Hearing the Universe Hum with Pulsar Timing Array:
Gravitational Waves from phase transition and Primordial Black Hole formation

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Corfu, Greece September 2024

Outline of the talk:

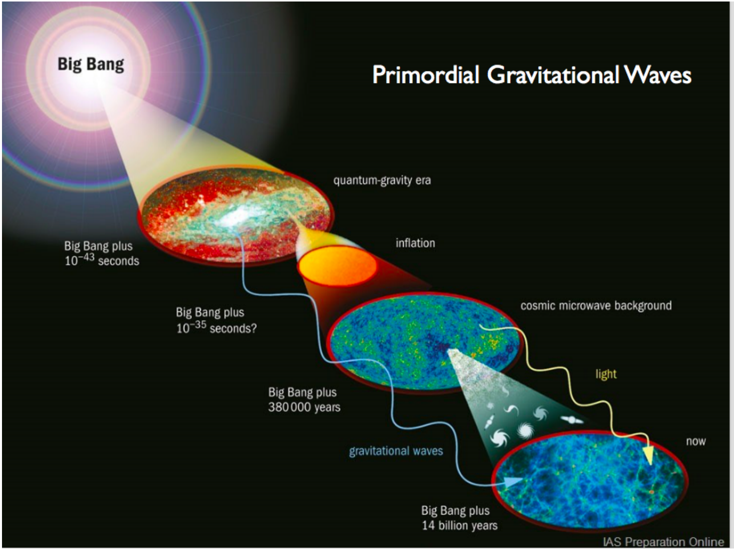
- Sources of Primordial Gravitational Waves
- Measurement of Stochastic GW background at Pulsar Timing Array
- Astrophysical Interpretation: supermassive black holes
- Cosmological Interpretation: strong first-order phase transition
- Primordial Blackholes from strong first order phase transition.
- 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

Disclaimer: separate analysis.

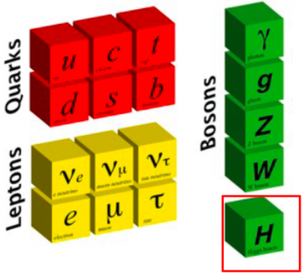
History of the Universe



History of the Universe

History of the Universe

The Standard Model.



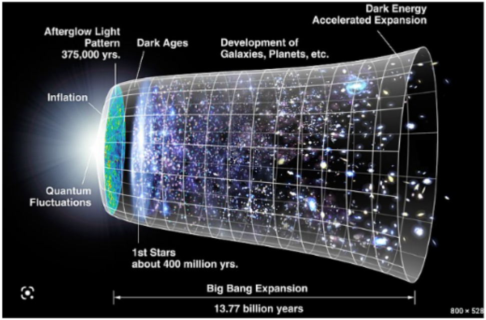
1961–1968

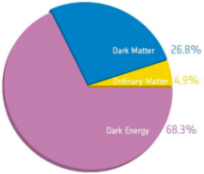
The Standard Model is very successful.

Many experimental tests. No cracks yet.

History of the Universe

Cosmos

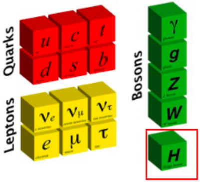




A standard model of cosmology.

History of the Universe

Open questions in the Standard Model



Very nice, but it looks like chemistry to me.

Hierarchy, nautralness

Flavor structure

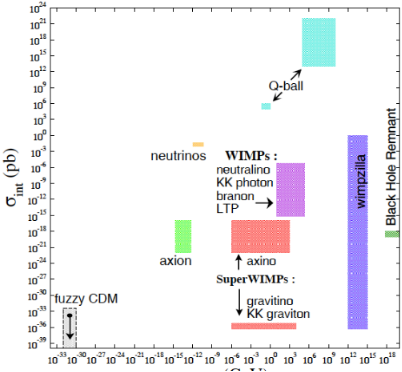
CP violation

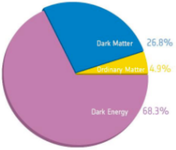
Unification? . . .

What gives us the Standard Model?

History of the Universe

Dark world

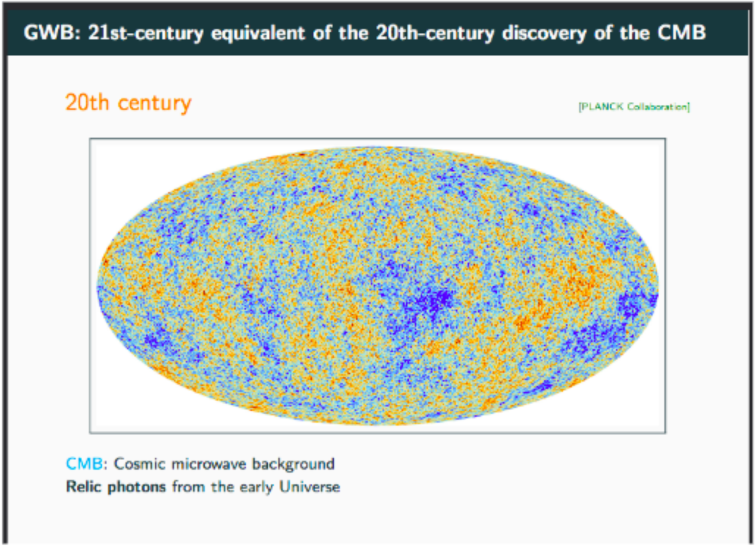




Vast gaps!

Need more lampposts!

History of the Universe

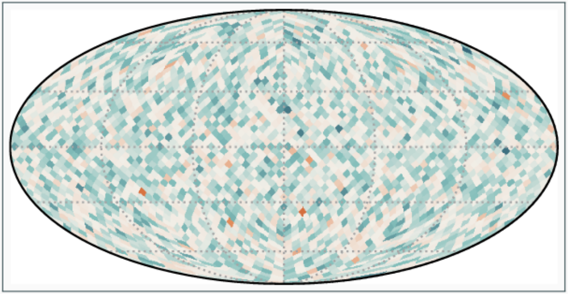


History of the Universe

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

21th century

[Sato-Polito, Kamionkowski: 2305.05690]



