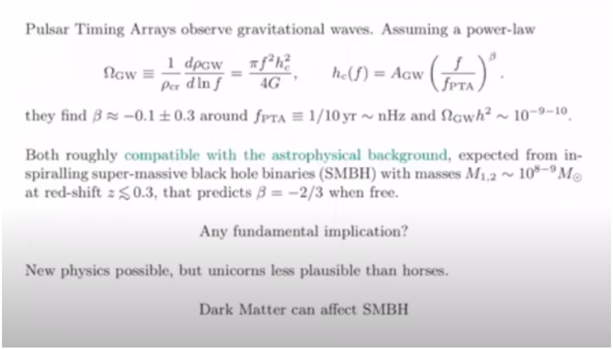
[a] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Poland*
[b] *Dipartimento di Fisica, Università di Pisa, Italia*

History of the Universe



Pulsar Timing Arrays observe gravitational waves. Assuming a power-law

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_{\rm cr}} \frac{d\rho_{\rm GW}}{d\ln f} = \frac{\pi f^2 h_c^2}{4G}, \qquad h_c(f) = A_{\rm GW} \left(\frac{f}{f_{\rm PTA}}\right)^{\beta}.$$

they find $\beta \approx -0.1 \pm 0.3$ around $f_{\rm PTA} \equiv 1/10\,{\rm yr} \sim {\rm nHz}$ and $\Omega_{\rm GW} h^2 \sim 10^{-9-10}$.

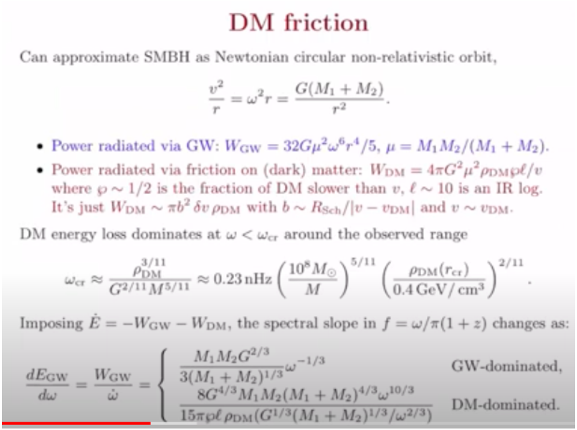
Both roughly compatible with the astrophysical background, expected from in-spiralling super-massive black hole binaries (SMBH) with masses $M_{1,2} \sim 10^{8-9} M_\odot$ at red-shift $z \lesssim 0.3$, that predicts $\beta = -2/3$ when free.

Any fundamental implication?

New physics possible, but unicorns less plausible than horses.

Dark Matter can affect SMBH

History of the Universe



DM friction

Can approximate SMBH as Newtonian circular non-relativistic orbit,

$$\frac{v^2}{r} = \omega^2 r = \frac{G(M_1+M_2)}{r^2}.$$

- Power radiated via GW: $W_{\rm GW} = 32G\mu^2\omega^6 r^4/5$, $\mu = M_1 M_2/(M_1+M_2)$.
- Power radiated via friction on (dark) matter: $W_{\rm DM} = 4\pi G^2\mu^2\rho_{\rm DM}\wp\ell/v$ where $\wp \sim 1/2$ is the fraction of DM slower than v, $\ell \sim 10$ is an IR log. It's just $W_{\rm DM} \sim \pi b^2\,\delta v\,\rho_{\rm DM}$ with $b \sim R_{\rm Sch}/|v - v_{\rm DM}|$ and $v \sim v_{\rm DM}$.

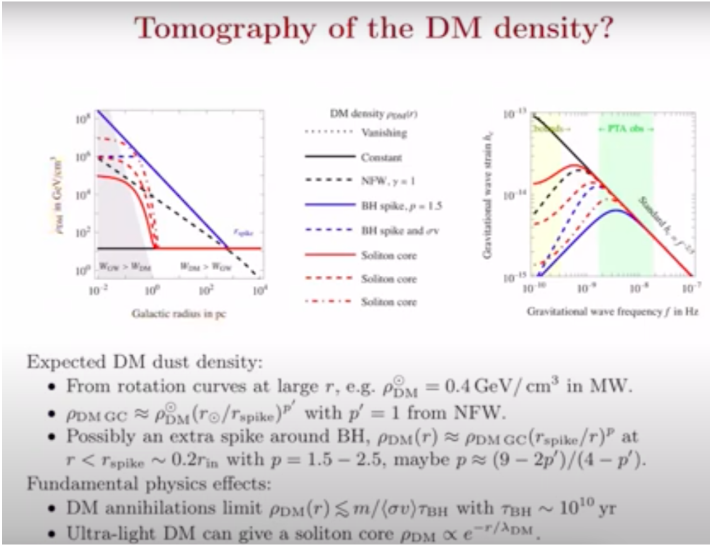
DM energy loss dominates at $\omega < \omega_{\rm cr}$ around the observed range

$$\omega_{\rm cr} \approx \frac{\rho_{\rm DM}^{3/11}}{G^{2/11}M^{5/11}} \approx 0.23\,{\rm nHz}\left(\frac{10^8 M_\odot}{M}\right)^{5/11}\left(\frac{\rho_{\rm DM}(r_{\rm cr})}{0.4\,{\rm GeV/\,cm^3}}\right)^{2/11}.$$

Imposing $\dot E = -W_{\rm GW} - W_{\rm DM}$, the spectral slope in $f = \omega/\pi(1+z)$ changes as:

$$\frac{dE_{\rm GW}}{d\omega} = \frac{W_{\rm GW}}{\dot\omega} = \begin{cases} \dfrac{M_1 M_2 G^{2/3}}{3(M_1+M_2)^{1/3}}\omega^{-1/3} & \text{GW-dominated,} \\ \dfrac{8G^{4/3}M_1M_2(M_1+M_2)^{4/3}\omega^{10/3}}{15\pi\wp\ell\,\rho_{\rm DM}(G^{1/3}(M_1+M_2)^{1/3}/\omega^{2/3})} & \text{DM-dominated.} \end{cases}$$

History of the Universe



Tomography of the DM density?

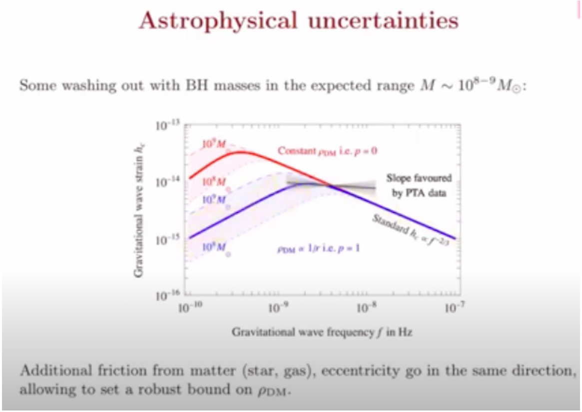
Expected DM dust density:

- From rotation curves at large r, e.g. $\rho_{\rm DM}^{\odot} = 0.4\,{\rm GeV/cm^3}$ in MW.
- $\rho_{\rm DM\,GC} \approx \rho_{\rm DM}^{\odot}(r_{\odot}/r_{\rm spike})^{p'}$ with $p' = 1$ from NFW.
- Possibly an extra spike around BH, $\rho_{\rm DM}(r) \approx \rho_{\rm DM\,GC}(r_{\rm spike}/r)^{p}$ at $r < r_{\rm spike} \sim 0.2 r_{\rm in}$ with $p = 1.5 - 2.5$, maybe $p \approx (9 - 2p')/(4 - p')$.

Fundamental physics effects:

- DM annihilations limit $\rho_{\rm DM}(r) \lesssim m/\langle\sigma v\rangle\tau_{\rm BH}$ with $\tau_{\rm BH} \sim 10^{10}\,{\rm yr}$
- Ultra-light DM can give a soliton core $\rho_{\rm DM} \propto e^{-r/\lambda_{\rm DM}}$.

History of the Universe

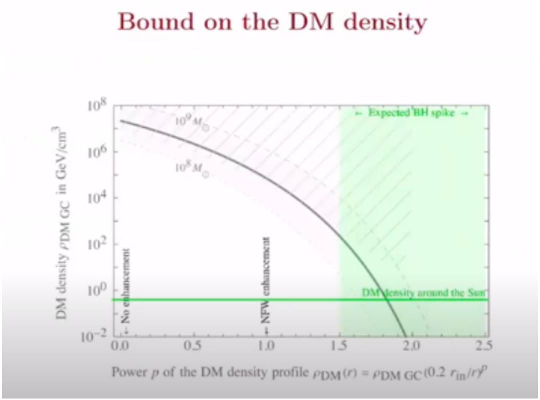


Astrophysical uncertainties

Some washing out with BH masses in the expected range $M \sim 10^{8-9} M_\odot$:

Additional friction from matter (star, gas), eccentricity go in the same direction, allowing to set a robust bound on ρ_{DM}.

History of the Universe



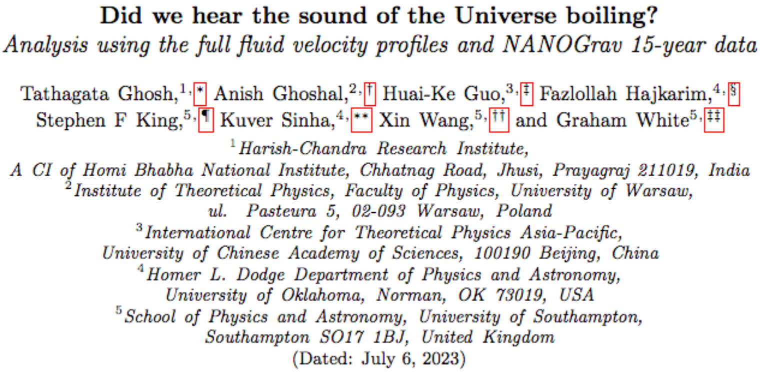
Bound on the DM density

DM density could be probes via measurements in pulsar timing arrays.

History of the Universe

NOW LET US HEAR THE SOUND OF THE UNIVERSE !

History of the Universe



Did we hear the sound of the Universe boiling?

Analysis using the full fluid velocity profiles and NANOGrav 15-year data

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Stephen F King,[5,¶] Kuver Sinha,[4,**] Xin Wang,[5,††] and Graham White[5,‡‡]
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[2] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw,*
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University of Chinese Academy of Sciences, 100190 Beijing, China
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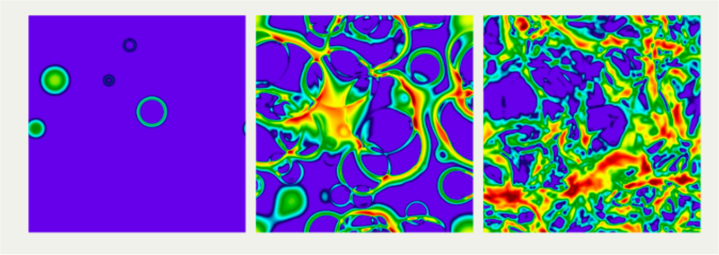
University of Oklahoma, Norman, OK 73019, USA
[5] *School of Physics and Astronomy, University of Southampton,*
Southampton SO17 1BJ, United Kingdom

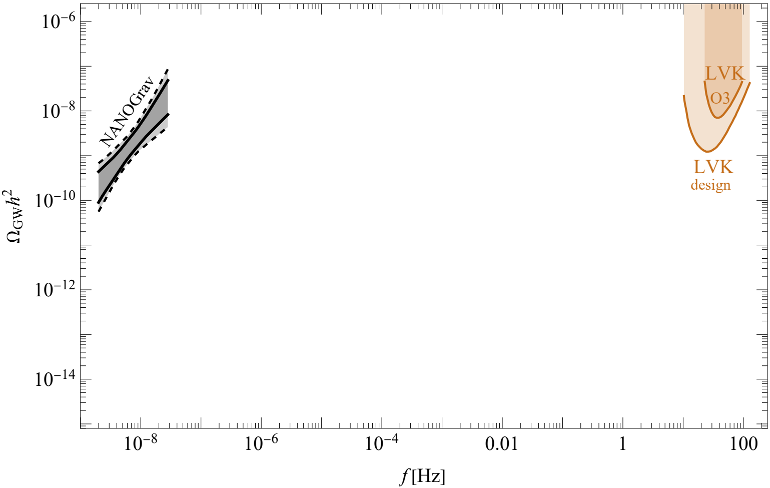
(Dated: July 6, 2023)

History of the Universe

Phase Transitions:

- Bubbles nucleate and grow.
- Expand in plasma.
- Bubbles and fronts collide - - violent process.
- Sound Waves left behind in thermal plasma.
- Turbulence, damping.




10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
$\Omega_{\rm GW}h^2$
NANOGrav
LVK
O3
LVK
design
10^{-8}
10^{-6}
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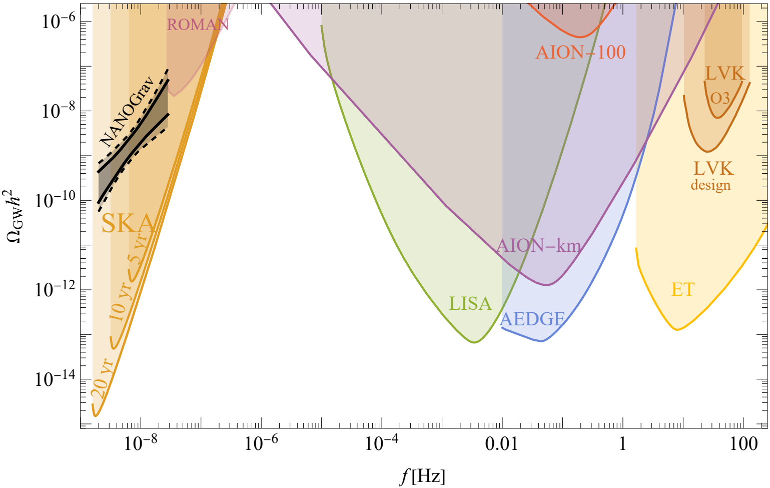
0.01
1
100
$f\,$[Hz]


ROMAN
NANOGrav
SKA
5 yr
10 yr
20 yr
AION−100
LVK
O3
LVK
design
AION−km
LISA
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ET
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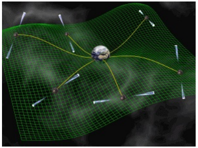
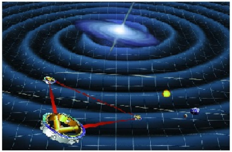
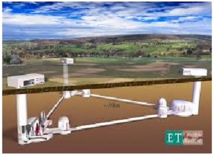
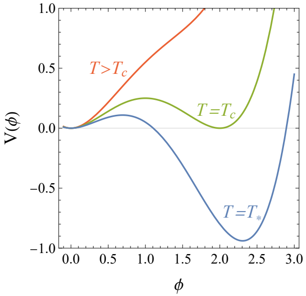
$f\,$[Hz]






ET

First Order Phase Transition: bubble nucleation



- Temperature corrections to the potential

$$V(\phi, T) = \frac{g_{m^2}}{24}\left(T^2 - T_0^2\right)\phi^2 - \frac{g_m}{12\pi} T\phi^3 + \lambda\phi^4$$

- EOM → bubble profile

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} - \frac{\partial V(\phi, T)}{\partial\phi} = 0,$$

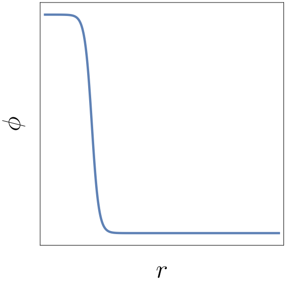
$$\phi(r \to \infty) = 0 \quad \text{and} \quad \dot{\phi}(r = 0) = 0.$$

- $\mathcal{O}(3)$ symmetric action

$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi, T)\right].$$

- nucleation temperature

$$\frac{\Gamma}{H^4} \approx \left(\frac{T}{H}\right)^4 \exp\left(-\frac{S_3(T)}{T}\right) \approx 1$$



Linde ’81 ’83

How do they form ?