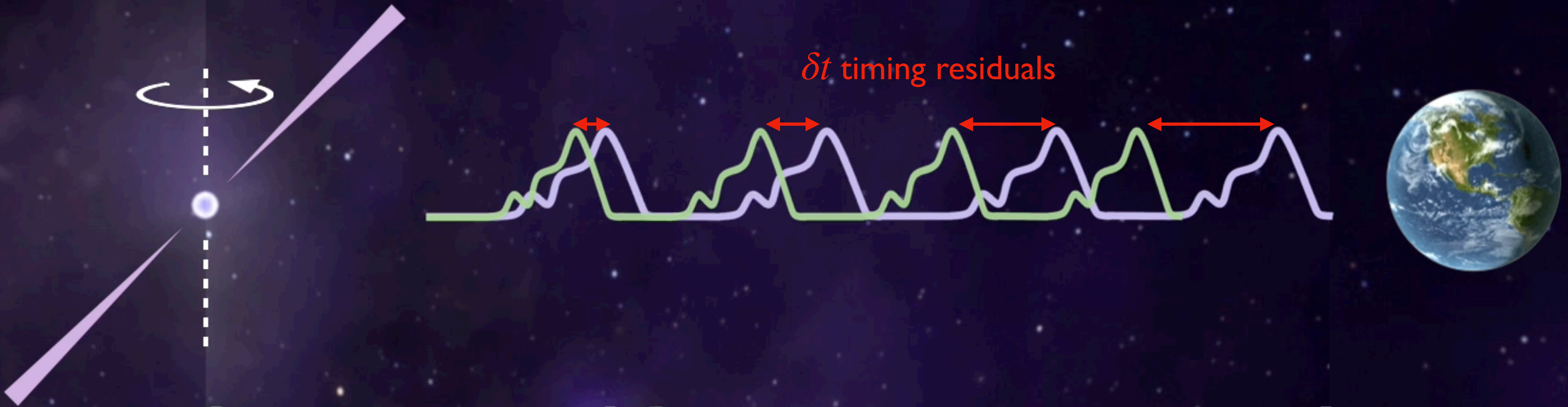
GWB: Gravitational-wave background

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

PULSARS

Animation by NASA's Goddard Space Flight Center

TIMING RESIDUALS



Pulses expected from Timing Model

Pulses Recorded by Radio Telescope

A GALAXY-SIZE DETECTOR FOR GWs

67 pulsars observed by NG

observing baseline of 15 yrs

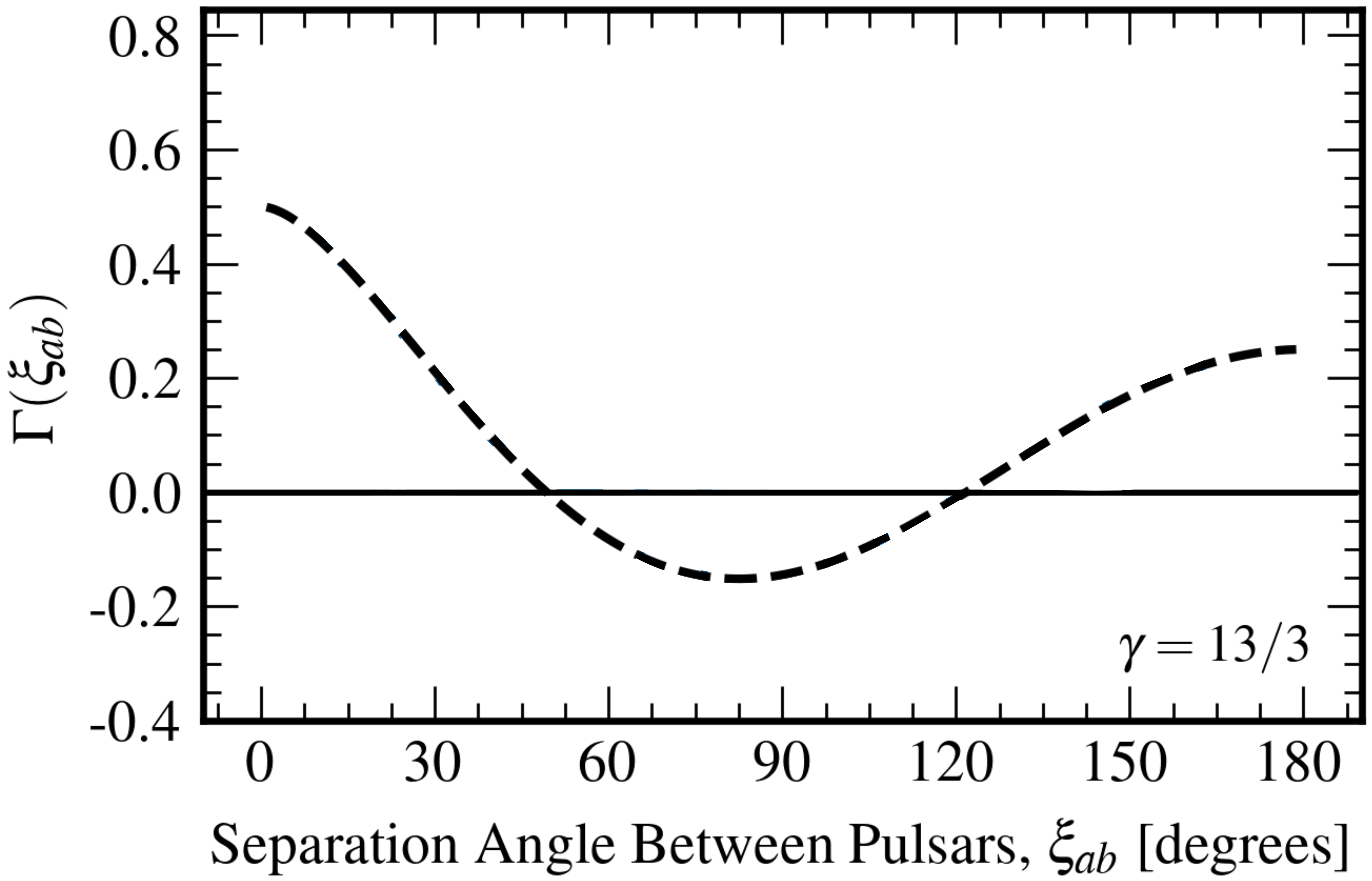
distance to pulsars up to ~kpc

IPTA DR3 will contain >100 pulsars

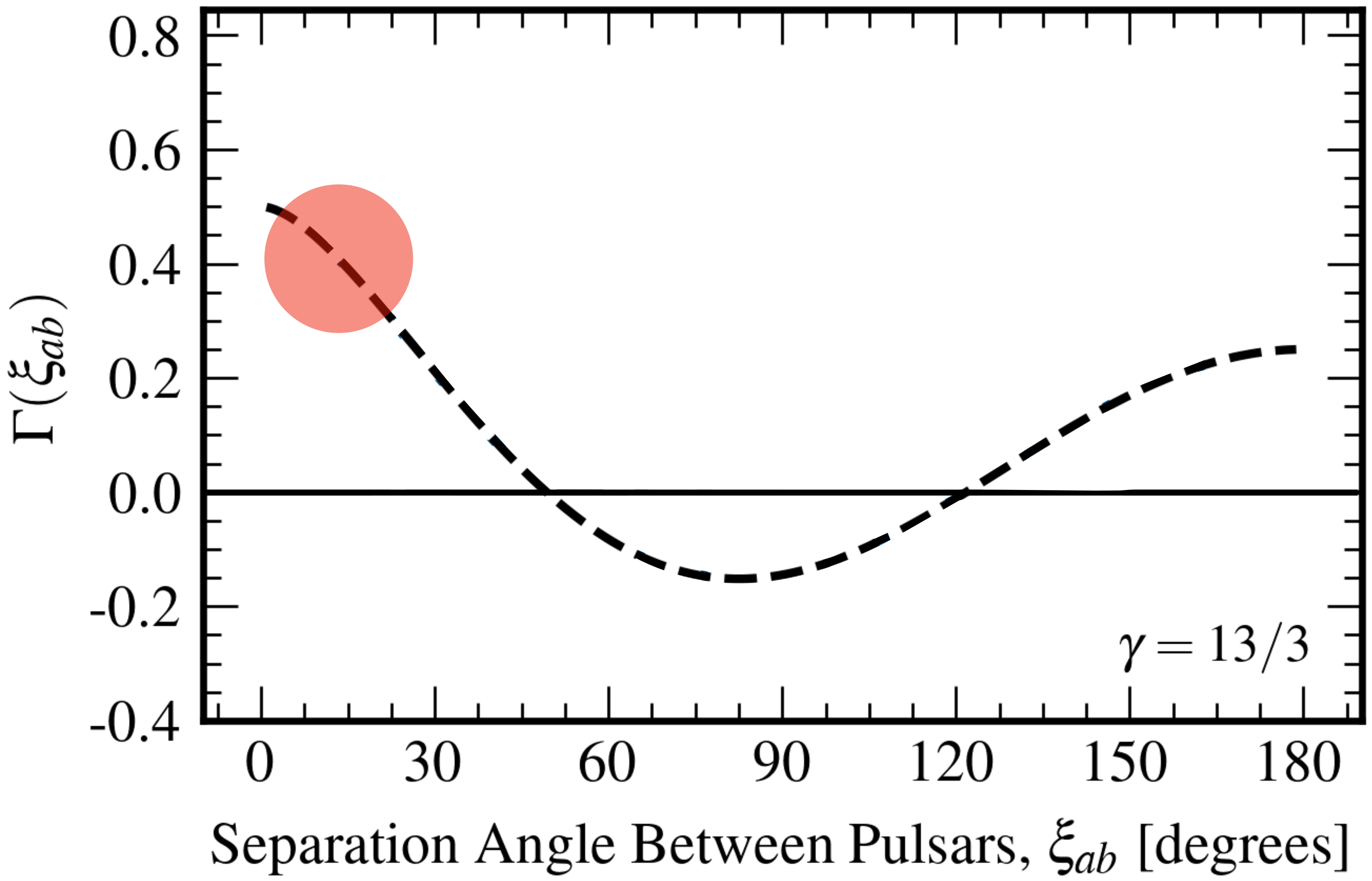
Animation by NSF

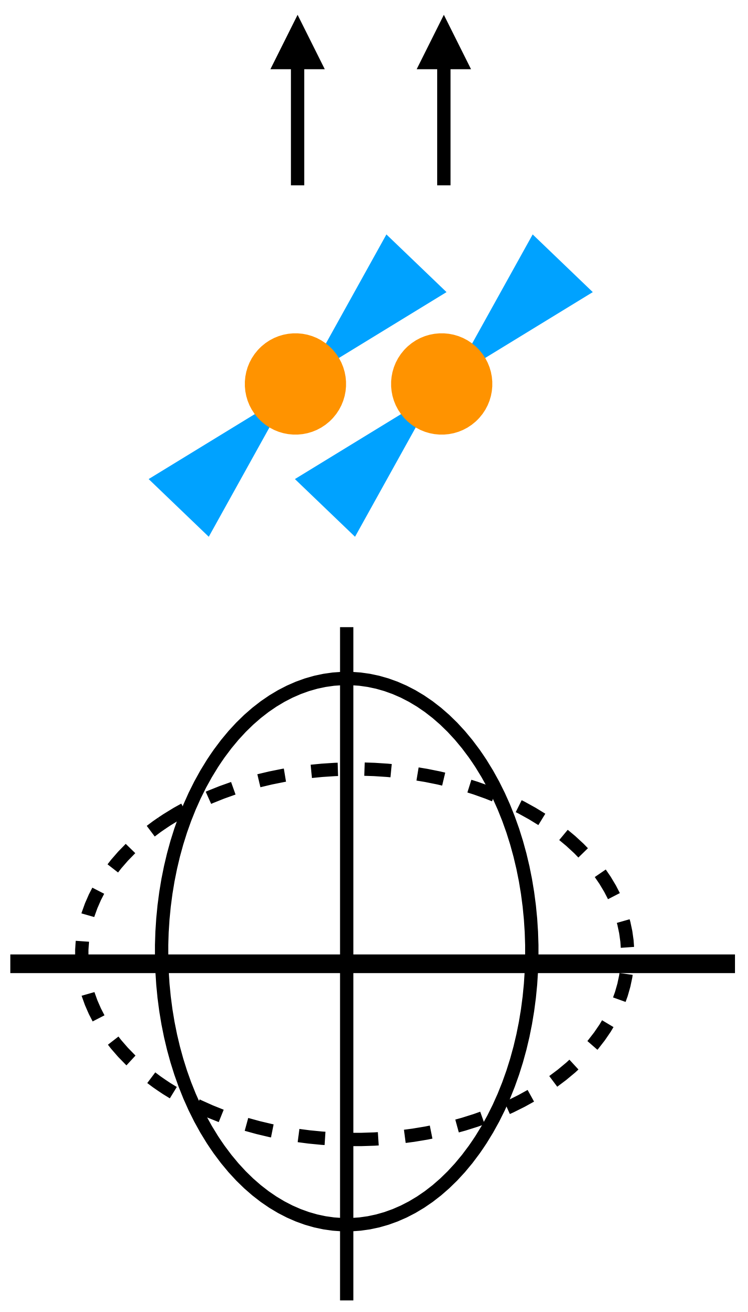
credits Keyi "Onyx" Li / NSF / NANOGrav

HELLINGS & DOWNS CURVE



HELLINGS & DOWNS CURVE





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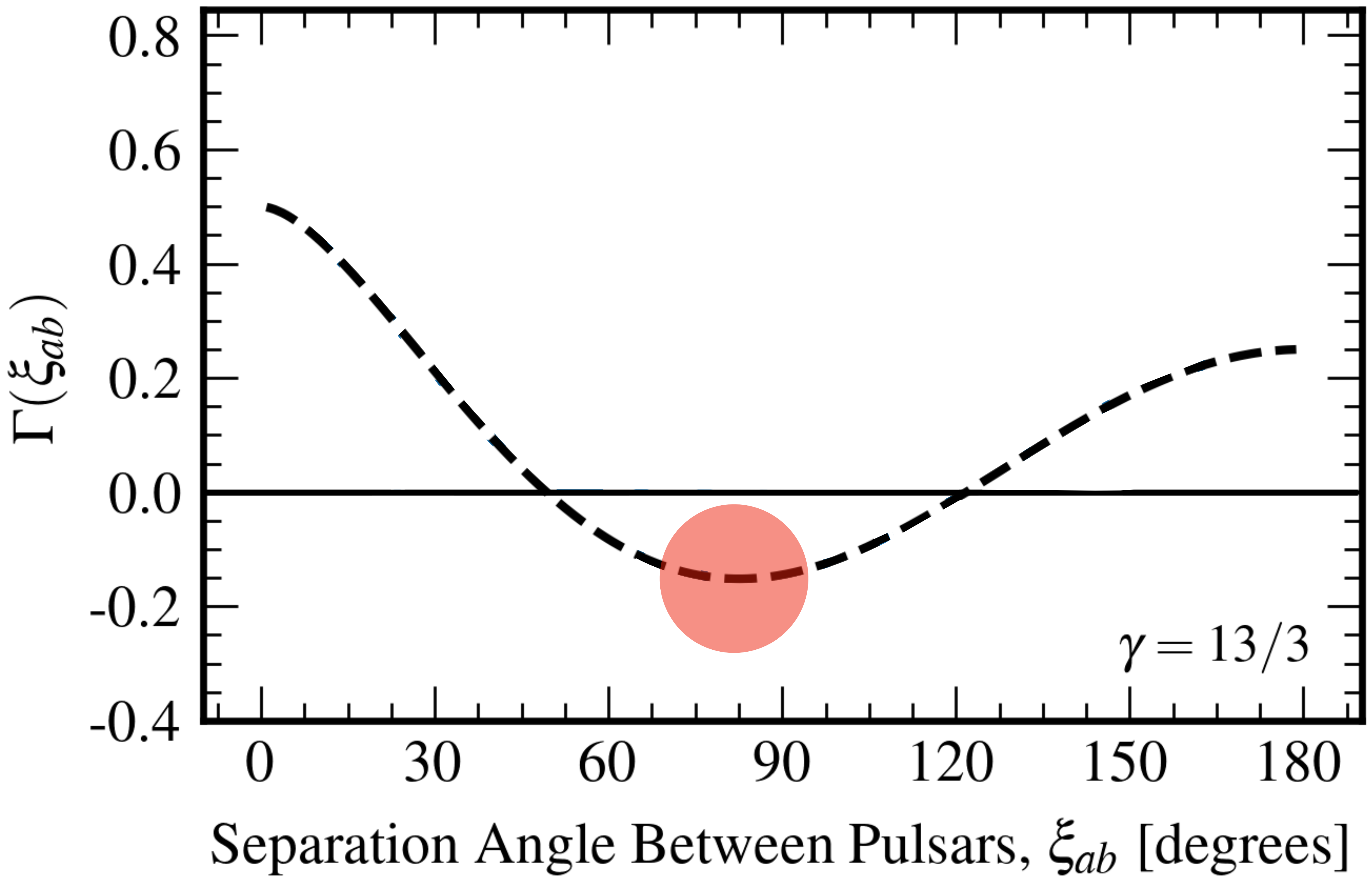