Friedmann's equation :

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

How do they form ?

Friedmann's equation :

$$H^{-3} \times H^2 = \frac{8\pi G}{3}\rho \times H^{-3}$$

How do they form ?

Friedmann's equation :

$$H^{-1} = 2G \times \frac{4\pi H^{-3}}{3}\rho$$

How do they form ?

Friedmann's equation :

$$\underbrace{H^{-1}}_{\equiv R_{\mathrm{H}}} = 2G \times \underbrace{\frac{4\pi H^{-3}}{3}\rho}_{\equiv M_{\mathrm{H}}}$$

How do they form ?

Friedmann's equation :

$$R_{\mathrm{H}} = 2GM_{\mathrm{H}}$$

How do they form ?

Friedmann’s equation :

$$R_{\mathrm{H}} = 2GM_{\mathrm{H}}$$

⇕

Schwarschild’s equation

How do they form ?

Friedmann’s equation :

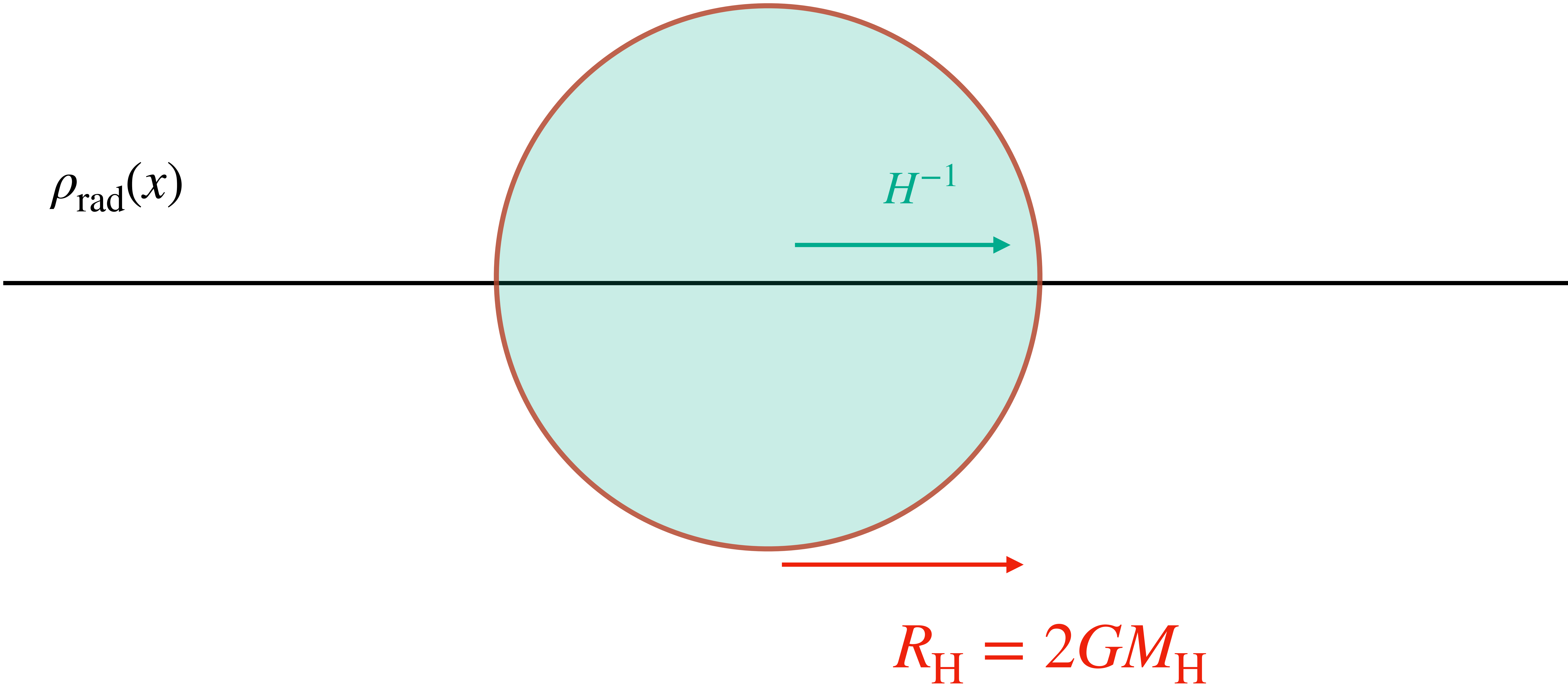
$$R_{\mathrm{H}} = 2GM_{\mathrm{H}}$$

⇕

Schwarschild’s equation

⟶ **Hubble patches are on the edge to collapse into black holes**

What is Primordial Black Holes ?

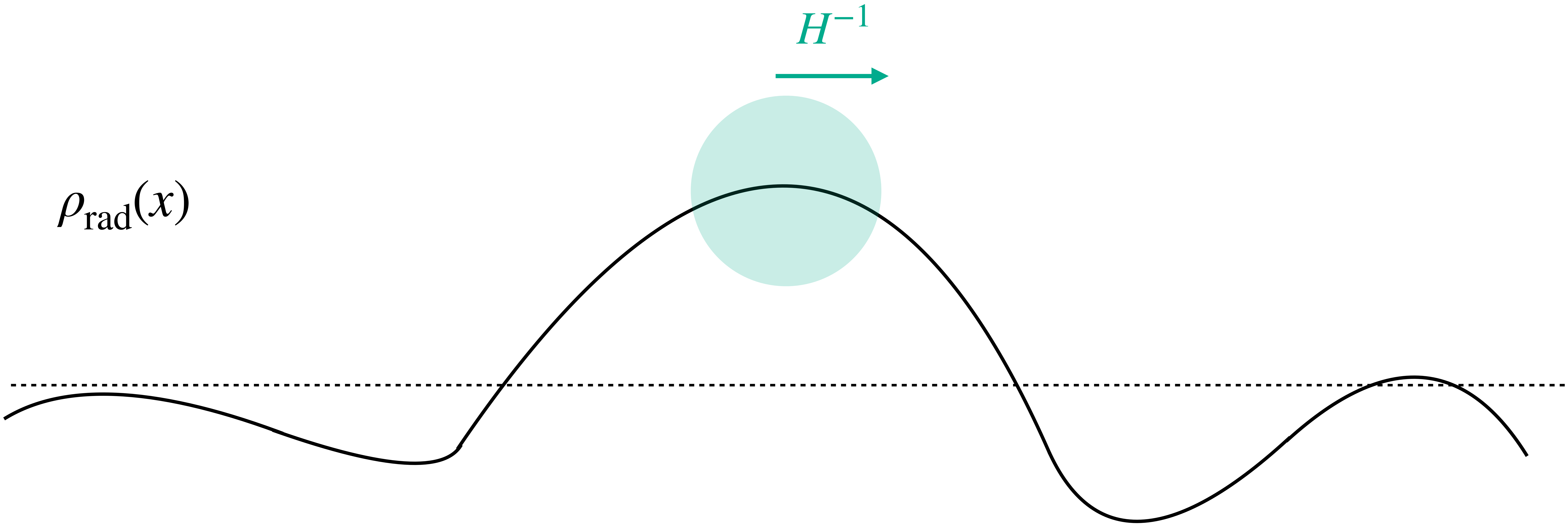


$\rho_{\mathrm{rad}}(x)$

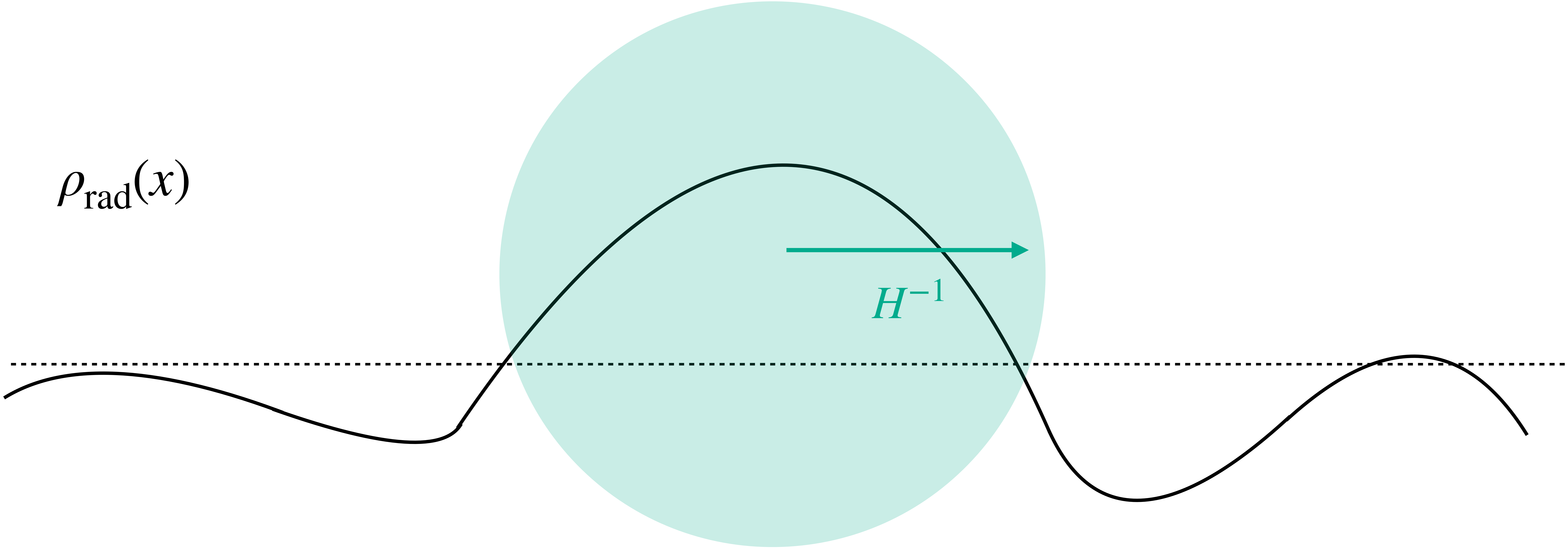
H^{-1}

$R_{\mathrm{H}} = 2GM_{\mathrm{H}}$

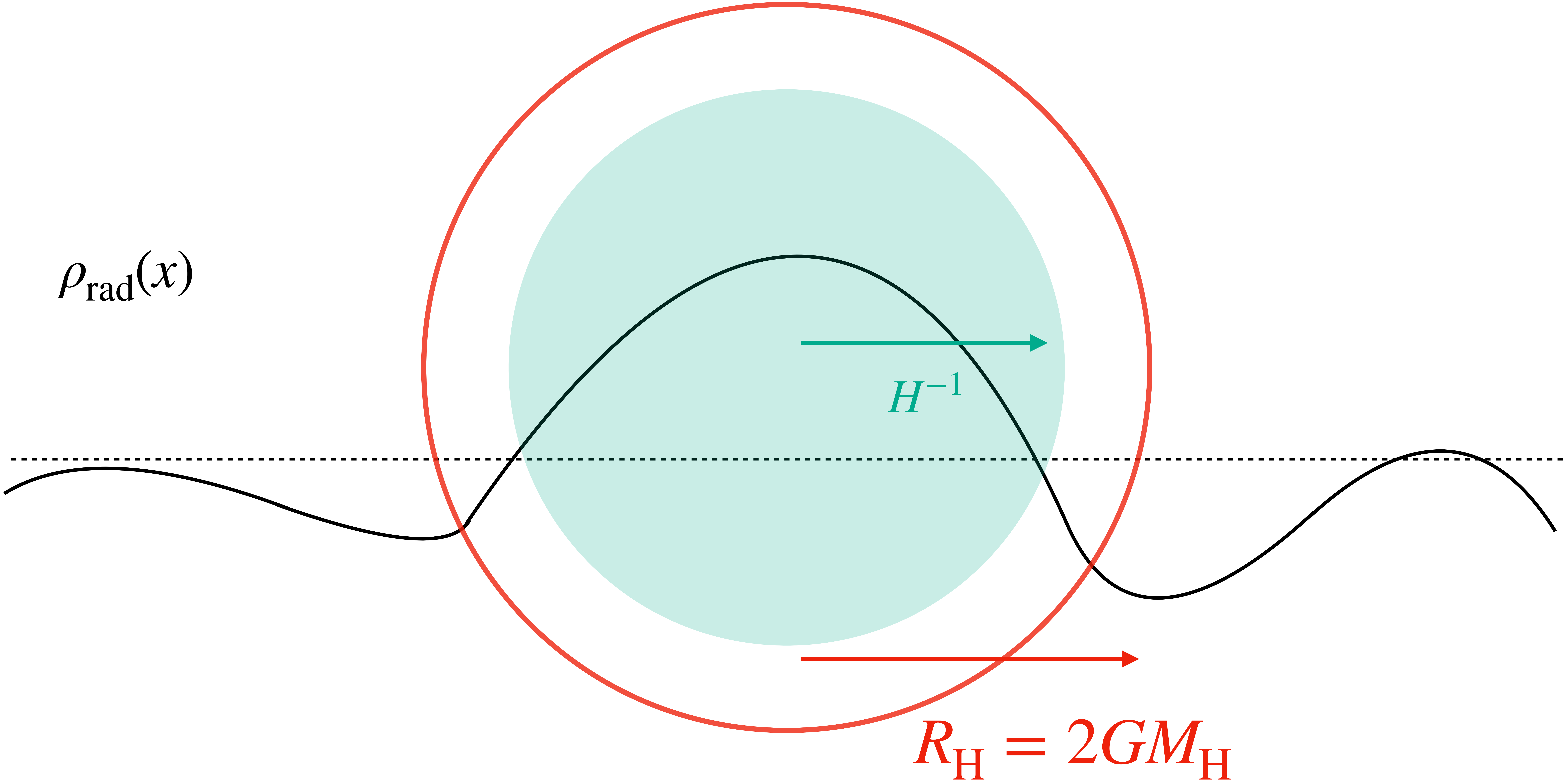
What is Primordial Black Holes ?



What is Primordial Black Holes ?