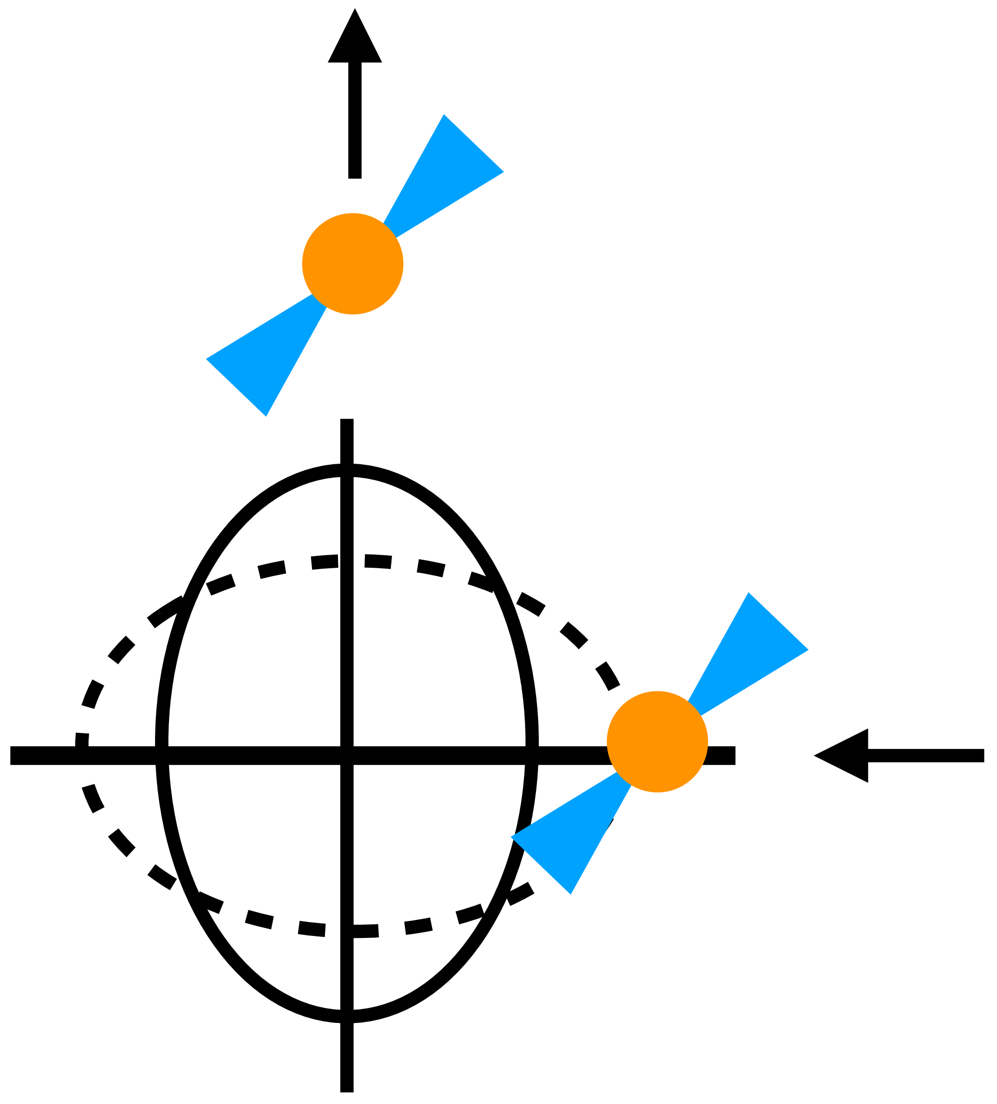

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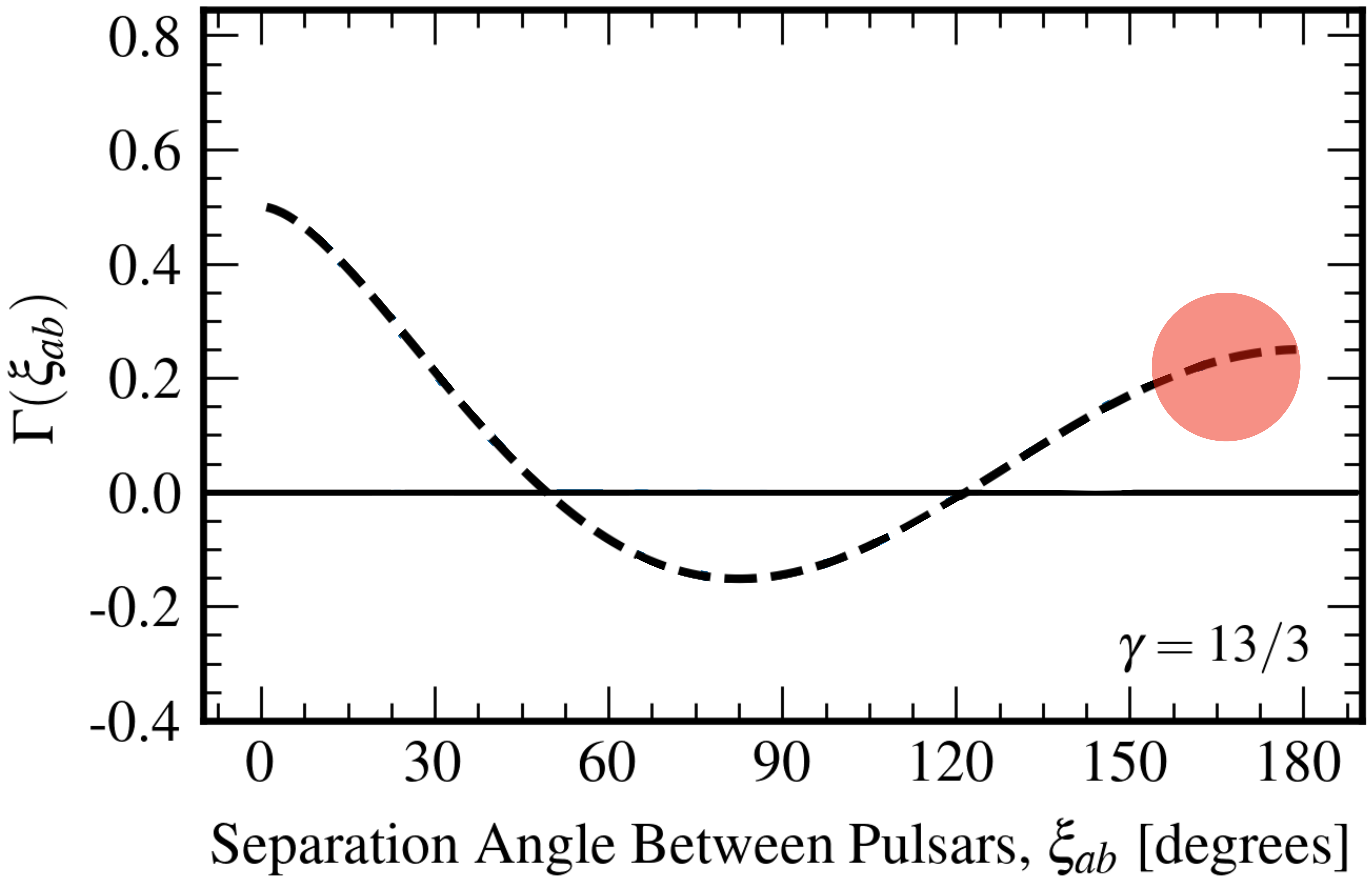
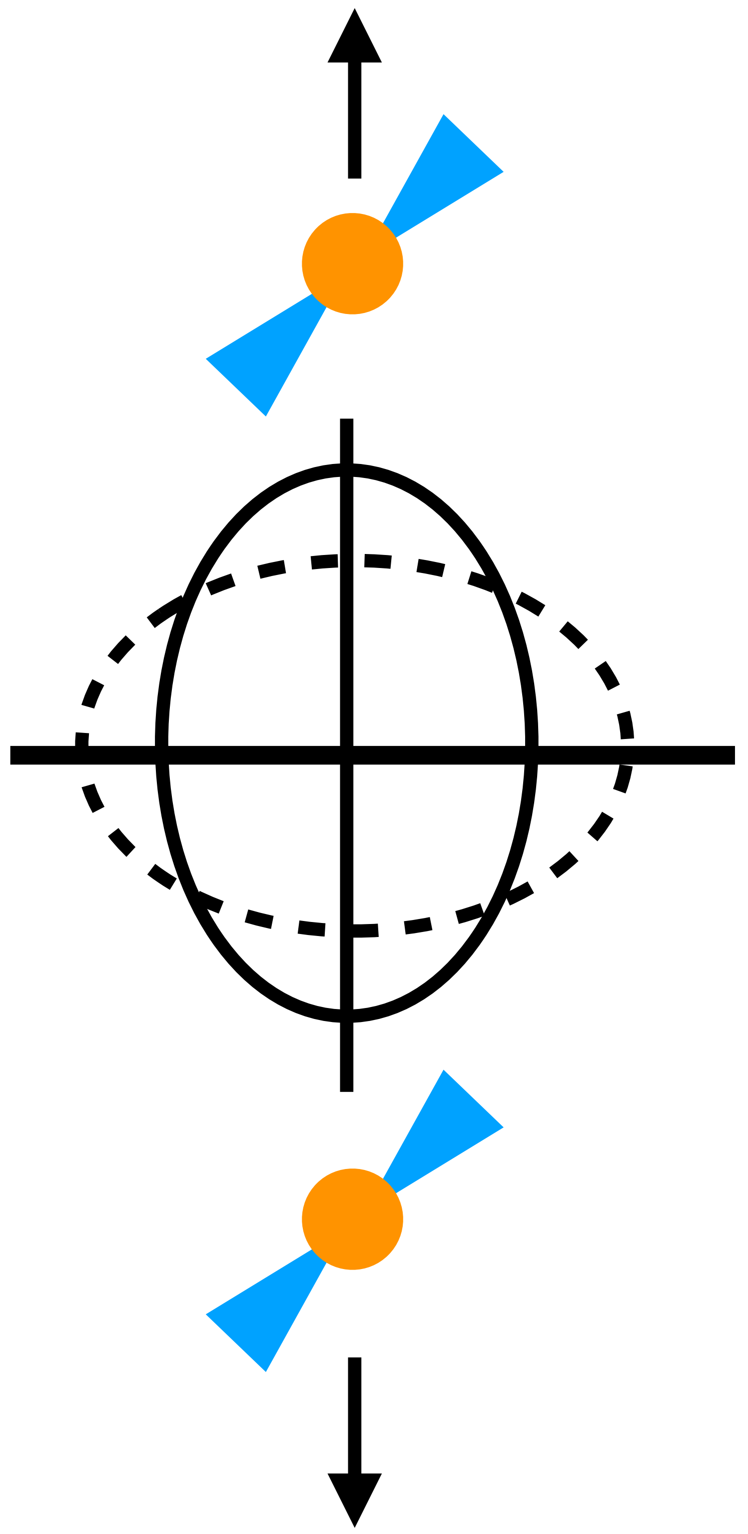
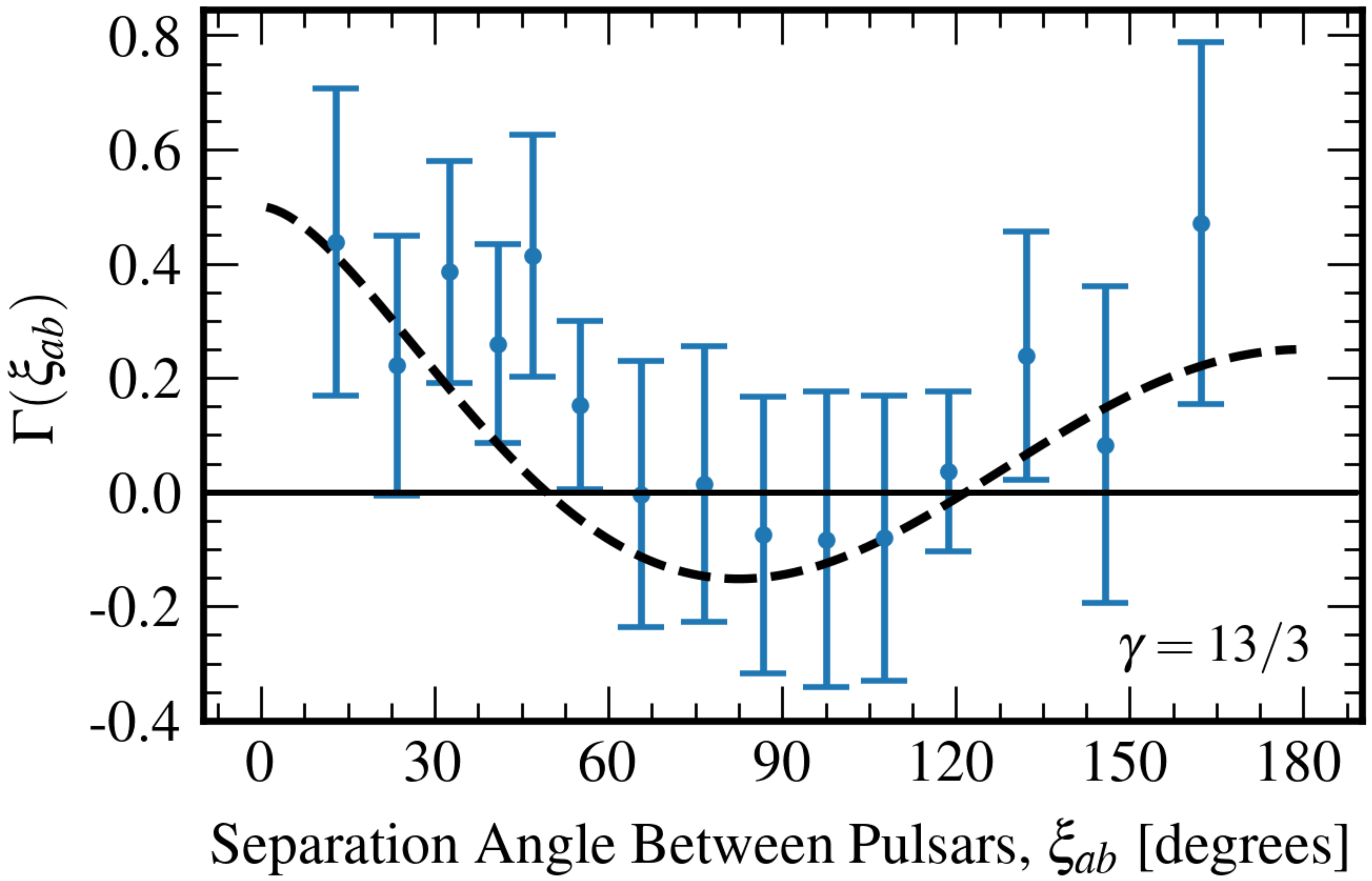




EVIDENCE FOR GWB

Agazie et al. [2306.16213]



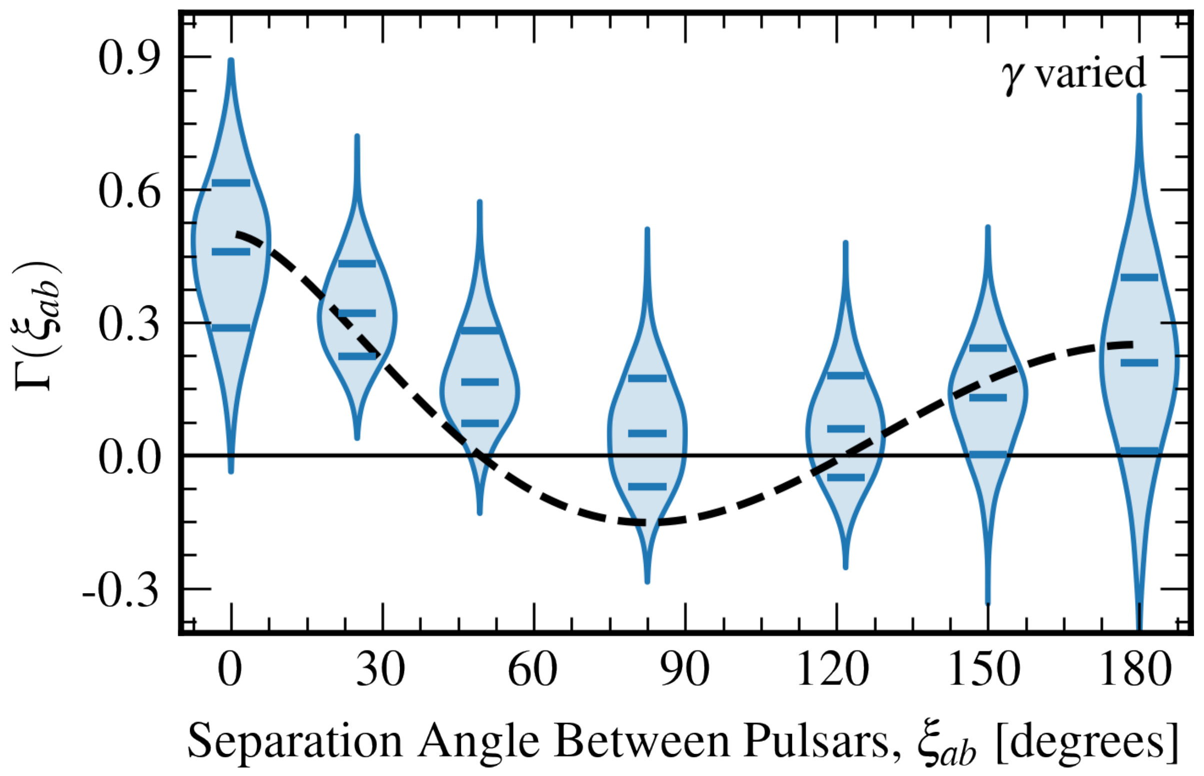
EVIDENCE FOR GWB

NANOGrav:

68 pulsars, 16yr of data

~3-4σ significance

Agazie et al. [2306.16213]

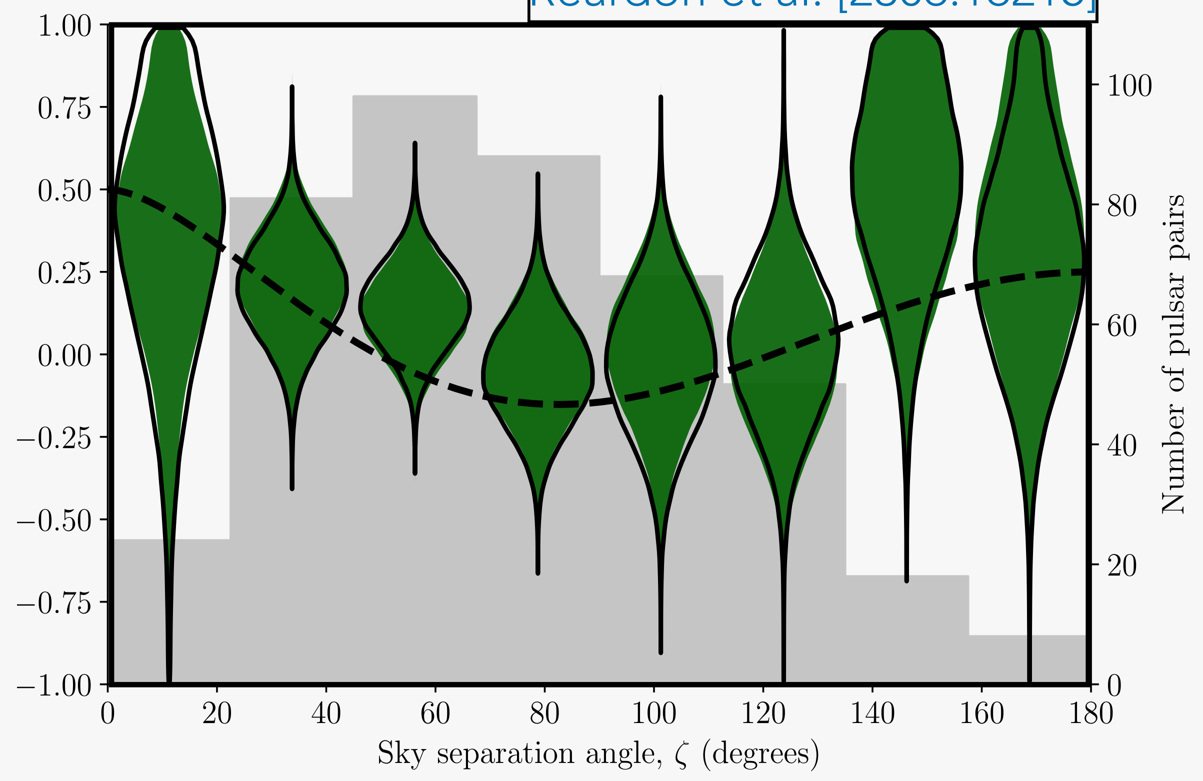


PPTA:

32 pulsars, 18yr of data

~2σ significance

Reardon et al. [2306.16215]

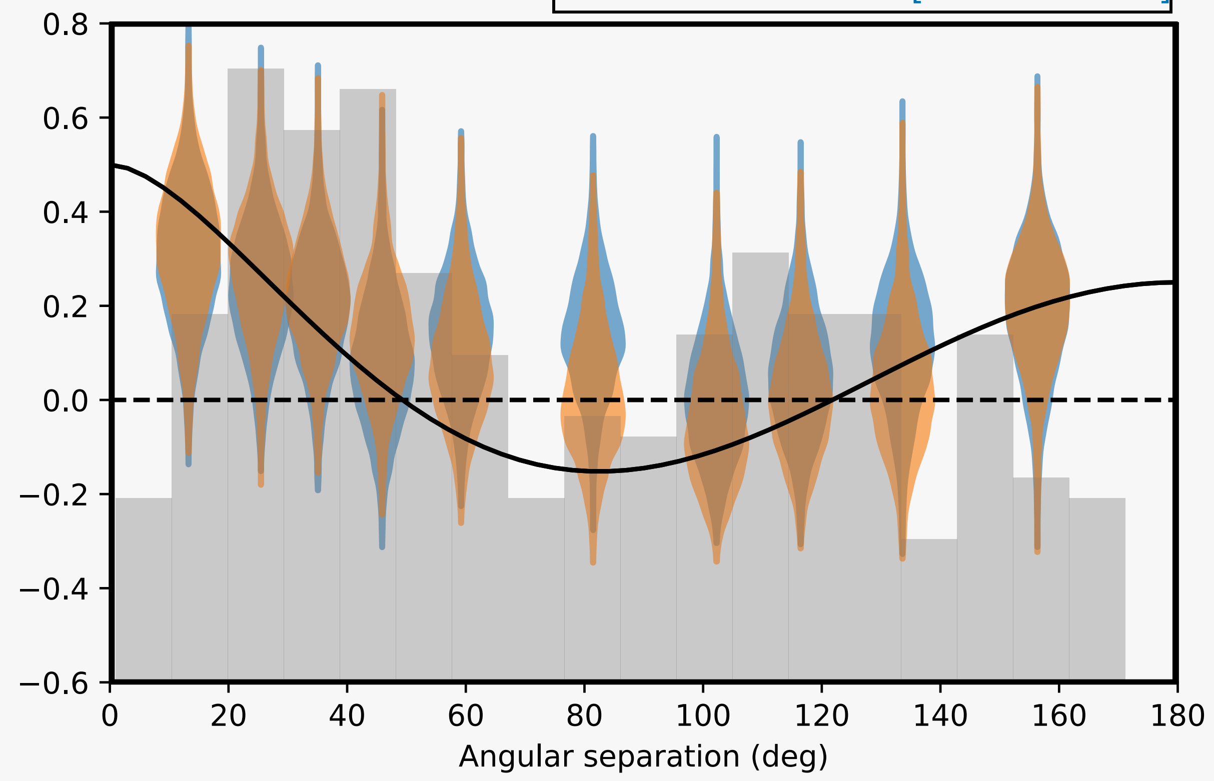


EPTA + InPTA:

25 pulsars, 24yr of data

~3σ significance

Antoniadis et al. [2306.16214]

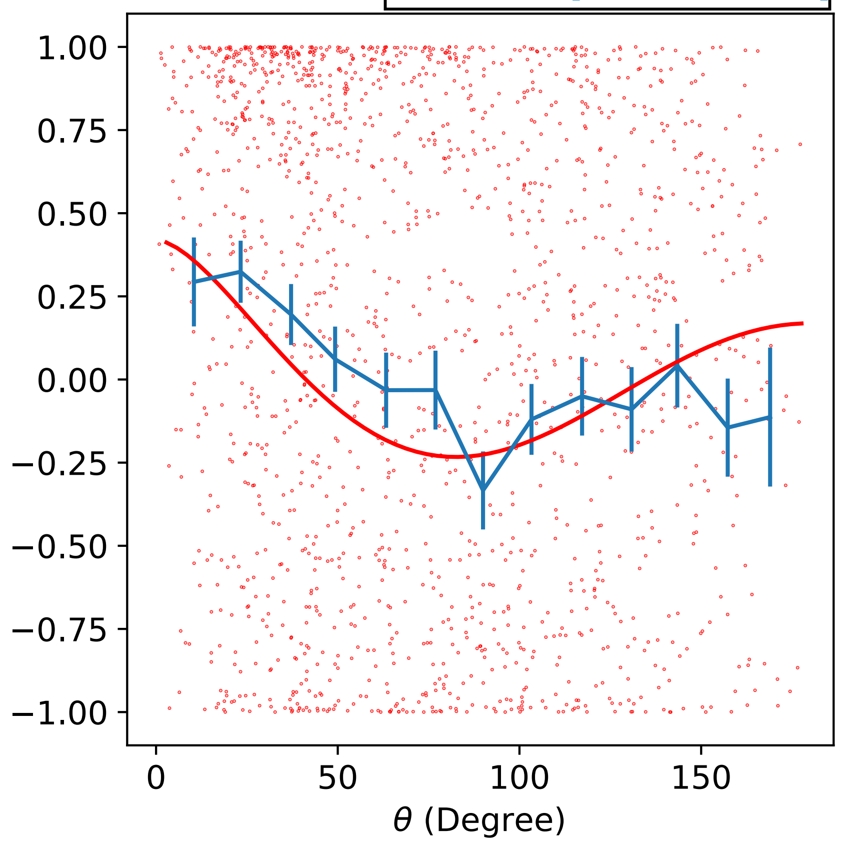


CPTA:

57 pulsars, 3yr of data

~4.6σ significance

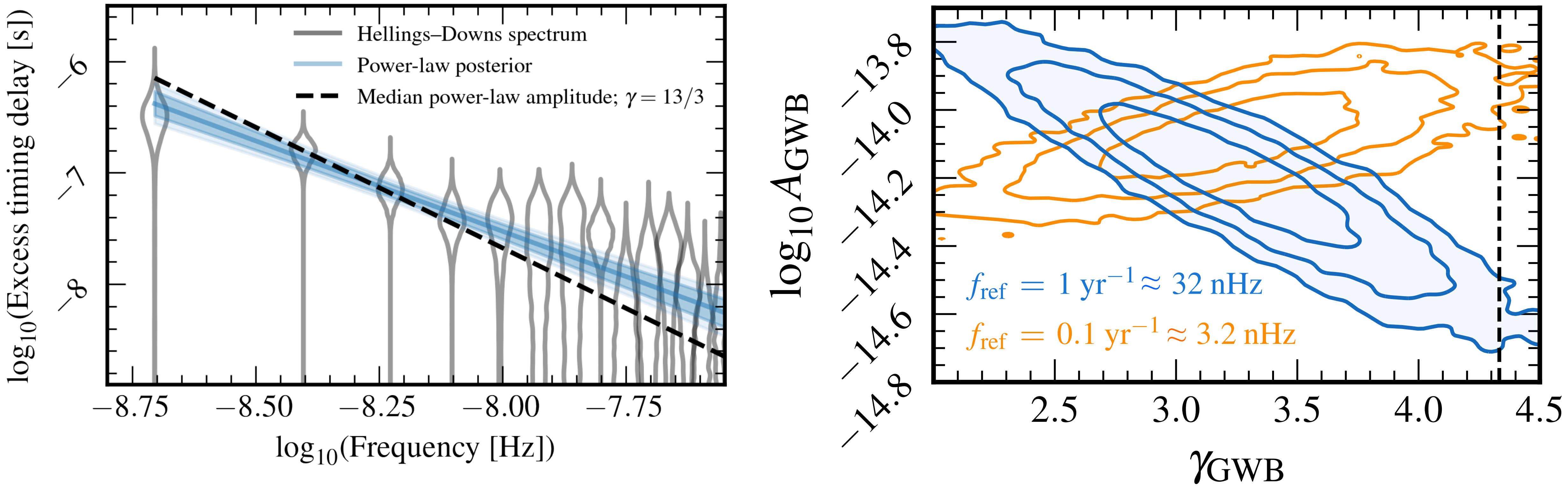
Xu et al. [2306.16216]