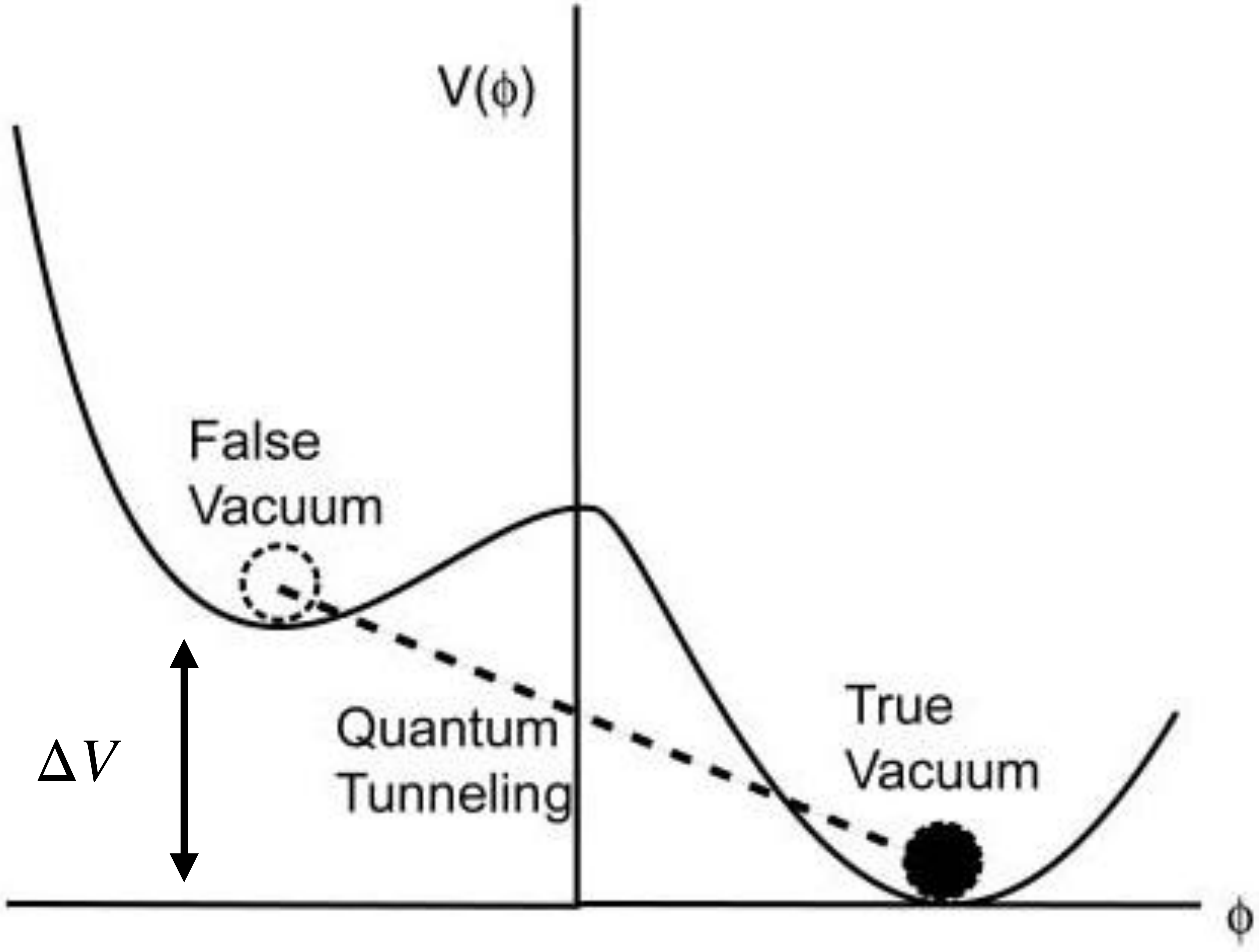


What is Primordial Black Holes ?

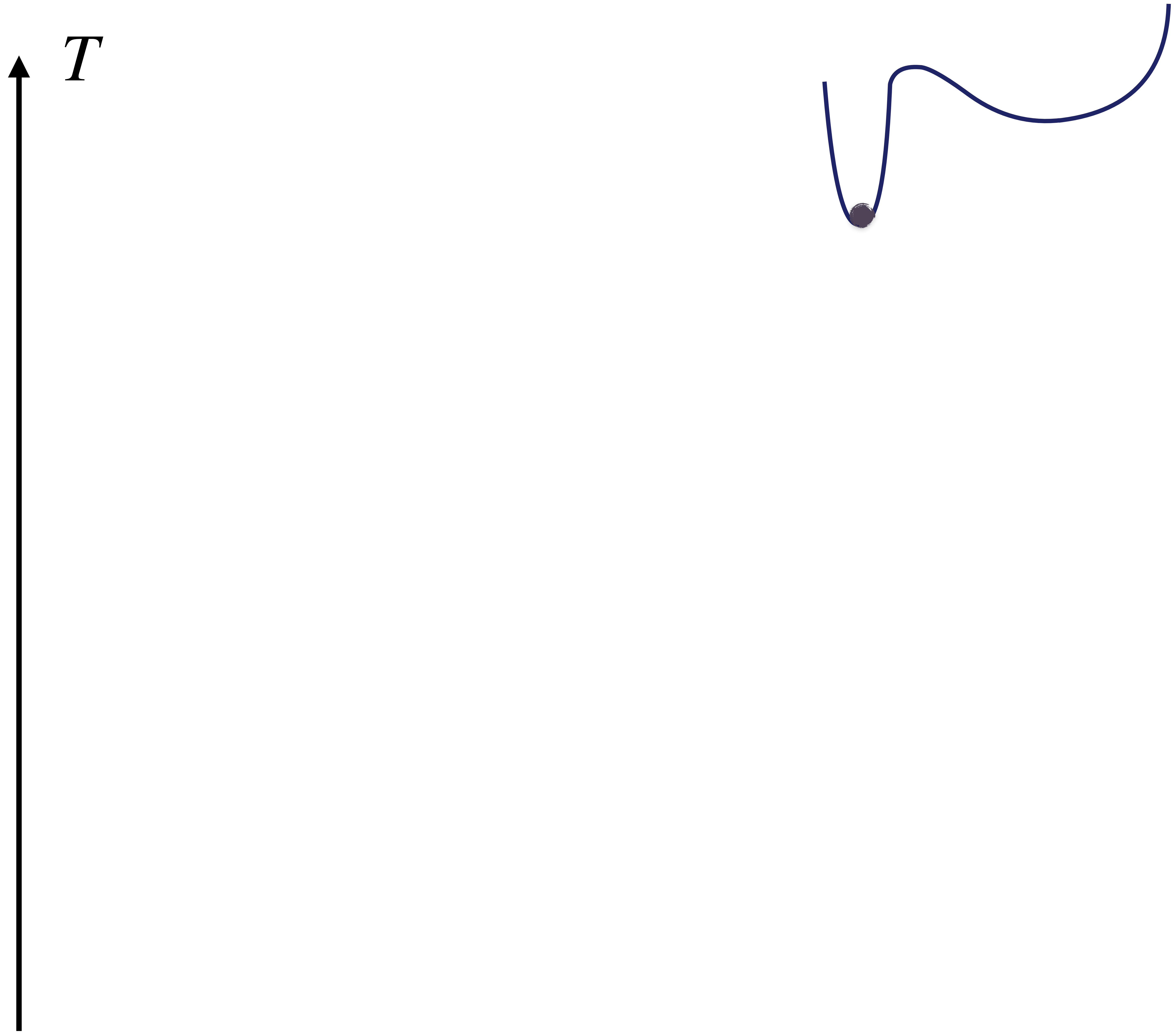


PBHs formation during supercooled phase transition

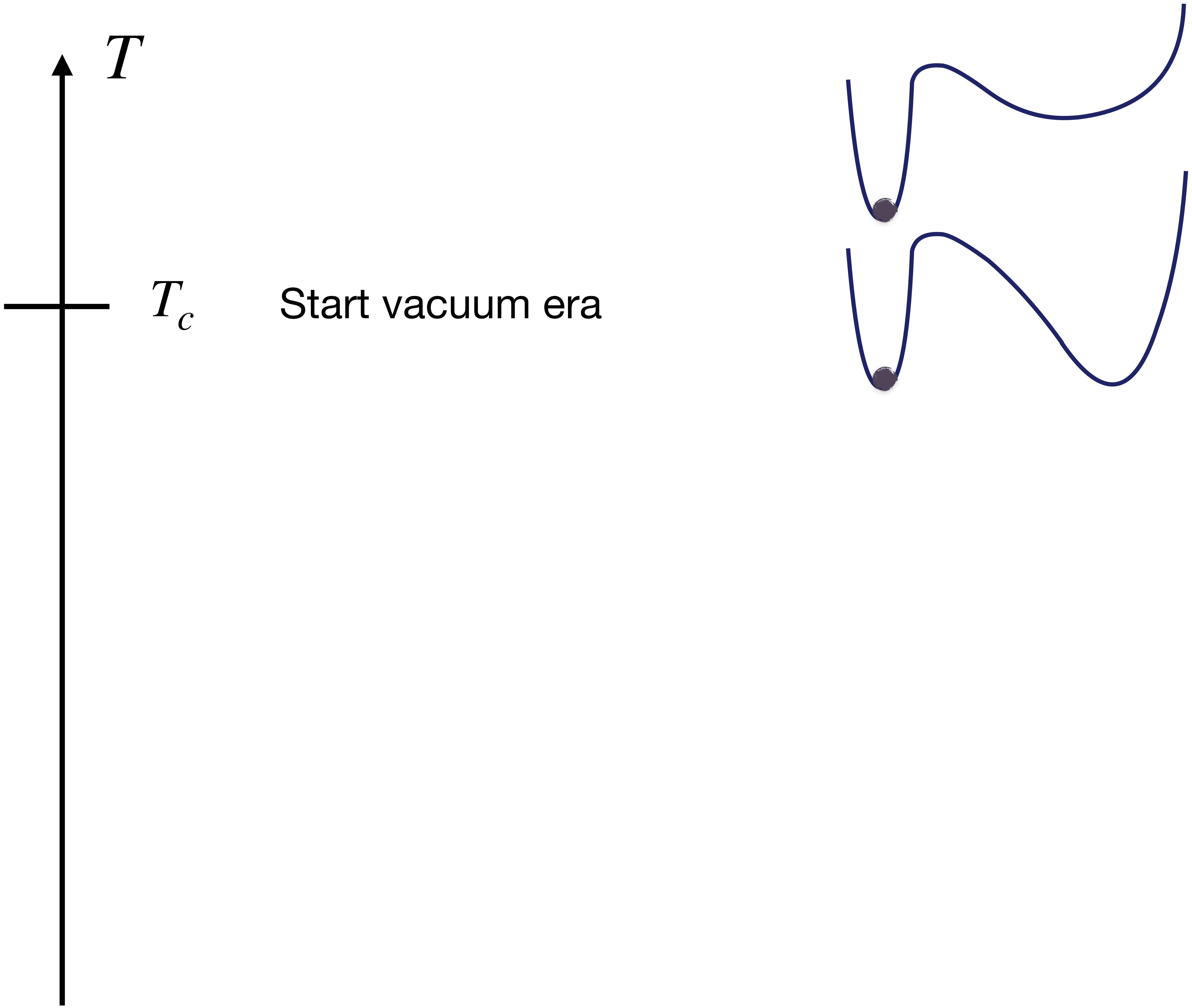
Guth 1980 "Old inflation idea"



Supercooled 1stOPT = delayed PT

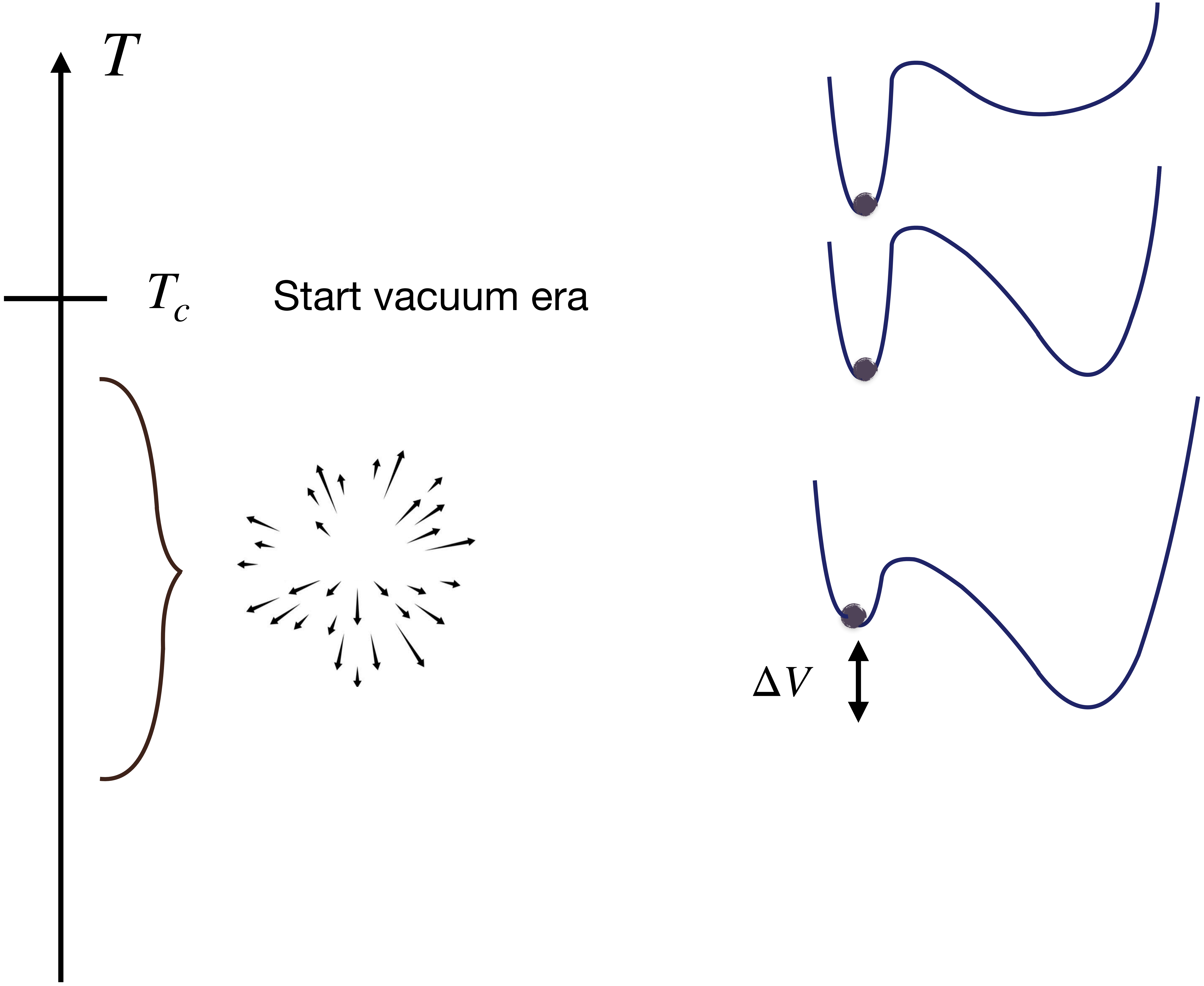


Supercooled 1stOPT = delayed PT



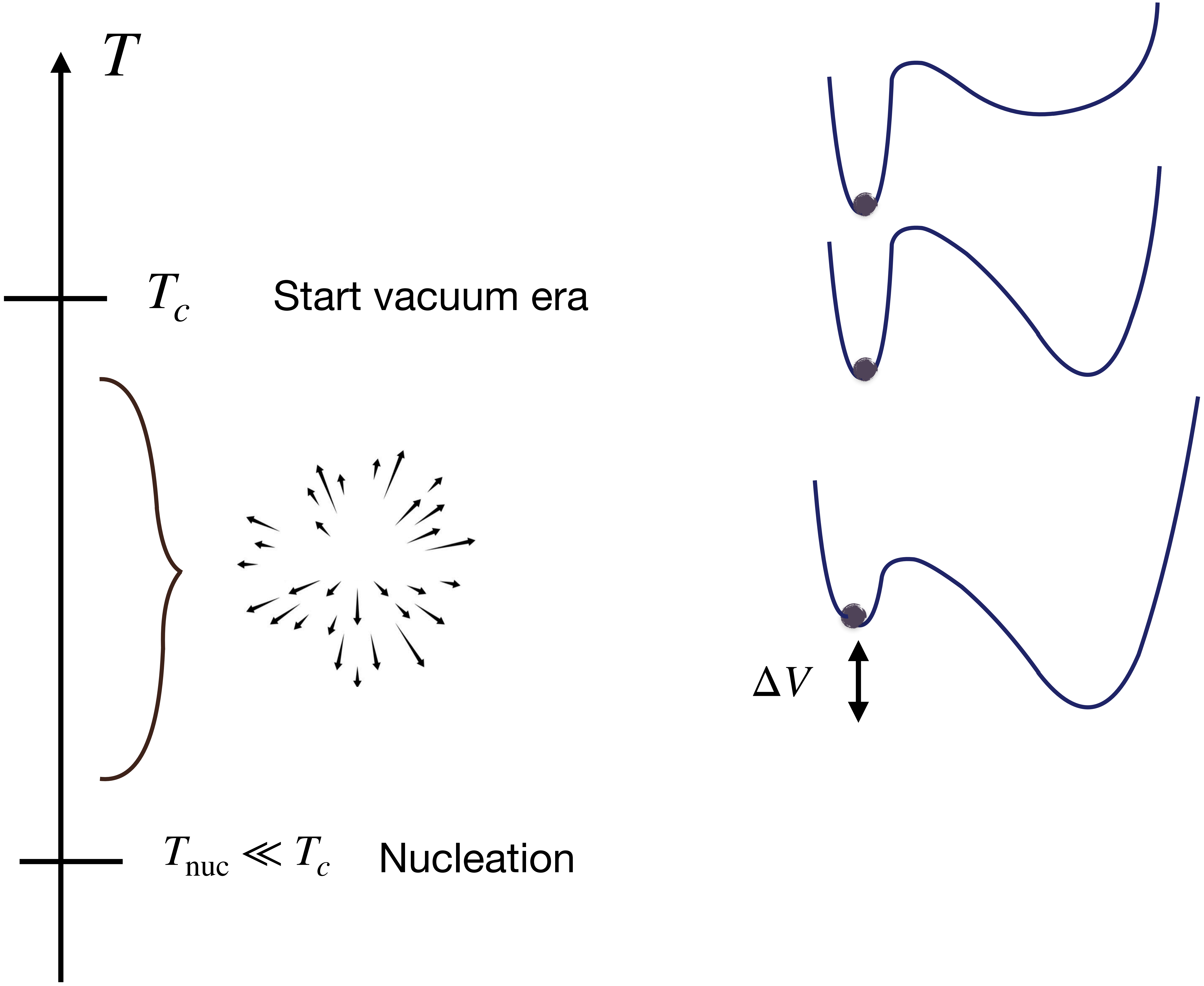
Start vacuum era

Supercooled 1stOPT = delayed PT



Start vacuum era

Supercooled 1stOPT = delayed PT



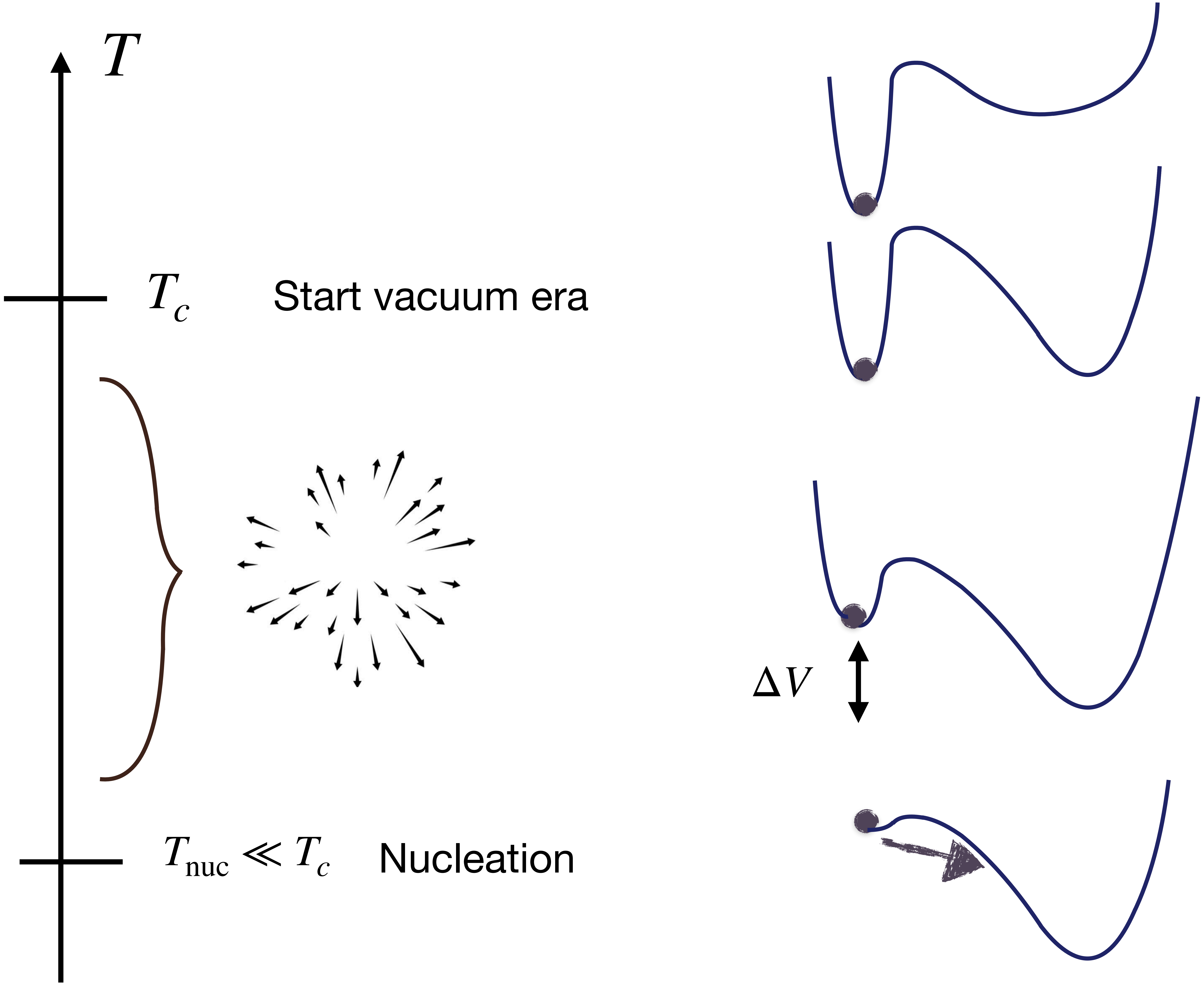
T

T_c Start vacuum era

$T_{\rm nuc} \ll T_c$ Nucleation

ΔV

Supercooled 1stOPT = delayed PT



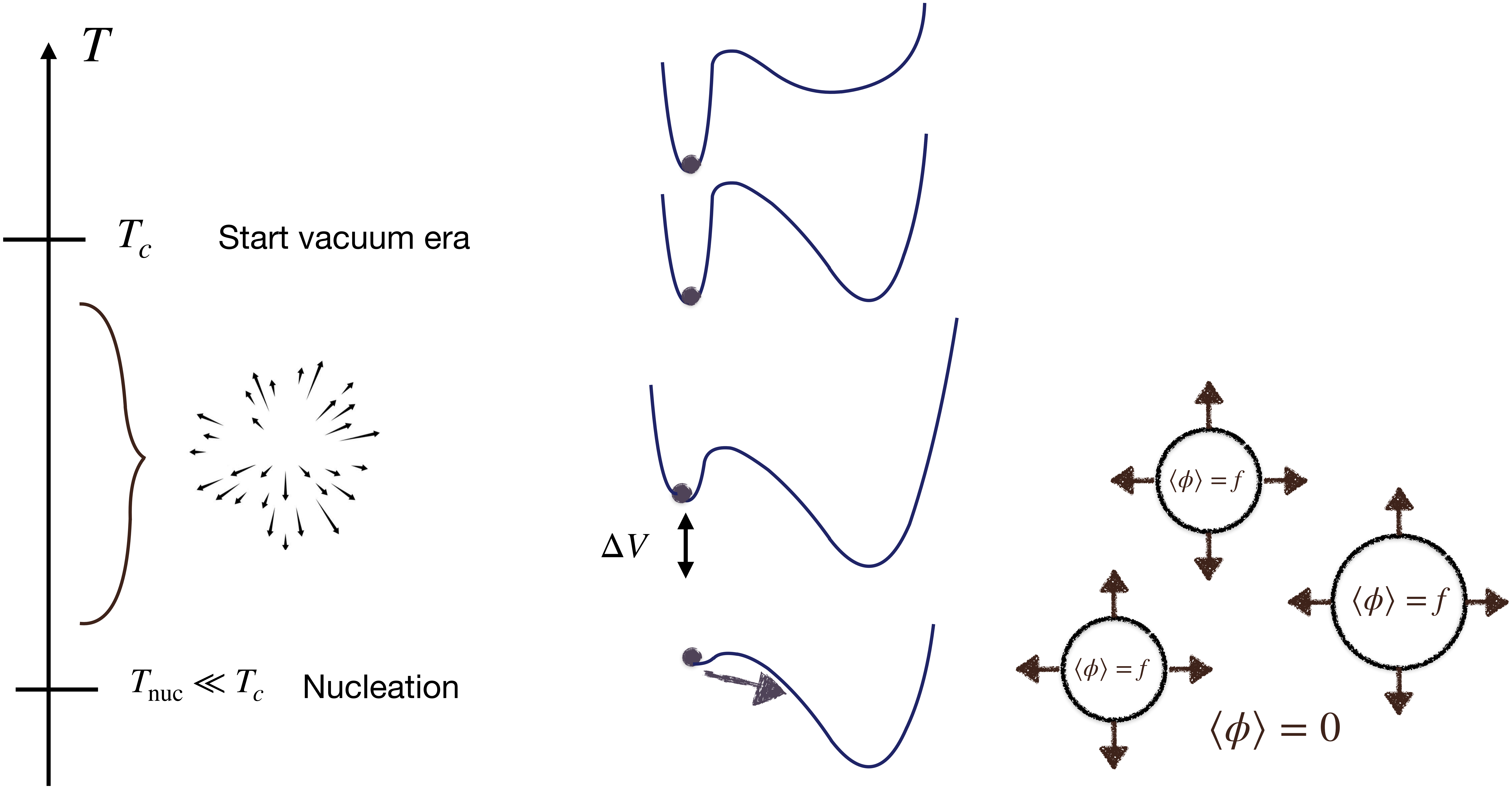
T

T_c Start vacuum era

$T_{\rm nuc} \ll T_c$ Nucleation

ΔV

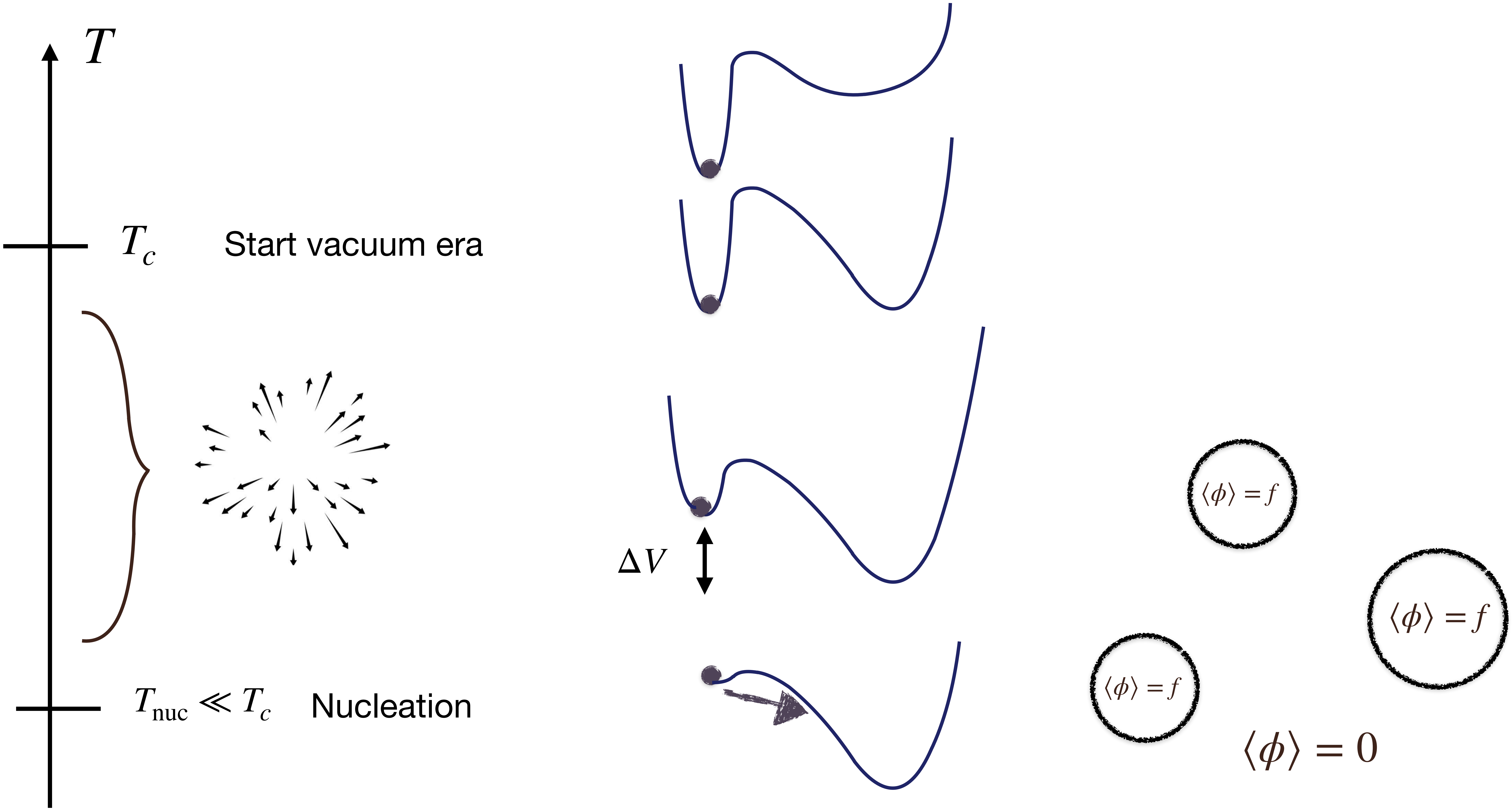
Supercooled 1stOPT = delayed PT



T_c Start vacuum era

$T_{\rm nuc} \ll T_c$ Nucleation

Supercooled 1stOPT = delayed PT



T

T_c Start vacuum era

ΔV

$T_{\rm nuc} \ll T_c$ Nucleation

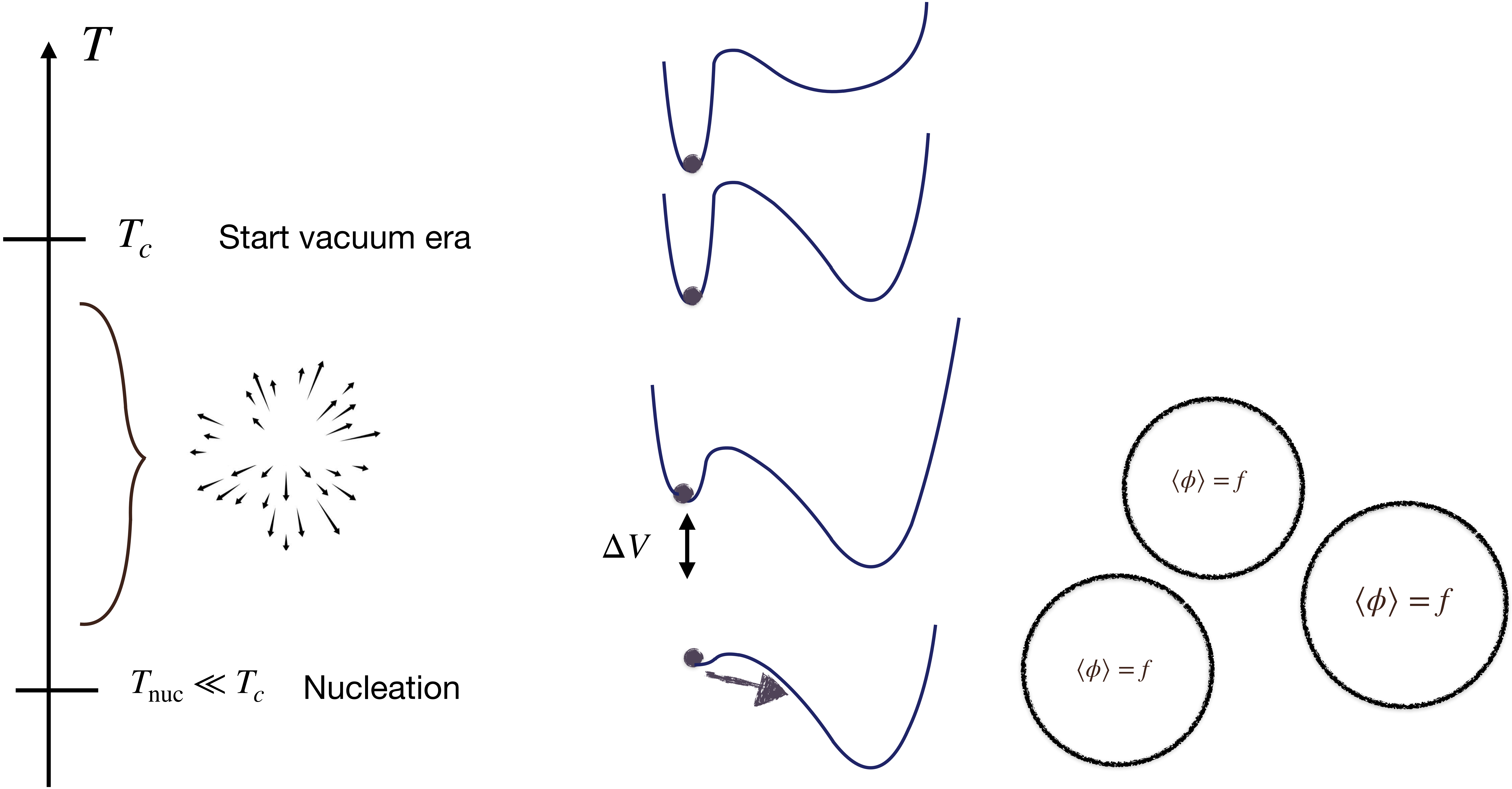
$\langle \phi \rangle = f$

$\langle \phi \rangle = f$

$\langle \phi \rangle = f$

$\langle \phi \rangle = 0$

Supercooled 1stOPT = delayed PT

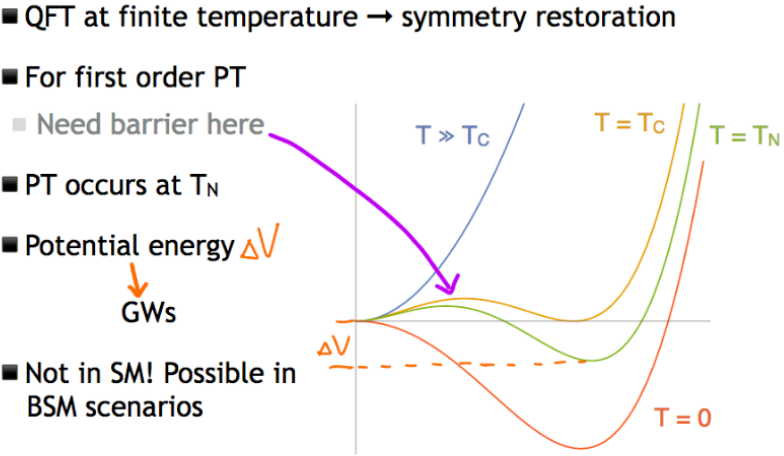


T

T_c Start vacuum era

$T_{\rm nuc} \ll T_c$ Nucleation

History of the Universe



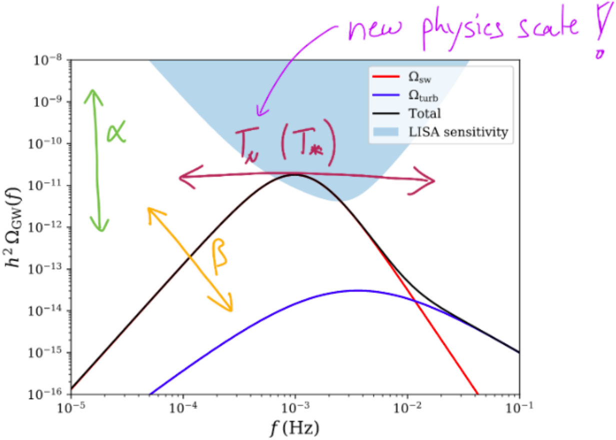
- QFT at finite temperature → symmetry restoration
- For first order PT
  - Need barrier here
- PT occurs at T_N
- Potential energy ΔV

  ↓

  GWs
- Not in SM! Possible in BSM scenarios

Schwaller (Amsterdam (2019))

History of the Universe

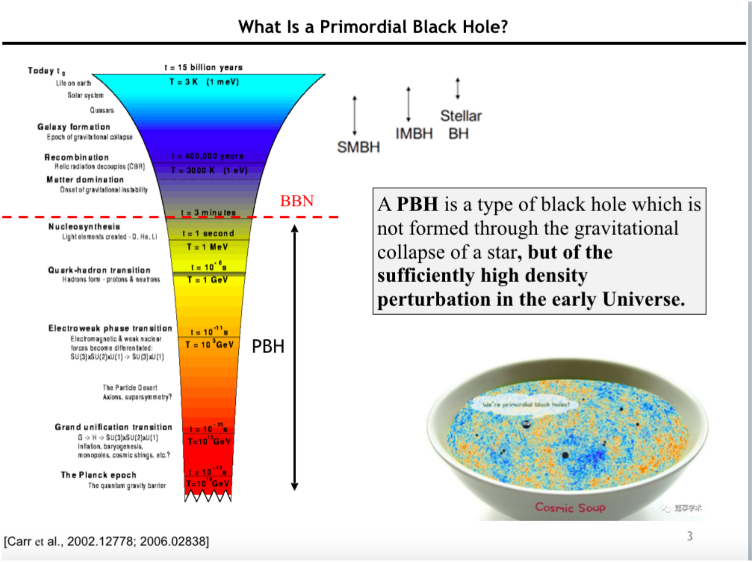


Schwaller (Amsterdam, 2019)

History of the Universe

WHAT DID WE LEARN: PBH formation from strong first-order phase transition and false vacuum (old Guth's idea) can give rise to PBH as entire DM candidate without any fine-tuning of initial condition. It can also explain NANOGRAV data. testability comes from the corresponding GW spectral shapes from phase transition.

History of the Universe



What Is a Primordial Black Hole?

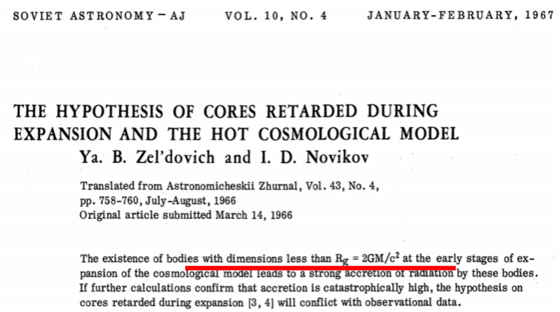
A **PBH** is a type of black hole which is not formed through the gravitational collapse of a star, **but of the sufficiently high density perturbation in the early Universe.**

[Carr et al., 2002.12778; 2006.02838]

History of the Universe

Original Idea

- [**Y. B. Zel'dovich** and **I. D. Novikov**, Sov. Astron. 10, 602 (1967)]



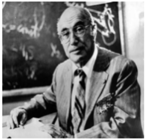
SOVIET ASTRONOMY – AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

THE HYPOTHESIS OF CORES RETARDED DURING EXPANSION AND THE HOT COSMOLOGICAL MODEL

Ya. B. Zel'dovich and I. D. Novikov

Translated from Astronomicheskii Zhurnal, Vol. 43, No. 4, pp. 758–760, July–August, 1966
Original article submitted March 14, 1966

The existence of bodies with dimensions less than $R_g = 2GM/c^2$ at the early stages of expansion of the cosmological model leads to a strong accretion of radiation by these bodies. If further calculations confirm that accretion is catastrophically high, the hypothesis on cores retarded during expansion [3, 4] will conflict with observational data.



Y. B. Zel'dovich

I. D. Novikov

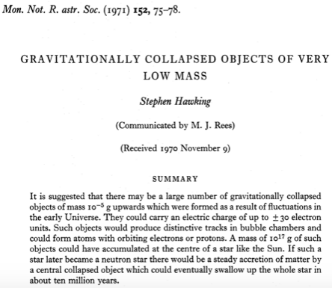
History of the Universe

Modern Mechanism

S. Hawking