SPECTRUM

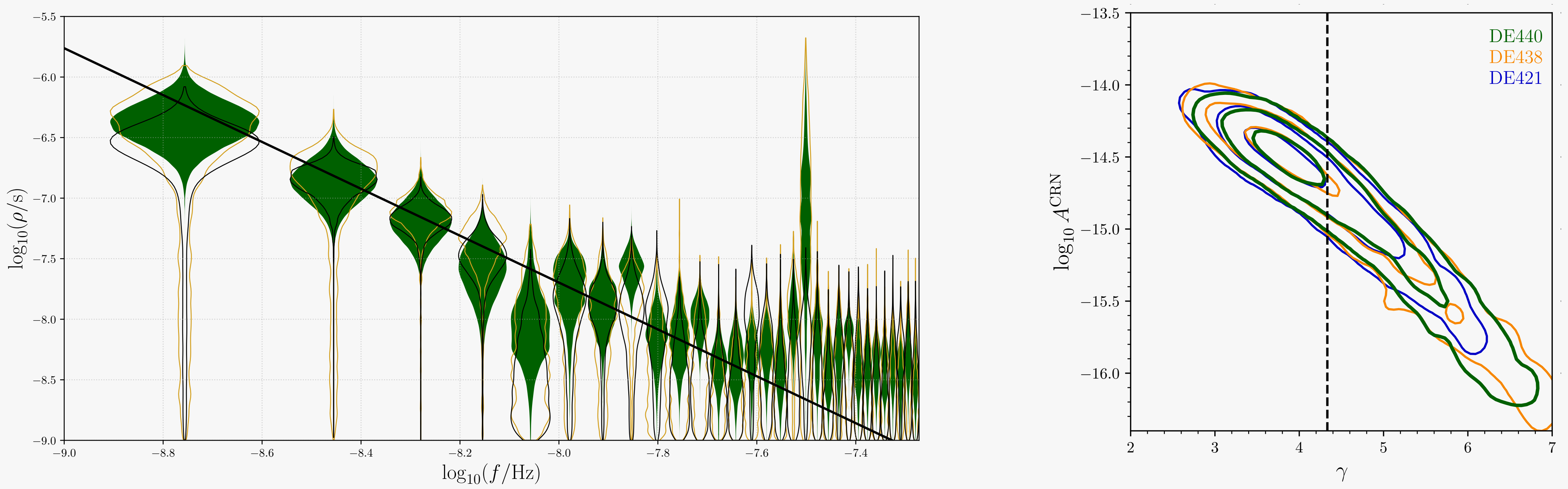
NANOGrav

Agazie et al. [2306.16213]



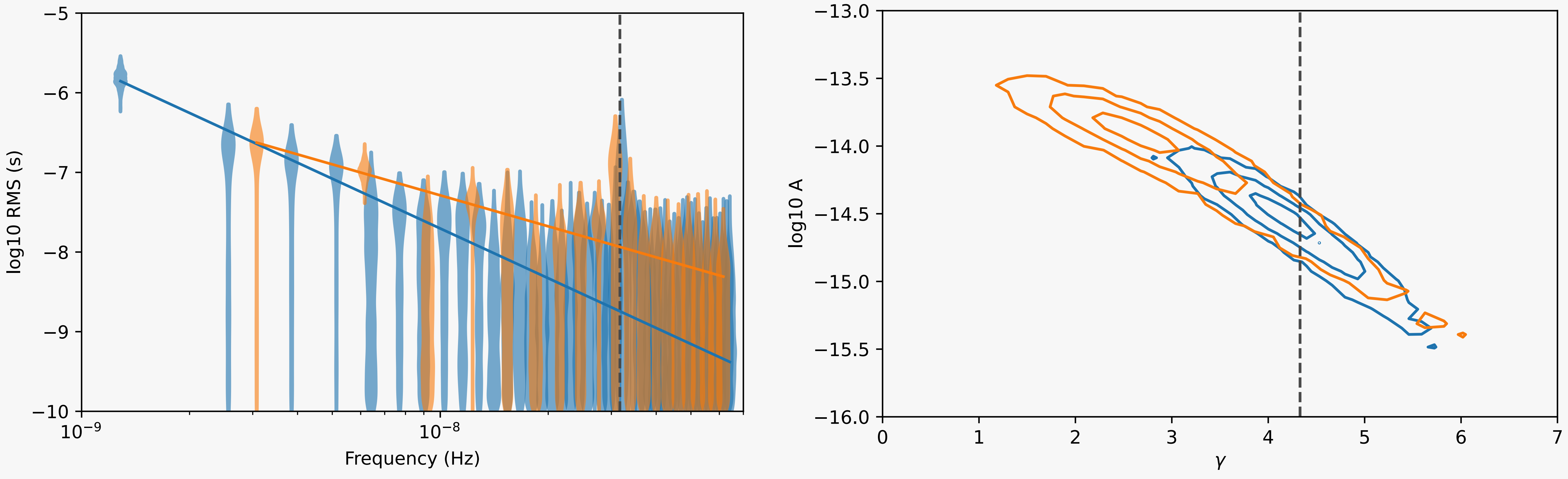
PPTA

Reardon et al. [2306.16215]



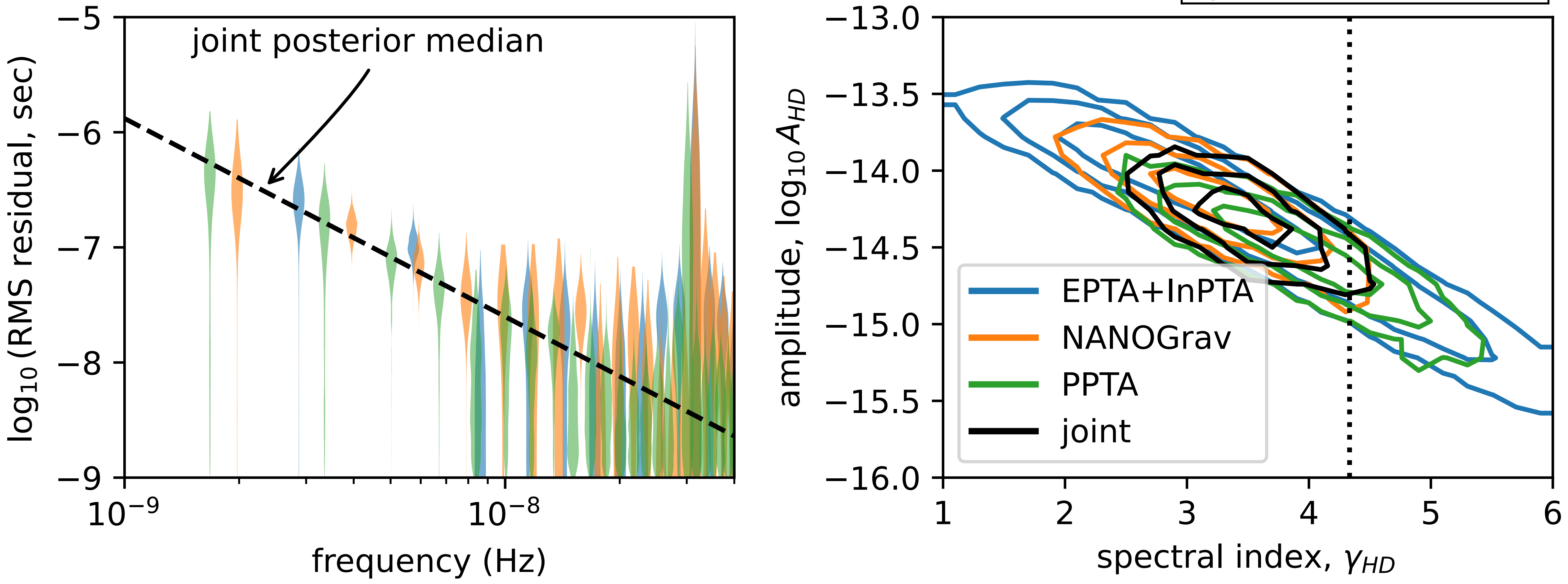
EPTA + InPTA

Antoniadis et al. [2306.16214]



IPTA early data combination

Agazie et al. [2309.00693]

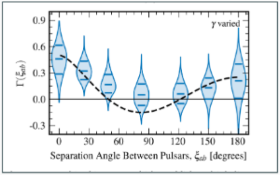


what is the source?

History of the Universe

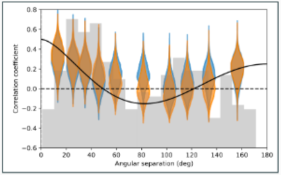
LIGO observed GW of astrohysical origin, we in PTA see stochastic GW background.

2306.16213: NANOGrav



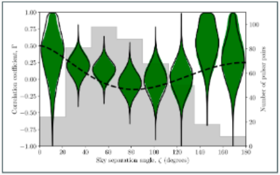
68 pulsars, 16 yr of data, HD at $\sim 3\cdots4\,\sigma$

2306.16214: EPTA+InPTA



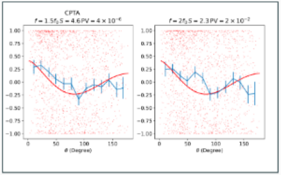
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



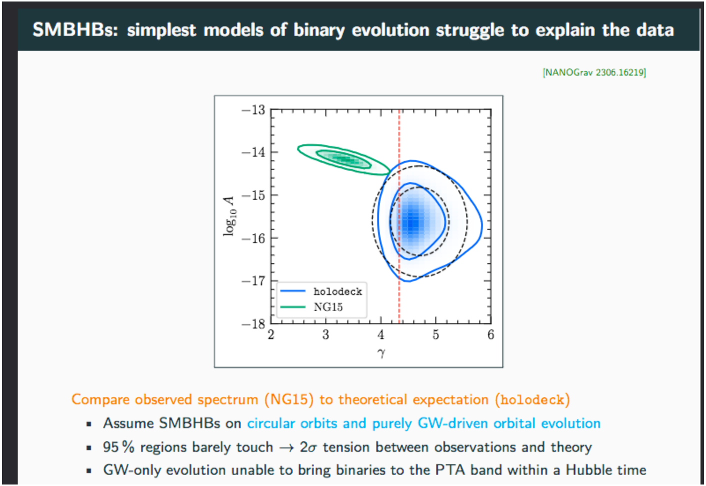
32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

2306.16216: CPTA



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

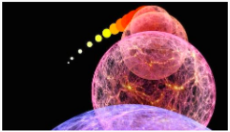
History of the Universe



History of the Universe

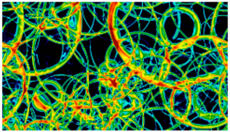
Inflation

- Nonminimal blue-tilted models
- Interplay with CMB observables



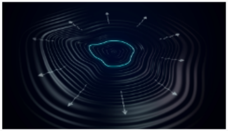
Phase transition

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



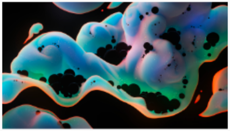
Cosmic defects

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

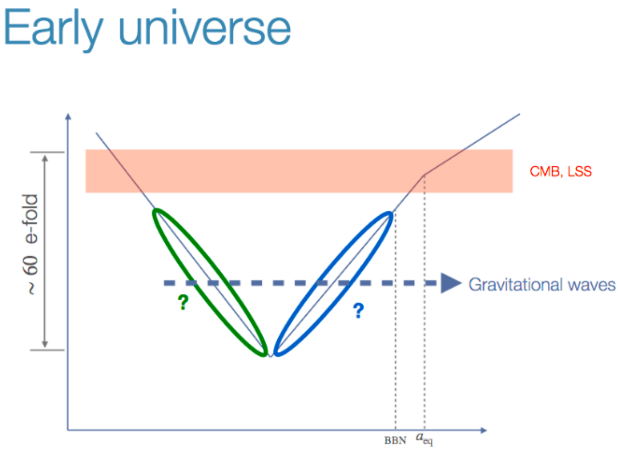


Scalar perturbations

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

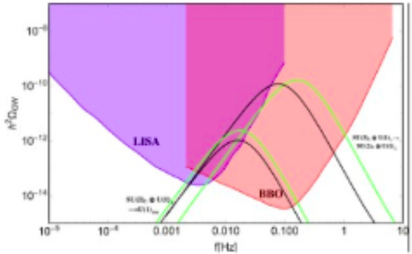


History of the Universe



History of the Universe

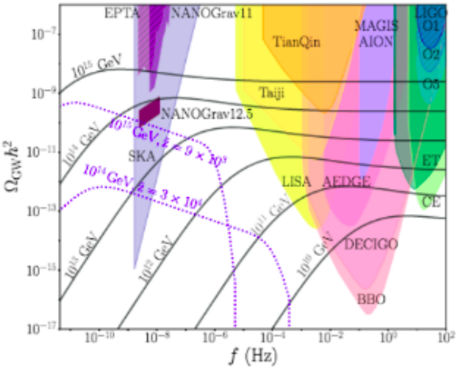
Typical GW spectrum from thermal first-order phase transition:



Huang (2018)

History of the Universe

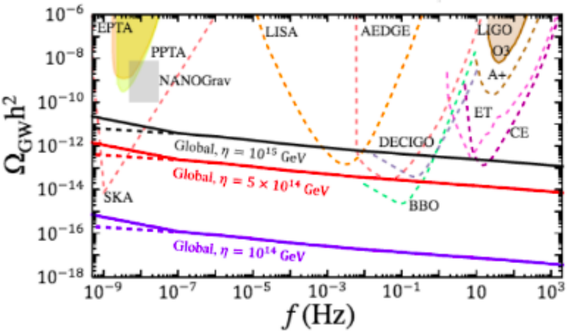
Topological defects like cosmic strings can be formed in early universe when some gauge $U(1)_X$ symmetry is broken in early universe. It give rise to scale invariant GW spectrum. Detection prospects lies on the symmetry breaking scale vev.