- [**S. Hawking**, Mon. Not. Roy. Astron. Soc.152, 75 (1971);
- **B. J. Carr** and **S. W. Hawking**, Mon. Not. Roy. Astron. Soc.168, 399 (1974).]

B. Carr



Mon. Not. R. astr. Soc. (1971) **152**, 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

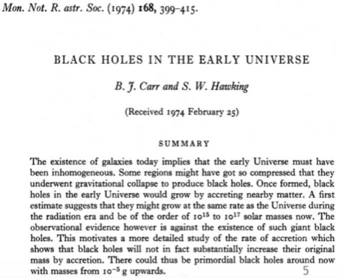
Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ± 30 electron units. Such objects would produce distinctive tracks in bubble chambers and could form atoms with orbiting electrons or protons. A mass of 10^{17} g of such objects could have accumulated at the centre of a star like the Sun. If such a star later became a neutron star there would be a steady accretion of matter by a central collapsed object which could eventually swallow up the whole star in about ten million years.



Mon. Not. R. astr. Soc. (1974) **168**, 399–415.

BLACK HOLES IN THE EARLY UNIVERSE

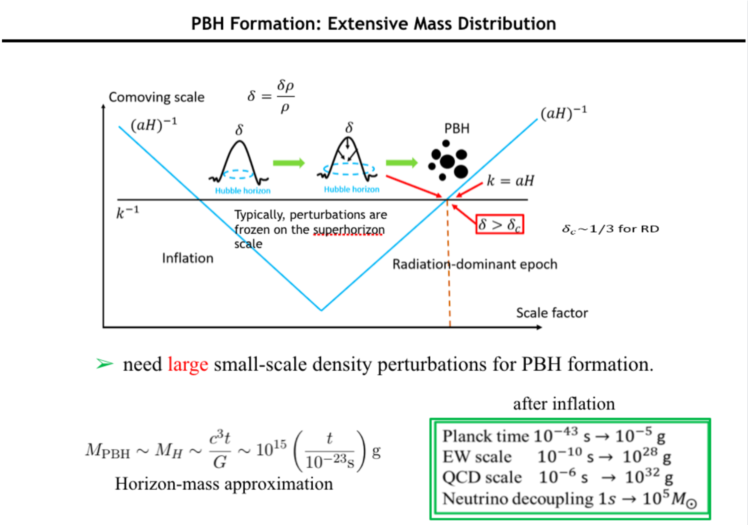
B. J. Carr and S. W. Hawking

(Received 1974 February 25)

SUMMARY

The existence of galaxies today implies that the early Universe must have been inhomogeneous. Some regions might have got so compressed that they underwent gravitational collapse to produce black holes. Once formed, black holes in the early Universe would grow by accreting nearby matter. A first estimate suggests that they might grow at the same rate as the Universe during the radiation era and be of the order of 10^{15} to 10^{17} solar masses now. The observational evidence however is against the existence of such giant black holes. This motivates a more detailed study of the rate of accretion which shows that black holes will not in fact substantially increase their original mass by accretion. There could thus be primordial black holes around now with masses from 10^{-5} g upwards.

History of the Universe



PBH Formation: Extensive Mass Distribution

Comoving scale

$\delta = \frac{\delta\rho}{\rho}$

$(aH)^{-1}$

δ

Hubble horizon

δ

Hubble horizon

PBH

$(aH)^{-1}$

$k = aH$

k^{-1}

Typically, perturbations are frozen on the superhorizon scale

$\boxed{\delta > \delta_c}$

$\delta_c \sim 1/3$ for RD

Inflation

Radiation-dominant epoch

Scale factor

- ➢ need large small-scale density perturbations for PBH formation.

$$M_{\rm PBH} \sim M_H \sim \frac{c^3 t}{G} \sim 10^{15}\left(\frac{t}{10^{-23}\text{s}}\right)\text{g}$$

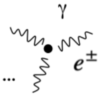
Horizon-mass approximation

after inflation

Planck time 10^{-43} s → 10^{-5} g
EW scale 10^{-10} s → 10^{28} g
QCD scale 10^{-6} s → 10^{32} g
Neutrino decoupling 1s → $10^{5} M_{\odot}$

History of the Universe

Observational Signals of PBHs



EHT(2019)

Hawking radiation:
BBN, CMB, EGB, GRB

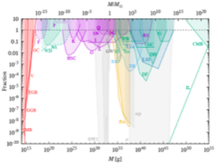
LIGO/Virgo events

Seeds for the SMBHs
in galactic nuclei

$\sim 10^{15}$ g

$\sim 10\ \mathrm{M}_\odot$

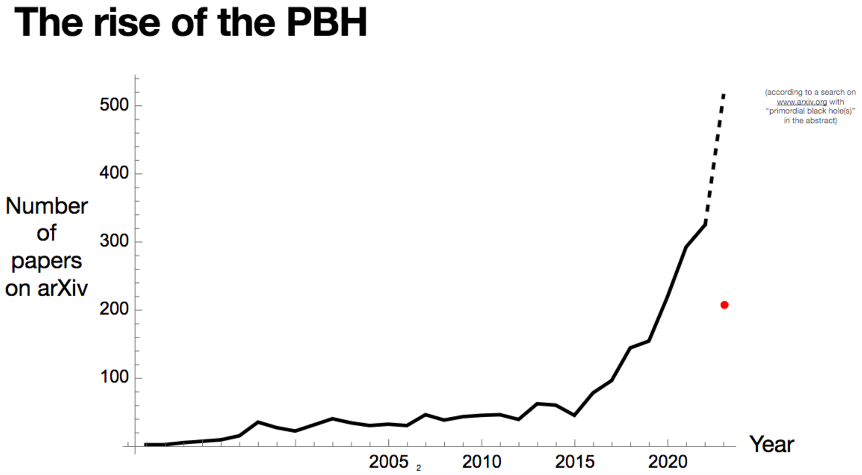
$\sim 10^{6}\ \mathrm{M}_\odot$



[B. Carr et al., 2002.12778; 2006.02838]

dark matter candidate (less interesting with more and more stringent constraints…personal bias)