King (2020)

History of the Universe

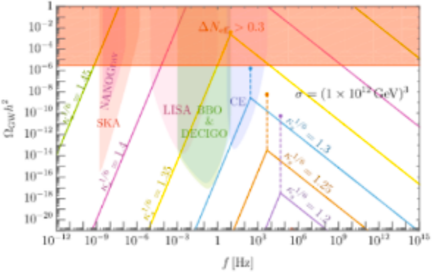
Topological defects like cosmic strings can be formed in early universe when some global $U(1)_X$ symmetry is broken in early universe. Detection prospects lies on the symmetry breaking scale vev which needs to be very high.



Cui (2021)

History of the Universe

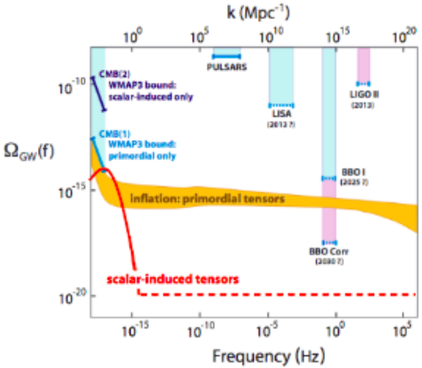
Topological defects like Domain Walls are formed when a discrete symmetry is broken and give rise to GW spectrum may look something like this (still under active research topic). Detection prospects lies of symmetry breaking scale as well as the asymmetry term in the potential, like cubic term.



Dunsky at. al. (2021)

History of the Universe

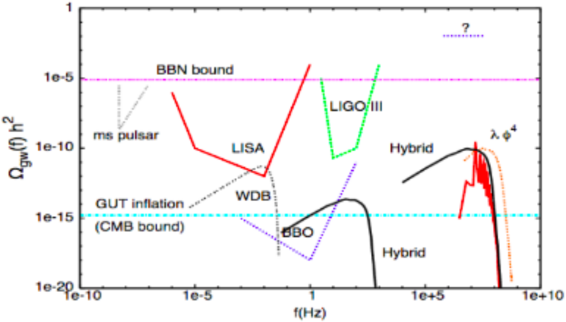
Primary Tensor Perturbations and Secondary Tensor Spectrum induced by first-order scalar perturbation via mixing. Can be tuned to generate high amplitude in high frequency regions. Acts as natural probes of particle models like Higgs inflation, axion inflation, MSSM inflation, etc.



Baumann (2007)

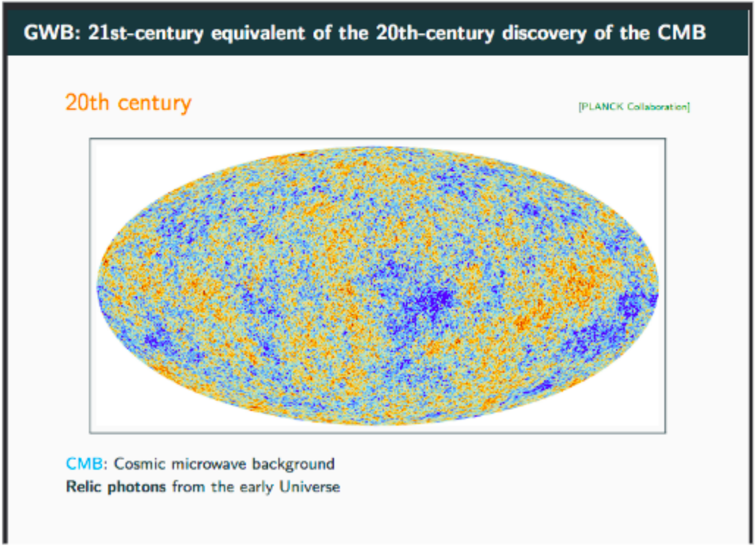
History of the Universe

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)

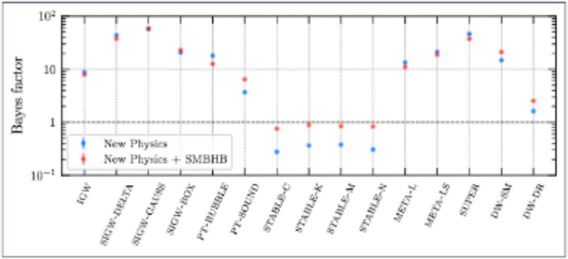
History of the Universe



History of the Universe

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

[NANOGrav 2306.16219] [See also: EPTA 2306.16227]

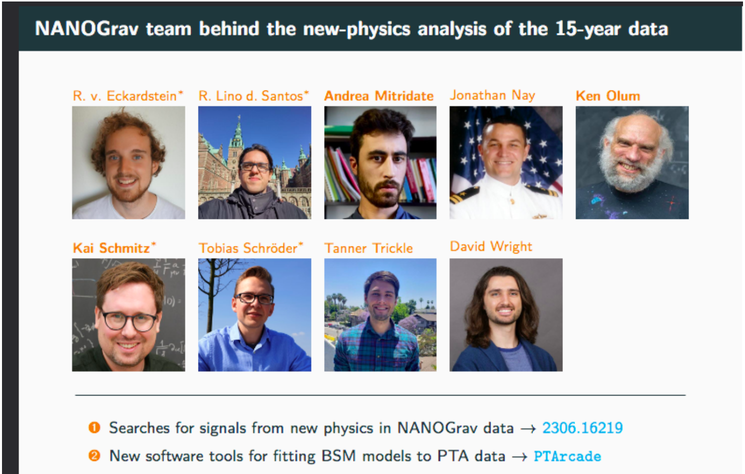


Bayesian model comparison

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

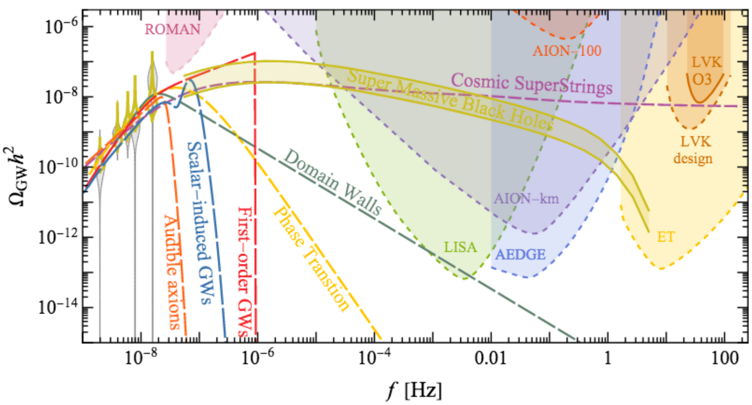
- Many BSM models reach Bayes of order $10 \cdots 100$.
- Interesting but not conclusive. Lots of uncertainties in SMBHB and BSM models.
- Bayes factors are sensitive to prior choices. No unique null distribution for $\mathcal{H}_0$.

History of the Universe



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

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

[a] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Poland*

[b] *Dipartimento di Fisica, Università di Pisa, Italia*

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

Tathagata Ghosh,[1,*] Anish Ghoshal,[2,†] Huai-Ke Guo,[3,‡] Fazlollah Hajkarim,[4,§] Stephen F King,[5,¶] Kuver Sinha,[4,**] Xin Wang,[5,††] and Graham White[5,‡‡]

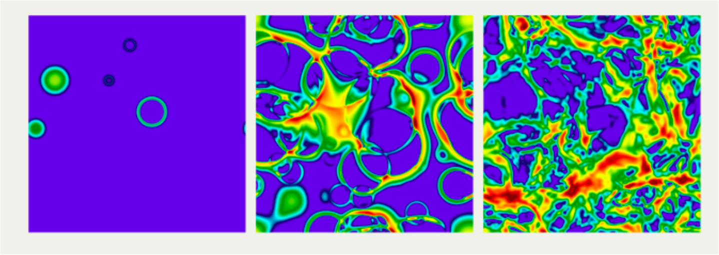
[1]*Harish-Chandra Research Institute,*
A CI of Homi Bhabha National Institute, Chhatnag Road, Jhusi, Prayagraj 211019, India
[2]*Institute of Theoretical Physics, Faculty of Physics, University of Warsaw,*
ul. Pasteura 5, 02-093 Warsaw, Poland
[3]*International Centre for Theoretical Physics Asia-Pacific,*
University of Chinese Academy of Sciences, 100190 Beijing, China
[4]*Homer L. Dodge Department of Physics and Astronomy,*
University of Oklahoma, Norman, OK 73019, USA
[5]*School of Physics and Astronomy, University of Southampton,*
Southampton SO17 1BJ, United Kingdom

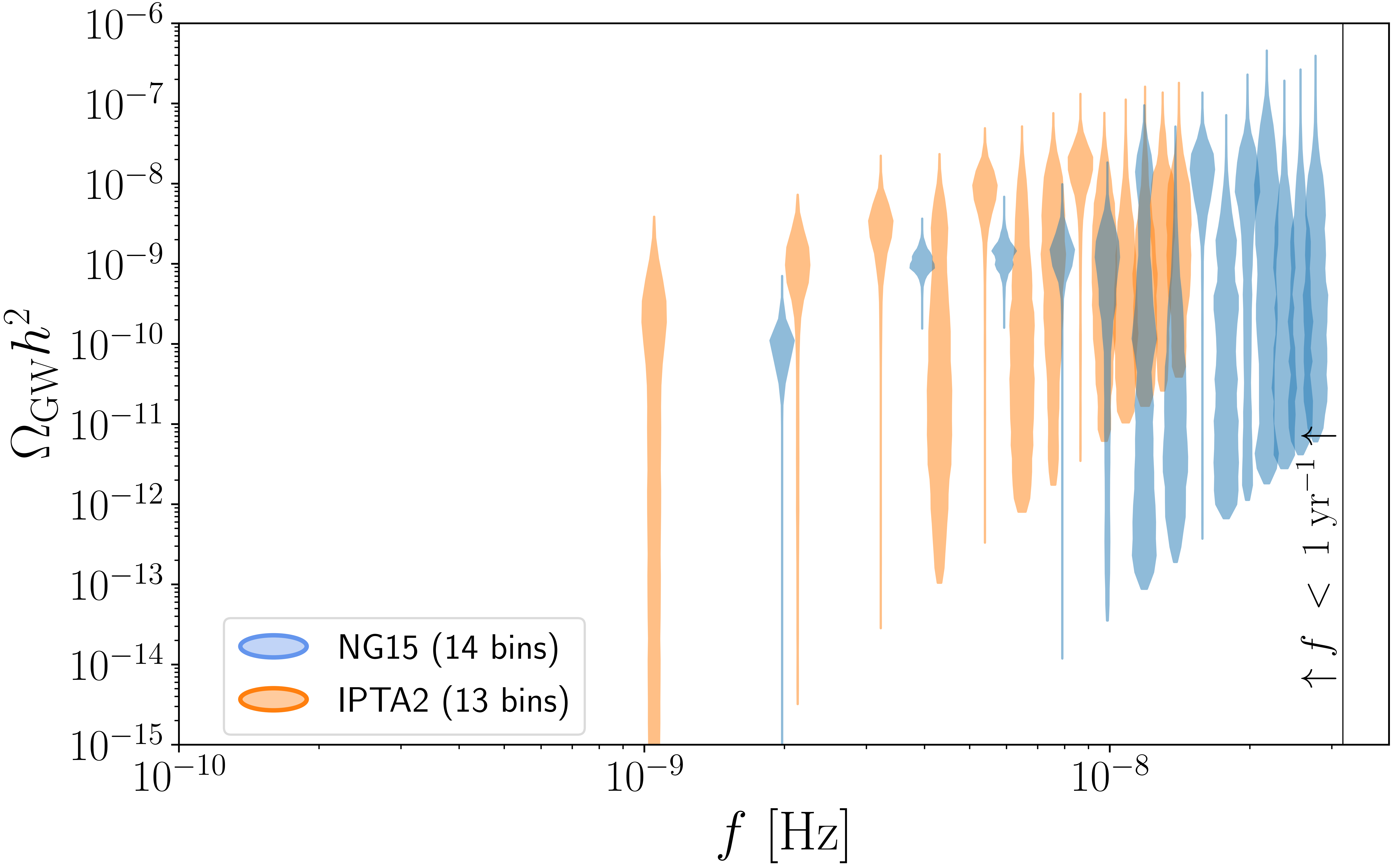
(Dated: July 6, 2023)

History of the Universe

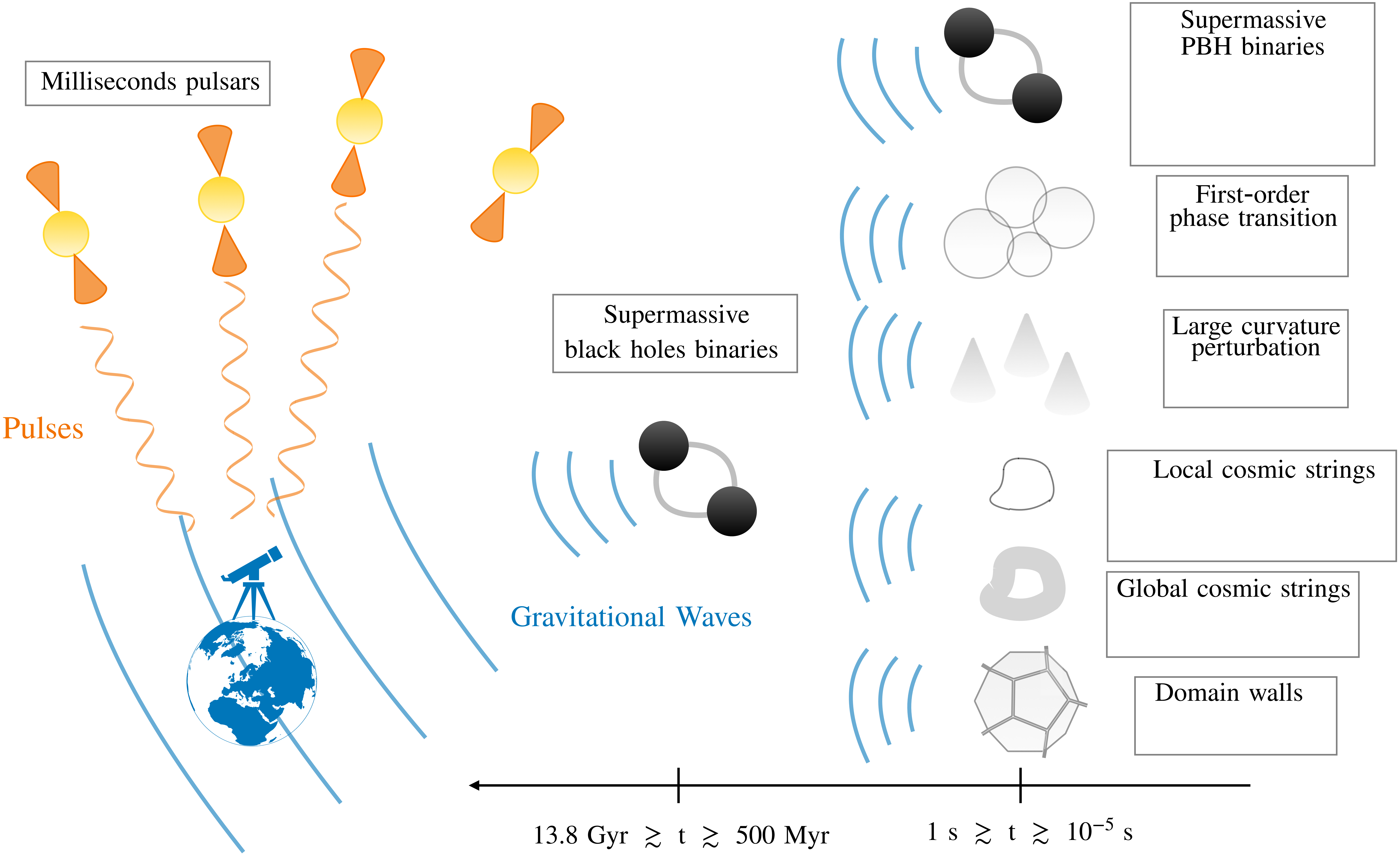
Phase Transitions:

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





$\Omega_{\rm GW}h^2$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-10}
10^{-9}
10^{-8}
f [Hz]
NG15 (14 bins)
IPTA2 (13 bins)
$\leftarrow f < 1\,{\rm yr}^{-1} \rightarrow$



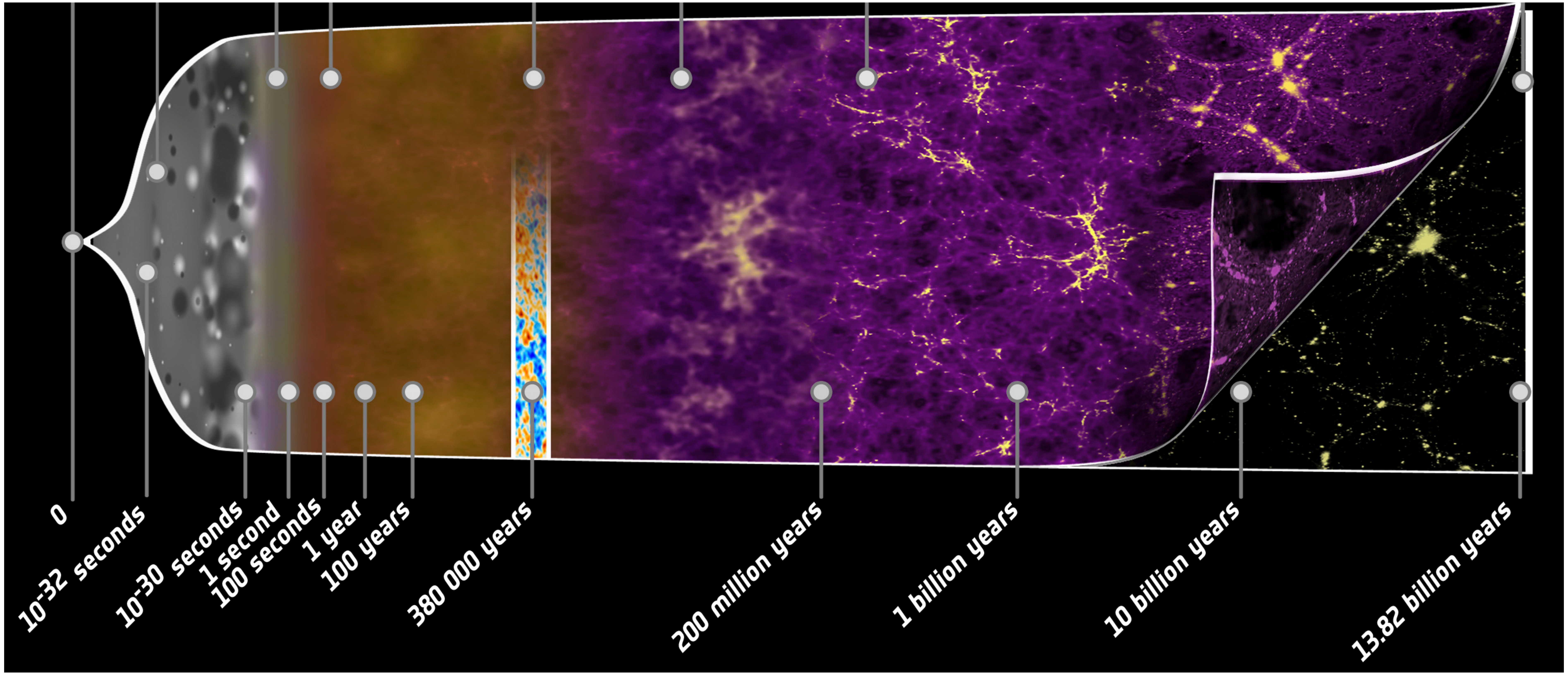
Milliseconds pulsars
Pulses
Supermassive black holes binaries
Gravitational Waves
Supermassive PBH binaries
First-order phase transition
Large curvature perturbation
Local cosmic strings
Global cosmic strings
Domain walls
13.8 Gyr $\gtrsim$ t $\gtrsim$ 500 Myr
1 s $\gtrsim$ t $\gtrsim$ 10^{-5} s

What is Primordial Black Holes ?

→ **BH formed before any astrophysical objects exists**

PBH formation $z \gg 10^3$

Star formation $z \lesssim 30$



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 :

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

$H^{-1} \equiv R_\mathrm{H}$

$\frac{4\pi H^{-3}}{3}\rho \equiv M_\mathrm{H}$

How do they form ?

Friedmann's equation :

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

How do they form ?

Friedmann's equation :

$$\Updownarrow$$

Schwarschild's equation

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

How do they form ?

Friedmann's equation :