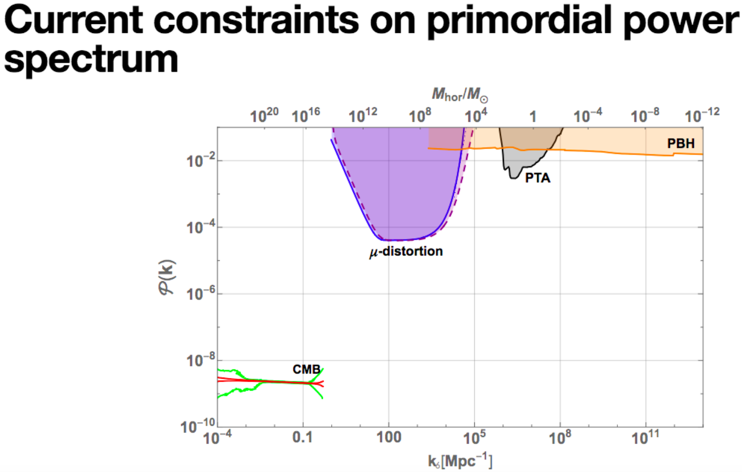
History of the Universe



The rise of the PBH

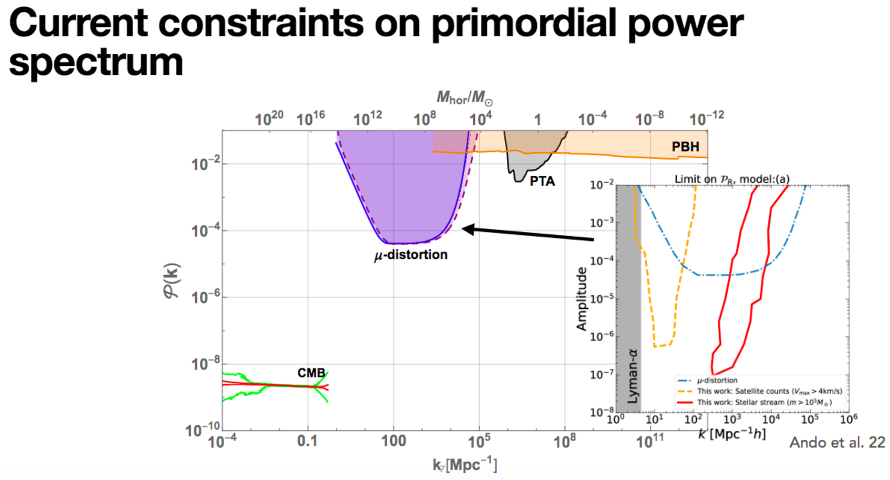
(according to a search on www.arxiv.org with “primordial black hole(s)” in the abstract)

History of the Universe



Current constraints on primordial power spectrum

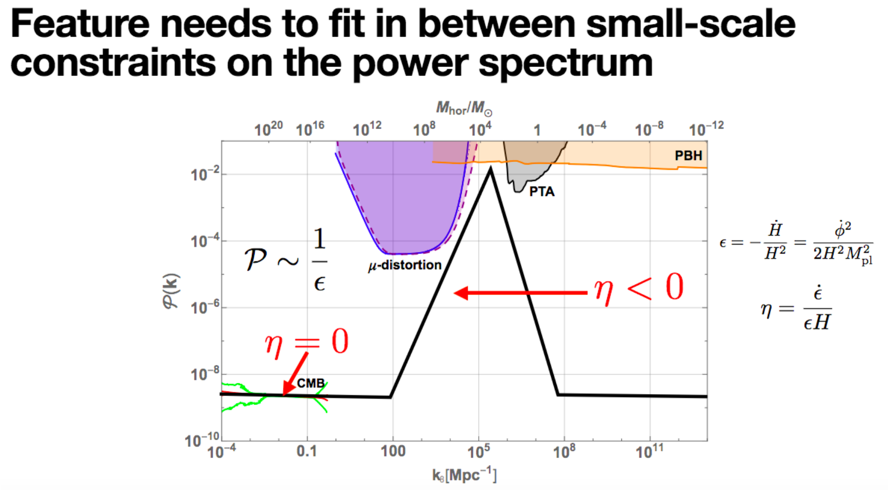
History of the Universe



Current constraints on primordial power spectrum

Ando et al. 22

History of the Universe



Feature needs to fit in between small-scale constraints on the power spectrum

$$\mathcal{P} \sim \frac{1}{\epsilon}$$

$$\eta < 0$$

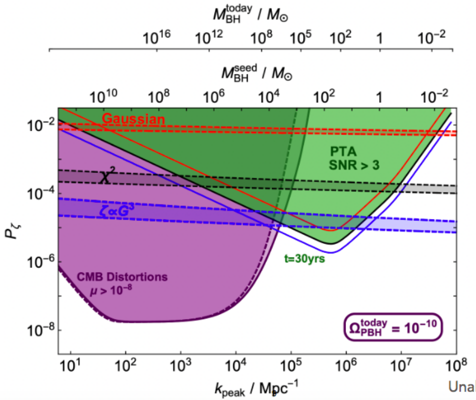
$$\eta = 0$$

$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2H^2 M_{\rm pl}^2}$$

$$\eta = \frac{\dot{\epsilon}}{\epsilon H}$$

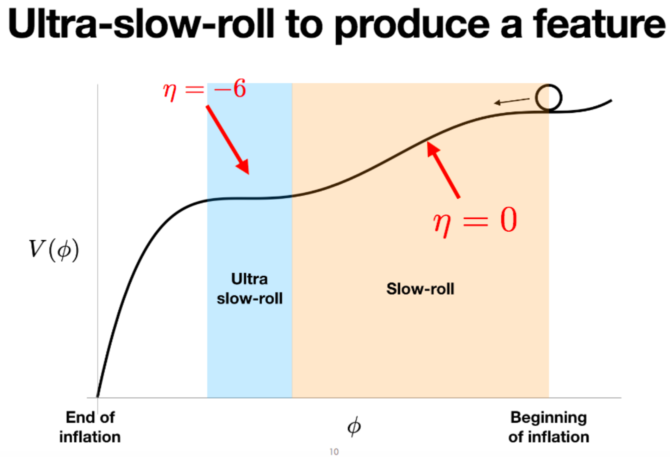
History of the Universe

Non-Gaussianity and accretion can help a little but won’t survive next-generation constraints



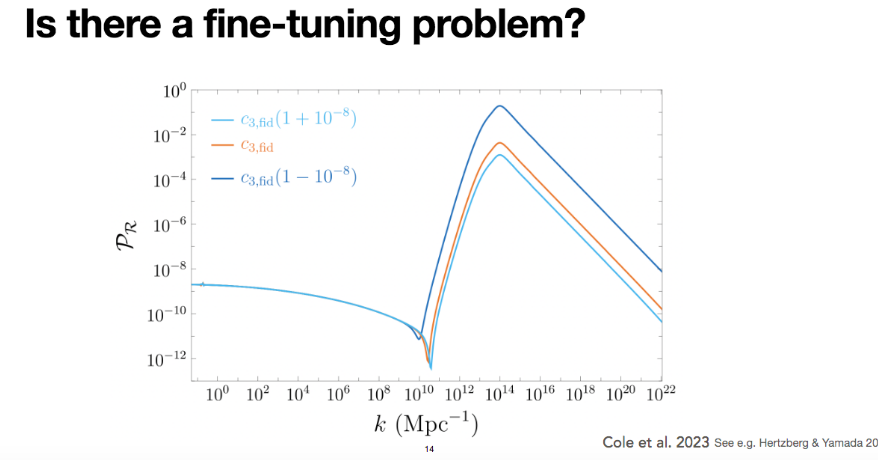
Unal et al. 2021

History of the Universe



Ultra-slow-roll to produce a feature

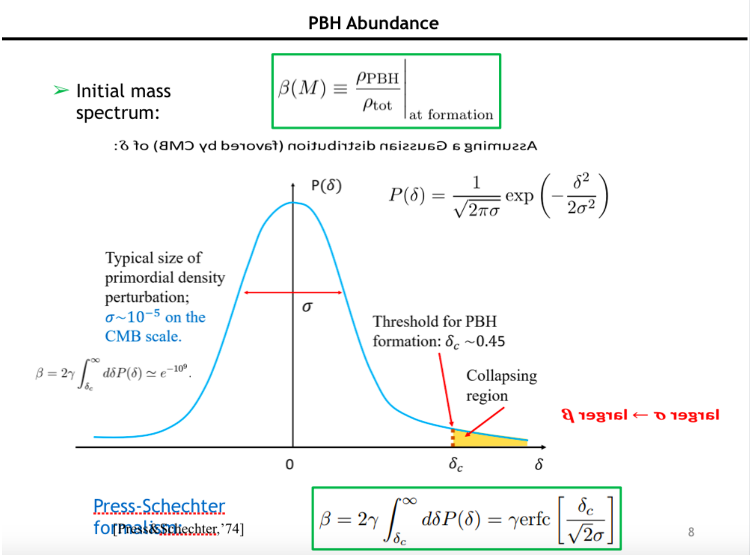
History of the Universe



Is there a fine-tuning problem?

Cole et al. 2023 See e.g. Hertzberg & Yamada 20

History of the Universe



PBH Abundance

- Initial mass spectrum: $\beta(M) \equiv \left.\frac{\rho_{\rm PBH}}{\rho_{\rm tot}}\right|_{\rm at\ formation}$

Assuming a Gaussian distribution (favored by CMB) of δ:

$$P(\delta) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{\delta^2}{2\sigma^2}\right)$$

Typical size of primordial density perturbation; $\sigma \sim 10^{-5}$ on the CMB scale.

$\beta = 2\gamma \int_{\delta_c}^{\infty} d\delta P(\delta) \simeq e^{-10^9}$.

Threshold for PBH formation: $\delta_c \sim 0.45$

Collapsing region

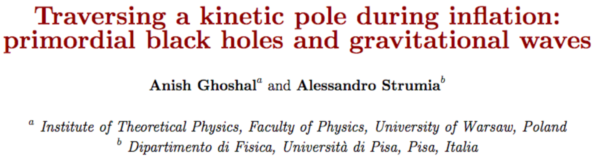
larger σ → larger β

Press-Schechter formalism: [Press&Schechter,'74]

$$\beta = 2\gamma \int_{\delta_c}^{\infty} d\delta P(\delta) = \gamma \text{erfc}\left[\frac{\delta_c}{\sqrt{2}\sigma}\right]$$

History of the Universe

What could particle physics do to help the scenario ?

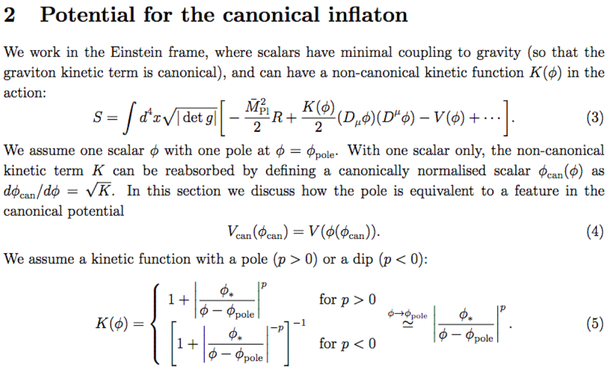


Traversing a kinetic pole during inflation: primordial black holes and gravitational waves

Anish Ghoshal[a] and **Alessandro Strumia**[b]

[a] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Poland*
[b] *Dipartimento di Fisica, Università di Pisa, Pisa, Italia*

History of the Universe



2 Potential for the canonical inflaton

We work in the Einstein frame, where scalars have minimal coupling to gravity (so that the graviton kinetic term is canonical), and can have a non-canonical kinetic function $K(\phi)$ in the action:

$$S=\int d^4x\sqrt{|\det g|}\Big[-\frac{\bar{M}_{\rm Pl}^2}{2}R+\frac{K(\phi)}{2}(D_\mu\phi)(D^\mu\phi)-V(\phi)+\cdots\Big]. \tag{3}$$

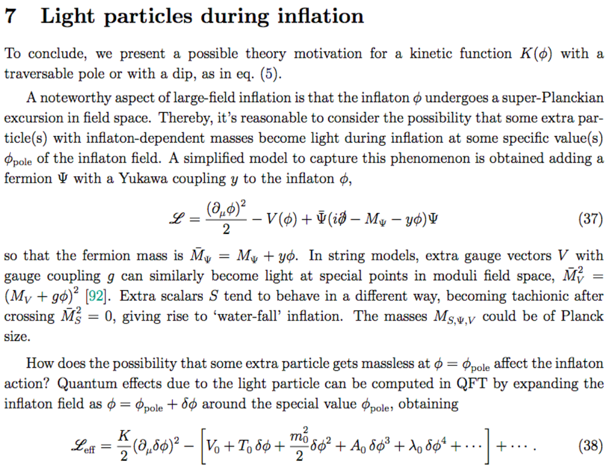
We assume one scalar ϕ with one pole at $\phi=\phi_{\rm pole}$. With one scalar only, the non-canonical kinetic term K can be reabsorbed by defining a canonically normalised scalar $\phi_{\rm can}(\phi)$ as $d\phi_{\rm can}/d\phi=\sqrt{K}$. In this section we discuss how the pole is equivalent to a feature in the canonical potential

$$V_{\rm can}(\phi_{\rm can})=V(\phi(\phi_{\rm can})). \tag{4}$$

We assume a kinetic function with a pole ($p>0$) or a dip ($p<0$):

$$K(\phi)=\begin{cases}1+\left|\dfrac{\phi_*}{\phi-\phi_{\rm pole}}\right|^p & \text{for } p>0\\[2ex] \left[1+\left|\dfrac{\phi_*}{\phi-\phi_{\rm pole}}\right|^{-p}\right]^{-1} & \text{for } p<0\end{cases}\ \overset{\phi\to\phi_{\rm pole}}{\simeq}\ \left|\frac{\phi_*}{\phi-\phi_{\rm pole}}\right|^p. \tag{5}$$

History of the Universe



7 Light particles during inflation

To conclude, we present a possible theory motivation for a kinetic function $K(\phi)$ with a traversable pole or with a dip, as in eq. (5).

A noteworthy aspect of large-field inflation is that the inflaton ϕ undergoes a super-Planckian excursion in field space. Thereby, it's reasonable to consider the possibility that some extra particle(s) with inflaton-dependent masses become light during inflation at some specific value(s) $\phi_{\rm pole}$ of the inflaton field. A simplified model to capture this phenomenon is obtained adding a fermion Ψ with a Yukawa coupling y to the inflaton ϕ,

$$\mathscr{L} = \frac{(\partial_\mu \phi)^2}{2} - V(\phi) + \bar{\Psi}(i\partial\!\!\!/ - M_\Psi - y\phi)\Psi \tag{37}$$

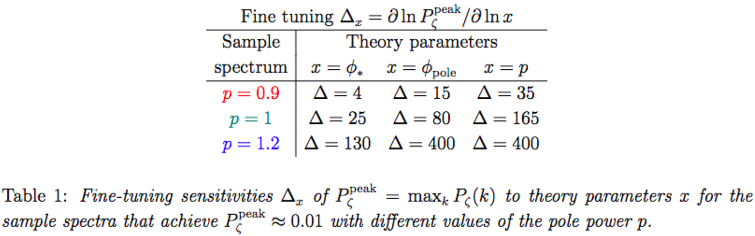
so that the fermion mass is $\bar{M}_\Psi = M_\Psi + y\phi$. In string models, extra gauge vectors V with gauge coupling g can similarly become light at special points in moduli field space, $\bar{M}_V^2 = (M_V + g\phi)^2$ [92]. Extra scalars S tend to behave in a different way, becoming tachionic after crossing $\bar{M}_S^2 = 0$, giving rise to 'water-fall' inflation. The masses $M_{S,\Psi,V}$ could be of Planck size.

How does the possibility that some extra particle gets massless at $\phi = \phi_{\rm pole}$ affect the inflaton action? Quantum effects due to the light particle can be computed in QFT by expanding the inflaton field as $\phi = \phi_{\rm pole} + \delta\phi$ around the special value $\phi_{\rm pole}$, obtaining

$$\mathscr{L}_{\rm eff} = \frac{K}{2}(\partial_\mu \delta\phi)^2 - \left[V_0 + T_0\,\delta\phi + \frac{m_0^2}{2}\delta\phi^2 + A_0\,\delta\phi^3 + \lambda_0\,\delta\phi^4 + \cdots\right] + \cdots . \tag{38}$$

History of the Universe

Less fine-tuning than traditional single-field inflation involving tiny bump/inflation point (see Sayantan-da's talk) !!



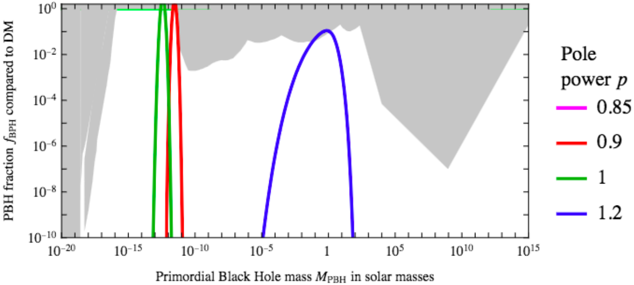
Fine tuning $\Delta_x = \partial \ln P_\zeta^{\rm peak} / \partial \ln x$

Sample spectrum	Theory parameters		
	$x = \phi_*$	$x = \phi_{\rm pole}$	$x = p$
$p = 0.9$	$\Delta = 4$	$\Delta = 15$	$\Delta = 35$
$p = 1$	$\Delta = 25$	$\Delta = 80$	$\Delta = 165$
$p = 1.2$	$\Delta = 130$	$\Delta = 400$	$\Delta = 400$

Table 1: *Fine-tuning sensitivities* Δ_x *of* $P_\zeta^{\rm peak} = \max_k P_\zeta(k)$ *to theory parameters* x *for the sample spectra that achieve* $P_\zeta^{\rm peak} \approx 0.01$ *with different values of the pole power* p.

History of the Universe

PBH as entire DM candidate.



History of the Universe

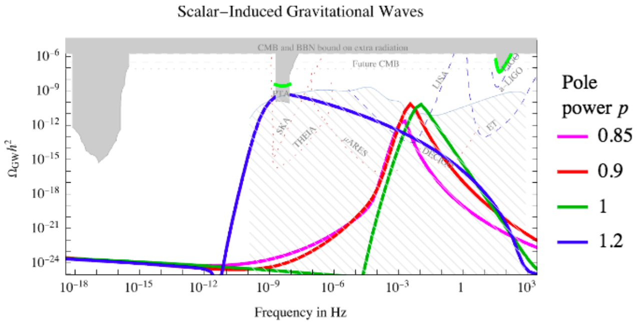
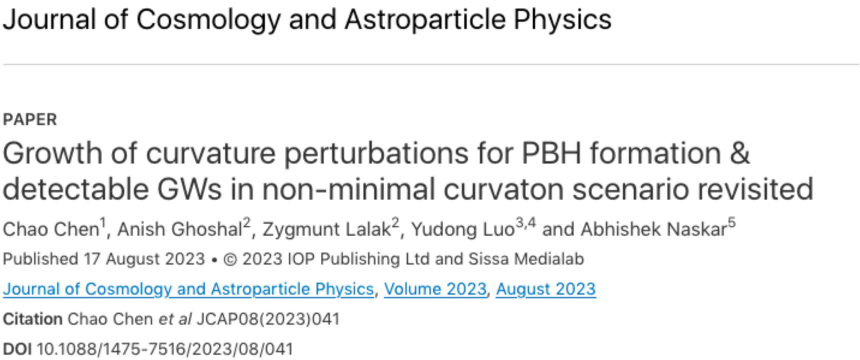


Figure 4: *Frequency spectra of scalar-induced gravitational waves corresponding to the* $P_\zeta(k)$ *of fig. 3 for the indicated pole powers p. The regions shaded in gray are excluded. The hatched regions are below the expected astrophysical foregrounds, that could be partially subtracted. The dashed (dotted) curves show the sensitivities of planned (futuristic) experiments. The green curves are the detections from LIGO/VIRGO and Pulsar Timing Arrays.*

History of the Universe

Why should the inflaton carry the burden for CMB scale as well as small-scales for PBH production ?

History of the Universe



Journal of Cosmology and Astroparticle Physics

PAPER

Growth of curvature perturbations for PBH formation & detectable GWs in non-minimal curvaton scenario revisited

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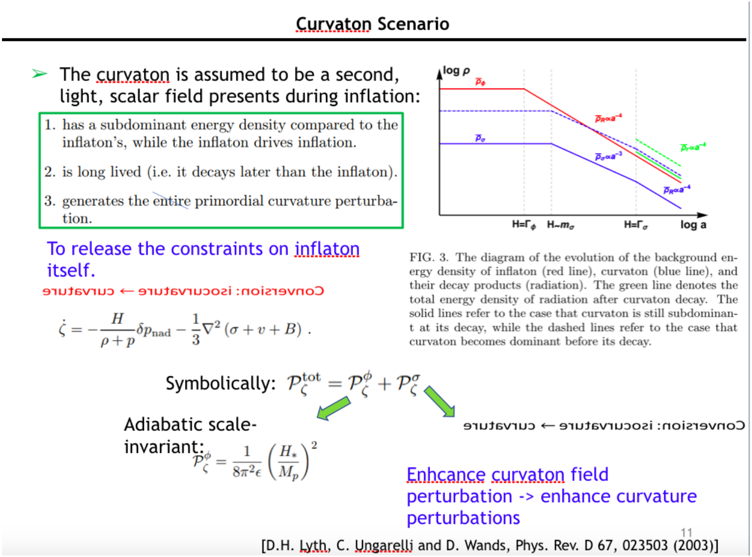
History of the Universe



Curvaton Scenario

- The curvaton is assumed to be a second, light, scalar field presents during inflation:

1. has a subdominant energy density compared to the inflaton's, while the inflaton drives inflation.
2. is long lived (i.e. it decays later than the inflaton).
3. generates the entire primordial curvature perturbation.

FIG. 3. The diagram of the evolution of the background energy density of inflaton (red line), curvaton (blue line), and their decay products (radiation). The green line denotes the total energy density of radiation after curvaton decay. The solid lines refer to the case that curvaton is still subdominant at its decay, while the dashed lines refer to the case that curvaton becomes dominant before its decay.

To release the constraints on inflaton itself.

Conversion: isocurvature → curvature

$$\dot{\zeta} = -\frac{H}{\rho + p}\delta p_{\rm nad} - \frac{1}{3}\nabla^2(\sigma + v + B) \ .$$

Symbolically: $\mathcal{P}_\zeta^{\rm tot} = \mathcal{P}_\zeta^\phi + \mathcal{P}_\zeta^\sigma$

Adiabatic scale-invariant: $\mathcal{P}_\zeta^\phi = \frac{1}{8\pi^2\epsilon}\left(\frac{H_*}{M_p}\right)^2$

Conversion: isocurvature → curvature

Enhcance curvaton field perturbation -> enhance curvature perturbations

[D.H. Lyth, C. Ungarelli and D. Wands, Phys. Rev. D 67, 023503 (2003)]

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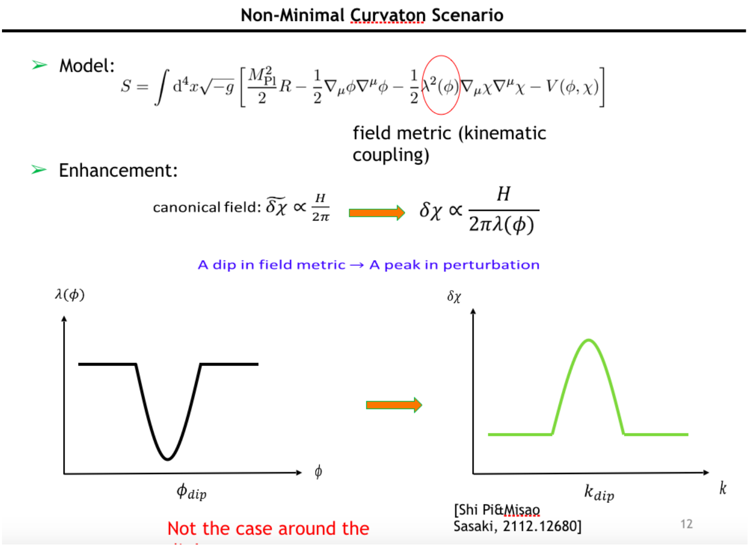


Non-Minimal Curvaton Scenario

- **Model:**

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{1}{2}\boxed{\lambda^2(\phi)}\nabla_\mu\chi\nabla^\mu\chi - V(\phi,\chi)\right]$$

field metric (kinematic coupling)

- **Enhancement:**

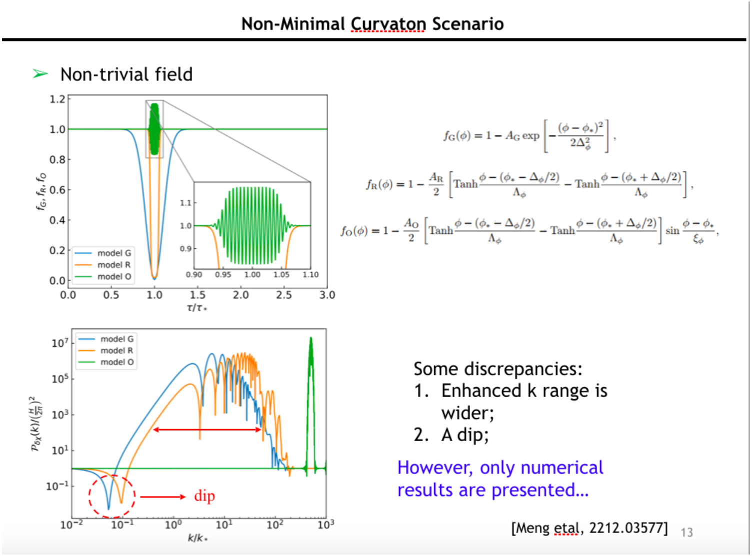
canonical field: $\widetilde{\delta\chi} \propto \frac{H}{2\pi}$ $\longrightarrow$ $\delta\chi \propto \frac{H}{2\pi\lambda(\phi)}$

A dip in field metric → A peak in perturbation

[Shi Pi&Misao Sasaki, 2112.12680]

Not the case around the

History of the Universe



Non-Minimal Curvaton Scenario

- Non-trivial field

$$f_{\rm G}(\phi) = 1 - A_{\rm G} \exp\left[-\frac{(\phi-\phi_*)^2}{2\Delta_\phi^2}\right],$$

$$f_{\rm R}(\phi) = 1 - \frac{A_{\rm R}}{2}\left[\mathrm{Tanh}\frac{\phi-(\phi_*-\Delta_\phi/2)}{\Lambda_\phi} - \mathrm{Tanh}\frac{\phi-(\phi_*+\Delta_\phi/2)}{\Lambda_\phi}\right],$$

$$f_{\rm O}(\phi) = 1 - \frac{A_{\rm O}}{2}\left[\mathrm{Tanh}\frac{\phi-(\phi_*-\Delta_\phi/2)}{\Lambda_\phi} - \mathrm{Tanh}\frac{\phi-(\phi_*+\Delta_\phi/2)}{\Lambda_\phi}\right]\sin\frac{\phi-\phi_*}{\xi_\phi},$$

Some discrepancies:

1. Enhanced k range is wider;
2. A dip;

However, only numerical results are presented...

[Meng etal, 2212.03577]

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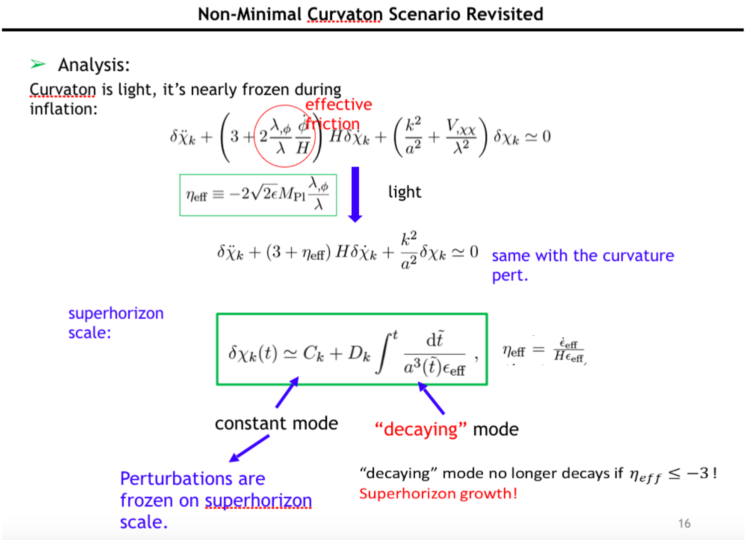


Non-Minimal Curvaton Scenario Revisited

- Analysis:

Curvaton is light, it's nearly frozen during inflation:

effective friction

$$\delta\ddot{\chi}_k + \left(3 + 2\frac{\lambda_{,\phi}}{\lambda}\frac{\dot{\phi}}{H}\right)H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + \frac{V_{,\chi\chi}}{\lambda^2}\right)\delta\chi_k \simeq 0$$

$$\boxed{\eta_{\rm eff} \equiv -2\sqrt{2\epsilon}M_{\rm Pl}\frac{\lambda_{,\phi}}{\lambda}}$$

light

$$\delta\ddot{\chi}_k + (3 + \eta_{\rm eff})\,H\delta\dot{\chi}_k + \frac{k^2}{a^2}\delta\chi_k \simeq 0$$

same with the curvature pert.

superhorizon scale:

$$\boxed{\delta\chi_k(t) \simeq C_k + D_k\int^t \frac{d\tilde{t}}{a^3(\tilde{t})\epsilon_{\rm eff}}\,,}\qquad \eta_{\rm eff} = \frac{\dot{\epsilon}_{\rm eff}}{H\epsilon_{\rm eff}},$$

constant mode

"decaying" mode

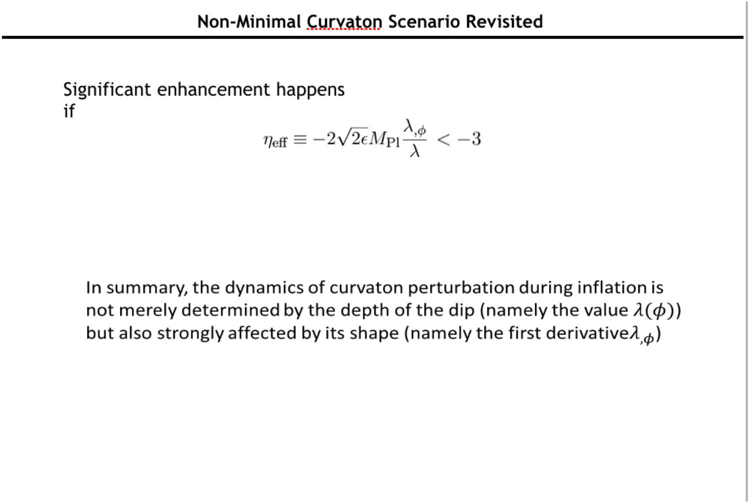
Perturbations are frozen on superhorizon scale.

"decaying" mode no longer decays if $\eta_{eff} \leq -3$!

Superhorizon growth!

16

History of the Universe



Non-Minimal Curvaton Scenario Revisited

Significant enhancement happens
if

$$\eta_{\rm eff} \equiv -2\sqrt{2\epsilon} M_{\rm Pl} \frac{\lambda_{,\phi}}{\lambda} < -3$$

In summary, the dynamics of curvaton perturbation during inflation is not merely determined by the depth of the dip (namely the value $\lambda(\phi)$) but also strongly affected by its shape (namely the first derivative$\lambda_{,\phi}$)

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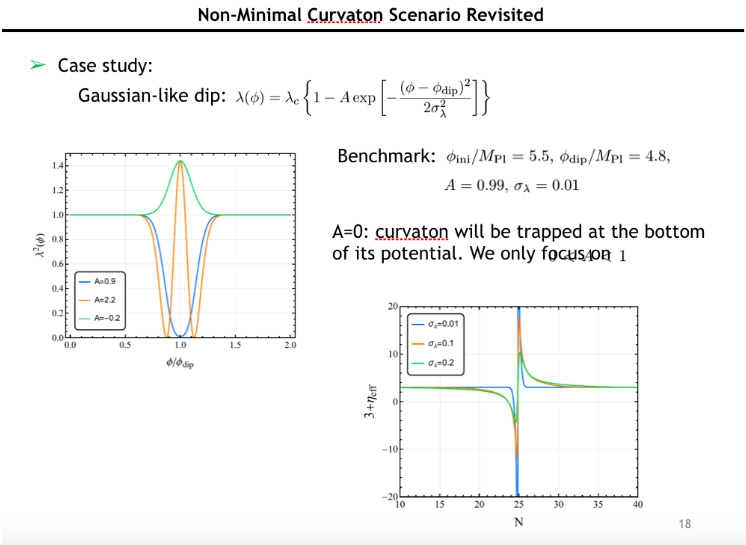

Non-Minimal Curvaton Scenario Revisited

- Case study:

Gaussian-like dip: $\lambda(\phi) = \lambda_c \left\{ 1 - A \exp\left[- \frac{(\phi - \phi_{\rm dip})^2}{2\sigma_\lambda^2} \right] \right\}$

Benchmark: $\phi_{\rm ini}/M_{\rm Pl} = 5.5,\ \phi_{\rm dip}/M_{\rm Pl} = 4.8,$

$A = 0.99,\ \sigma_\lambda = 0.01$

A=0: curvaton will be trapped at the bottom of its potential. We only focus on $0 < A < 1$

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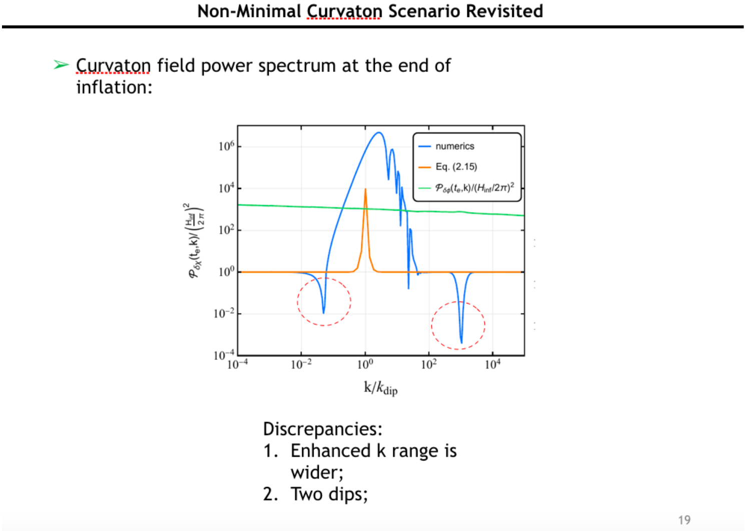


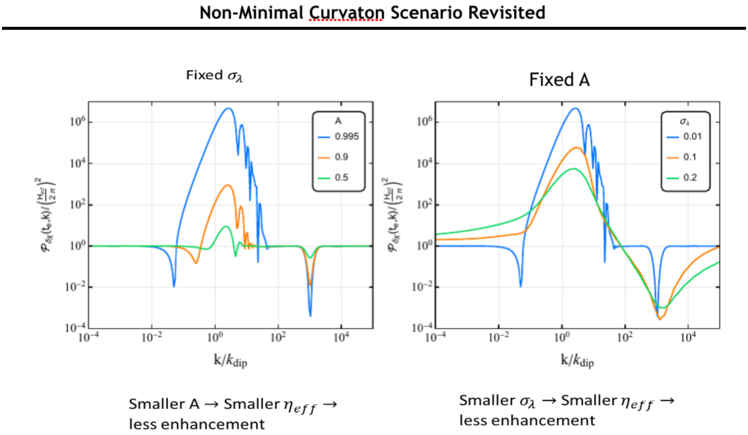
Non-Minimal Curvaton Scenario Revisited

- ➢ Curvaton field power spectrum at the end of inflation:

Discrepancies:

1. Enhanced k range is wider;
2. Two dips;

History of the Universe



Non-Minimal Curvaton Scenario Revisited

Smaller A → Smaller η_{eff} → less enhancement

Smaller σ_λ → Smaller η_{eff} → less enhancement

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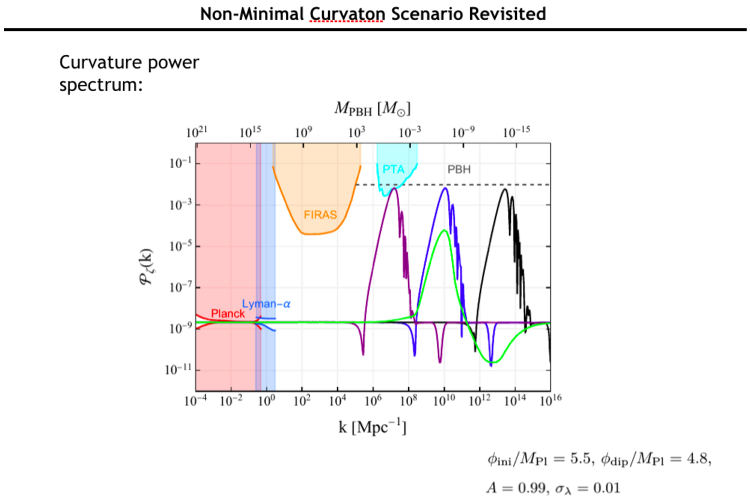

Non-Minimal Curvaton Scenario Revisited

Curvature power spectrum:

$\phi_{\rm ini}/M_{\rm Pl} = 5.5,\ \phi_{\rm dip}/M_{\rm Pl} = 4.8,$

$A = 0.99,\ \sigma_\lambda = 0.01$

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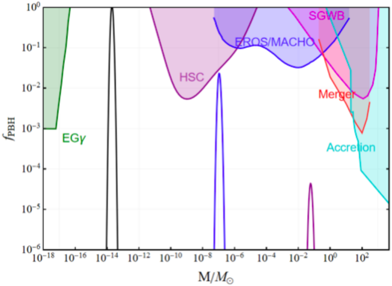
PBH Abundance

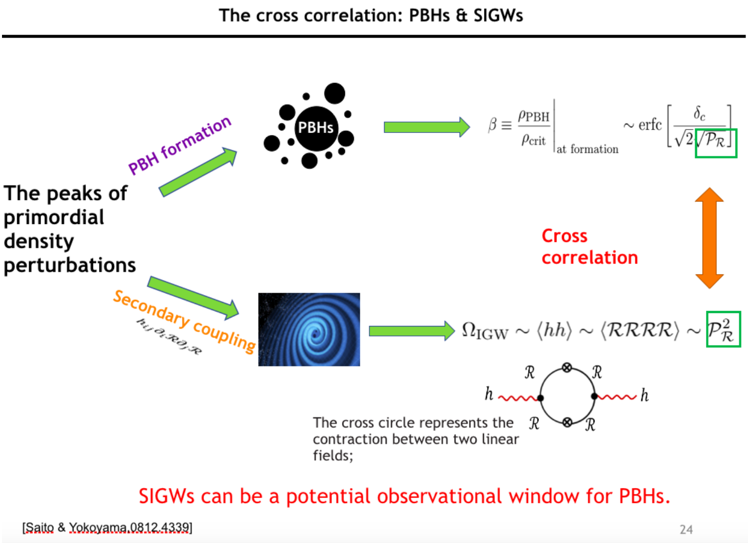


$$\beta(M) = 2\int_{\delta_c}^{\infty} P(\delta_R)\mathrm{d}\delta_R = \mathrm{erfc}\left[\frac{\delta_c}{\sqrt{2}\sigma_R}\right]$$

$$\sigma_R^2 \equiv \langle \delta_R^2 \rangle = \frac{1}{(2\pi)^3}\int \frac{\mathrm{d}k}{k} W(kR)^2 \mathcal{P}_\delta(k)$$

$$f_{\rm PBH}(M) \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \simeq 2.7\times 10^{8}\left(\frac{M}{M_\odot}\right)^{-1/2} \beta(M)$$

History of the Universe



The cross correlation: PBHs & SIGWs

The peaks of primordial density perturbations

PBH formation

Secondary coupling

$h_{ij}\partial_i\mathcal{R}\partial_j\mathcal{R}$

$$\beta \equiv \frac{\rho_{\rm PBH}}{\rho_{\rm crit}}\bigg|_{\text{at formation}} \sim \mathrm{erfc}\left[\frac{\delta_c}{\sqrt{2}\boxed{\sqrt{\mathcal{P}_{\mathcal{R}}}}}\right]$$

Cross correlation

$$\Omega_{\rm IGW} \sim \langle hh\rangle \sim \langle \mathcal{RRRR}\rangle \sim \boxed{\mathcal{P}_{\mathcal{R}}^2}$$

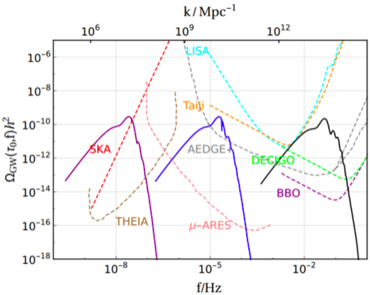
The cross circle represents the contraction between two linear fields;

SIGWs can be a potential observational window for PBHs.

[Saito & Yokoyama,0812.4339]

History of the Universe

Scalar-Induced GWs



$$\boxed{\mathcal{P}_h(\tau,k) = \int_0^\infty \mathrm{d}v \int_{|1-v|}^{|1+v|} \mathrm{d}u \left[\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right]^2 I^2(v,u,x)\mathcal{P}_\mathcal{R}(ku)\mathcal{P}_\mathcal{R}(kv)}$$

$$\Omega_{\mathrm{GW}}(\tau,k) = \frac{1}{48}\left(\frac{k}{aH}\right)^2 \overline{\mathcal{P}_h(\tau,k)}$$

$$\Omega_{\mathrm{GW}}(\tau_0,f)h^2 \simeq 1.6\times 10^{-5}\left(\frac{g_{*,s}}{106.75}\right)^{-1/3}\left(\frac{\Omega_{\mathrm{r},0}h^2}{4.1\times 10^{-5}}\right)\Omega_{\mathrm{GW}}(\tau_{\mathrm{eq}},f)$$

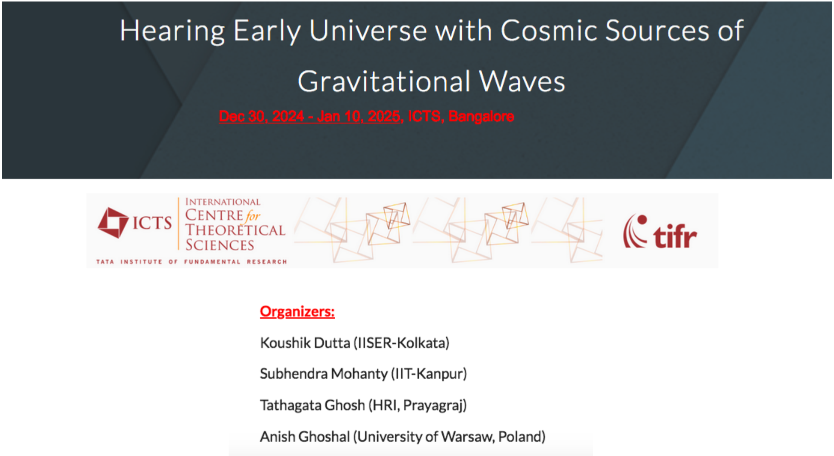
Summary:

- Any source of energy density in early can have primordial density fluctuations and if such fluctuations may be compactified inside a Schwarzchild critical mass and form Primordial Blackholes, we should not limit ourselves to inflation.
- Each source does not come for free, but its its corresponding stochastic GW signal, each of which looks different from each other in terms of GW spectral shapes.
- Data from Pulsar timing array have arrived to test your favorite cosmological models.
- Strong first-order phase transition can lead to both spinning and non-spinning PBH.
- Simple Axion-like Particle scenarios can be searched in 3-pronged complementarity: Lab searches, Gravitational Waves and Primordial Blackholes
- PBH can be the entire dark matter candidate of the universe in some parameter space. Or be two-component dark matter: ALP + PBH.
- Discovering ALP may mean huge constraints on PBH param space.
- Discovering PBH may mean constraints on ALP parameter space. KILL parameter space from PBH oberproduction when $f_{\rm PBH} > 1$.
- Other than Axion-like particles what could be other BSM scenarios involving Zprime, right handed neutrino, flavor physics that may lead of PBH formation and complementary laboratory searches.

Summary:

- NANOGrav and other PTA data sees evidence of stochastic GW background.
- astrophysical interpretation involves supermassive black holes with dynamical friction and dark matter density.
- cosmological interpretation involves any source of energy density in early can have primordial density fluctuations and if such fluctuations may be compactified inside a Schwarzchild critical mass and form Primordial Blackholes, we should not limit ourselves to inflation.
- Each source does not come for free, but its its corresponding stochastic GW signal, each of which looks different from each other in terms of GW spectral shapes.
- Very hard to form PBH in minimal single-field inflation and also satisfy NanoGRAV. Similar story goes with other sources.
- False vacuum phase transition leads to PBH and may explain the signal. Strong first-order phase transition can lead to both spinning and non-spinning PBH. No fine-tuning of initial conditions needed unlike single field inflation.
- particle physics interpretation involves axion physics leading to PBH and GW signals along with laboratory searches in complementary manner.
- Time has come to use data from Pulsar timing array to do serious cosmology, just like we do with BAO data, or PLANCK CMB data, or SNe data. Perhaps even combine PTA datasets with others for analysis.

Gravitational Waves Workshop in ICTS



Hearing Early Universe with Cosmic Sources of Gravitational Waves

Dec 30, 2024 - Jan 10, 2025, ICTS, Bangalore

Organizers:

Koushik Dutta (IISER-Kolkata)

Subhendra Mohanty (IIT-Kanpur)

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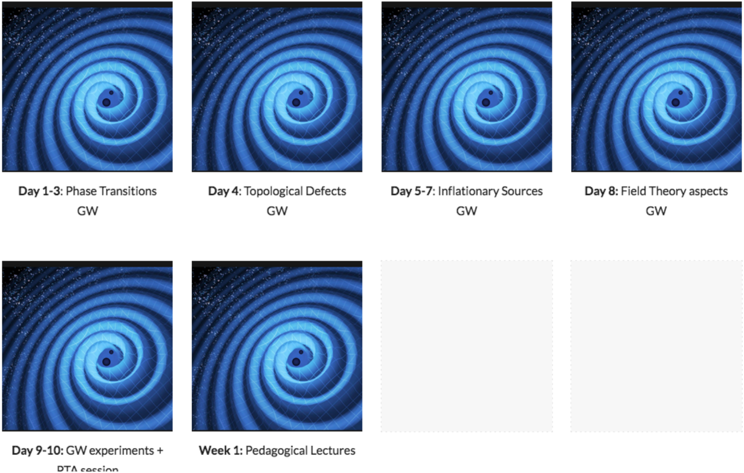
Gravitational Waves Workshop in ICTS

You are welcome, registration to open soon !!



Day 1-3: Phase Transitions GW

Day 4: Topological Defects GW

Day 5-7: Inflationary Sources GW

Day 8: Field Theory aspects GW

Day 9-10: GW experiments + PTA session

Week 1: Pedagogical Lectures

Thank You