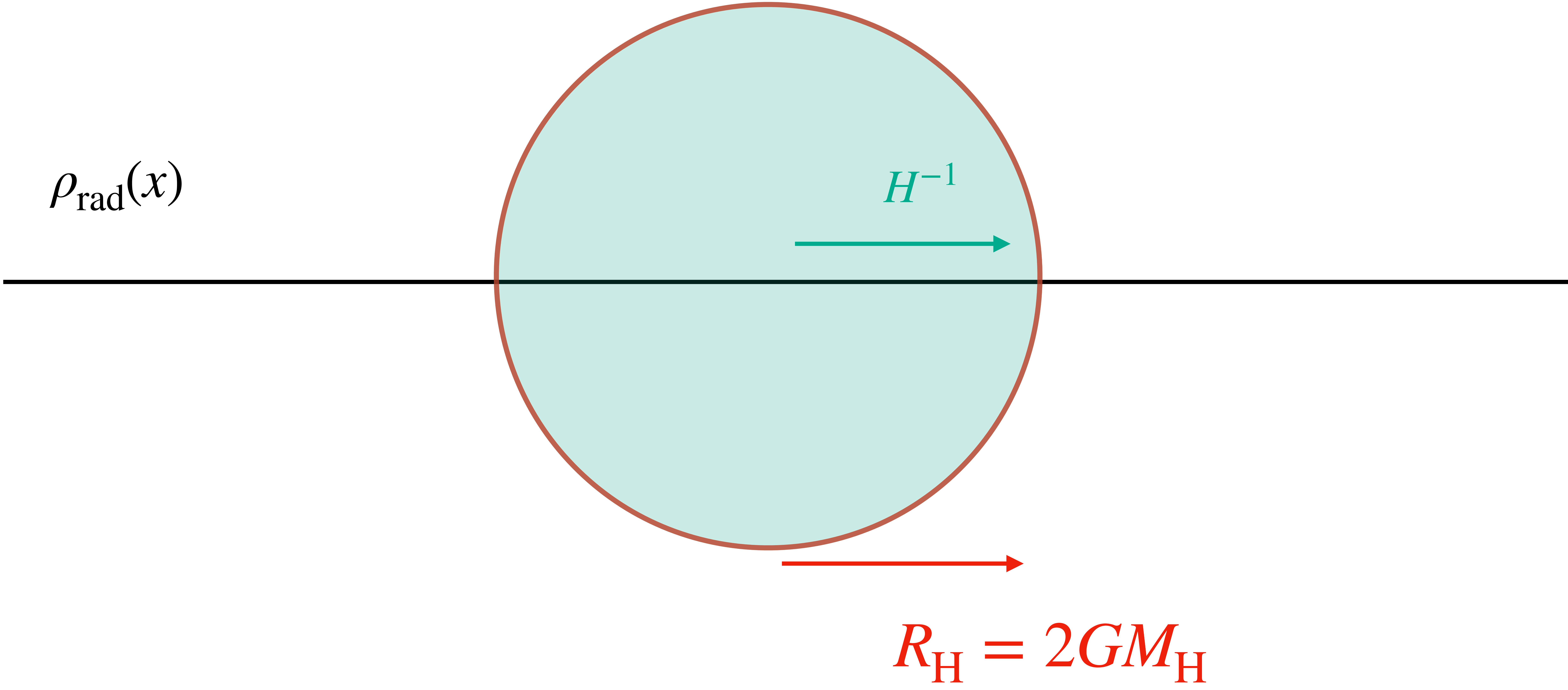
$$R_{\mathrm{H}} = 2GM_{\mathrm{H}}$$

$\Updownarrow$

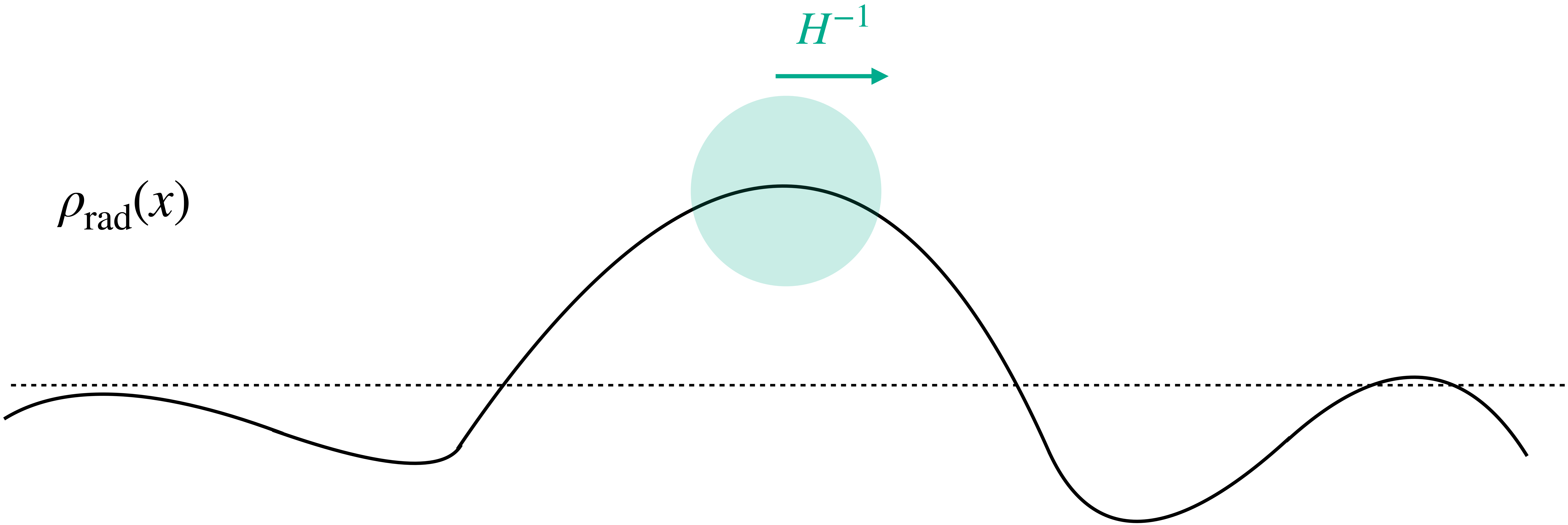
Schwarschild's equation

$\longrightarrow$ **Hubble patches are on the edge to collapse into black holes**

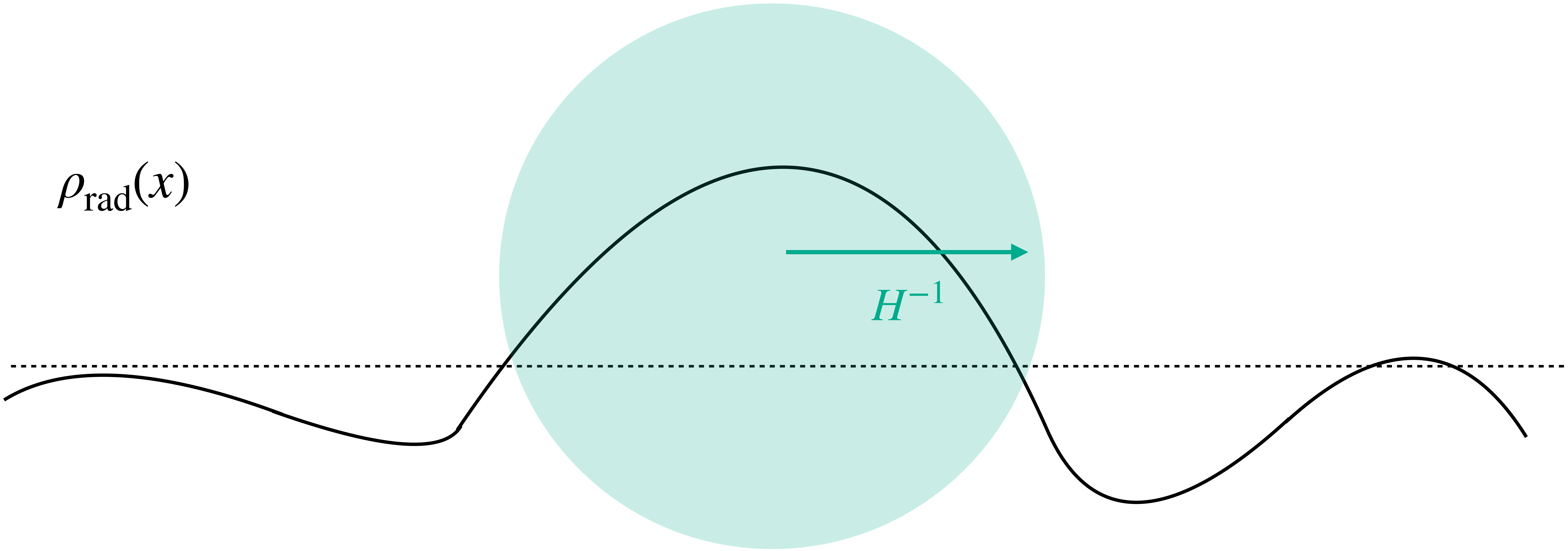
What is Primordial Black Holes ?



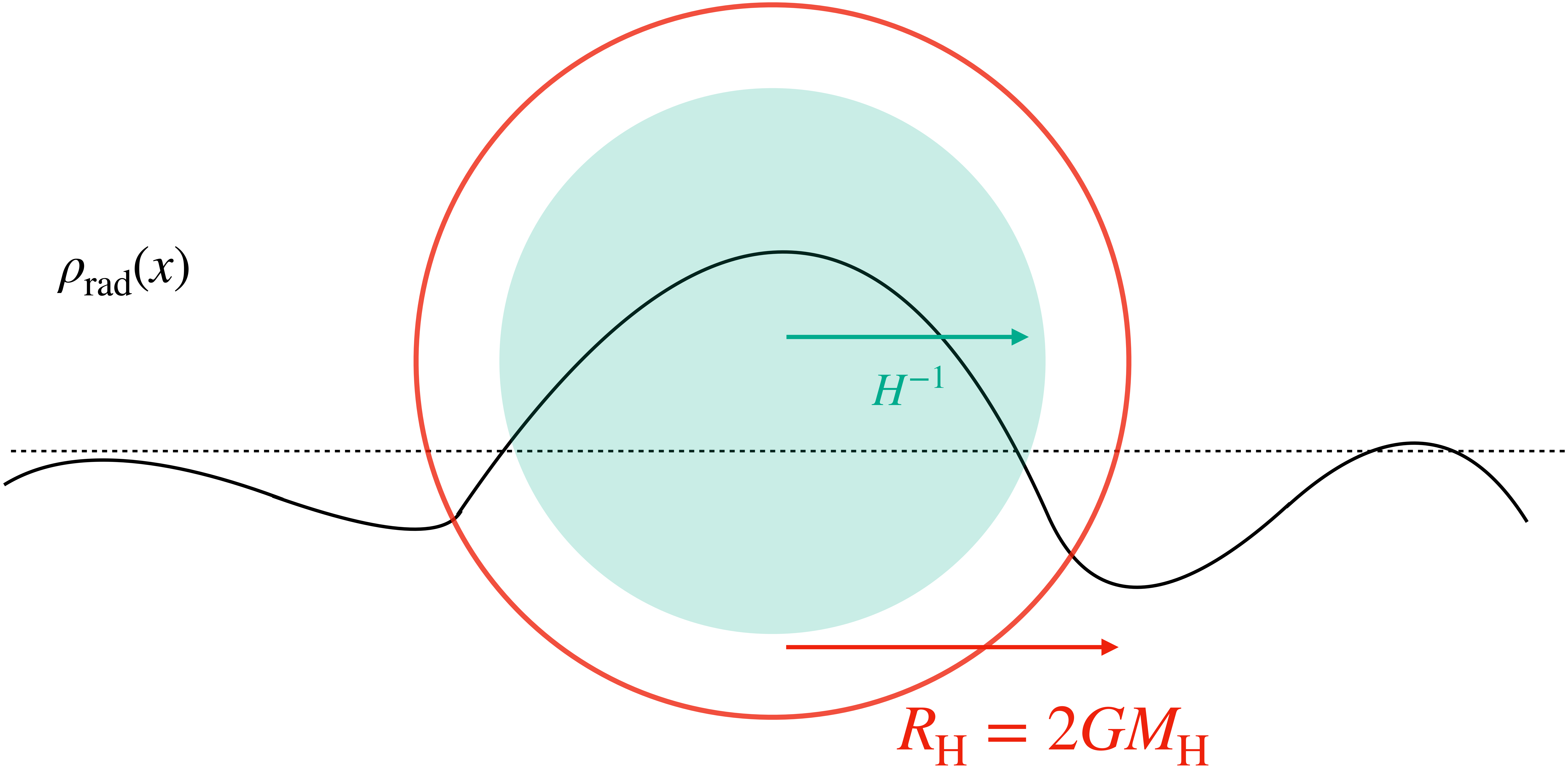
What is Primordial Black Holes ?



What is Primordial Black Holes ?

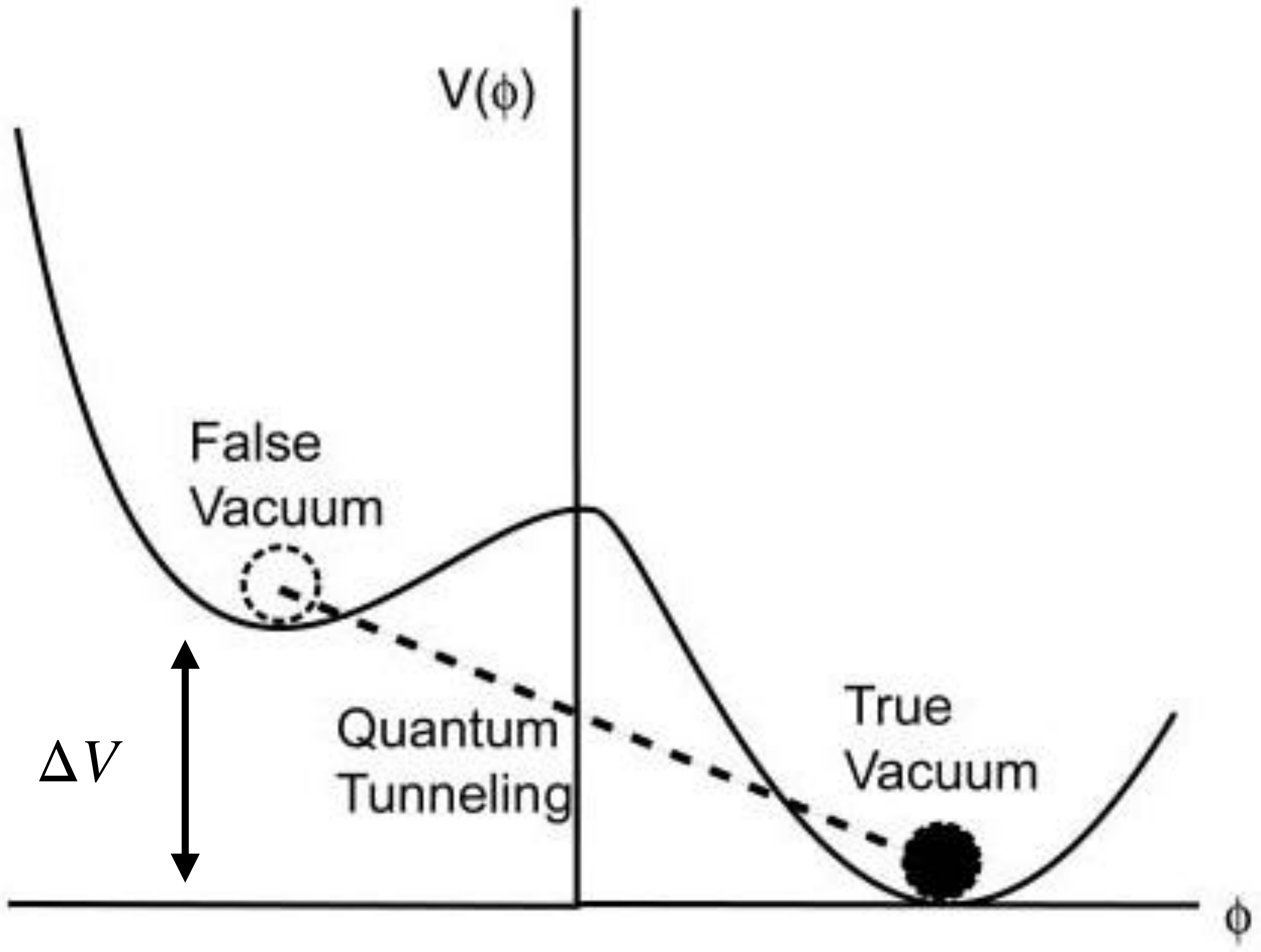


What is Primordial Black Holes ?

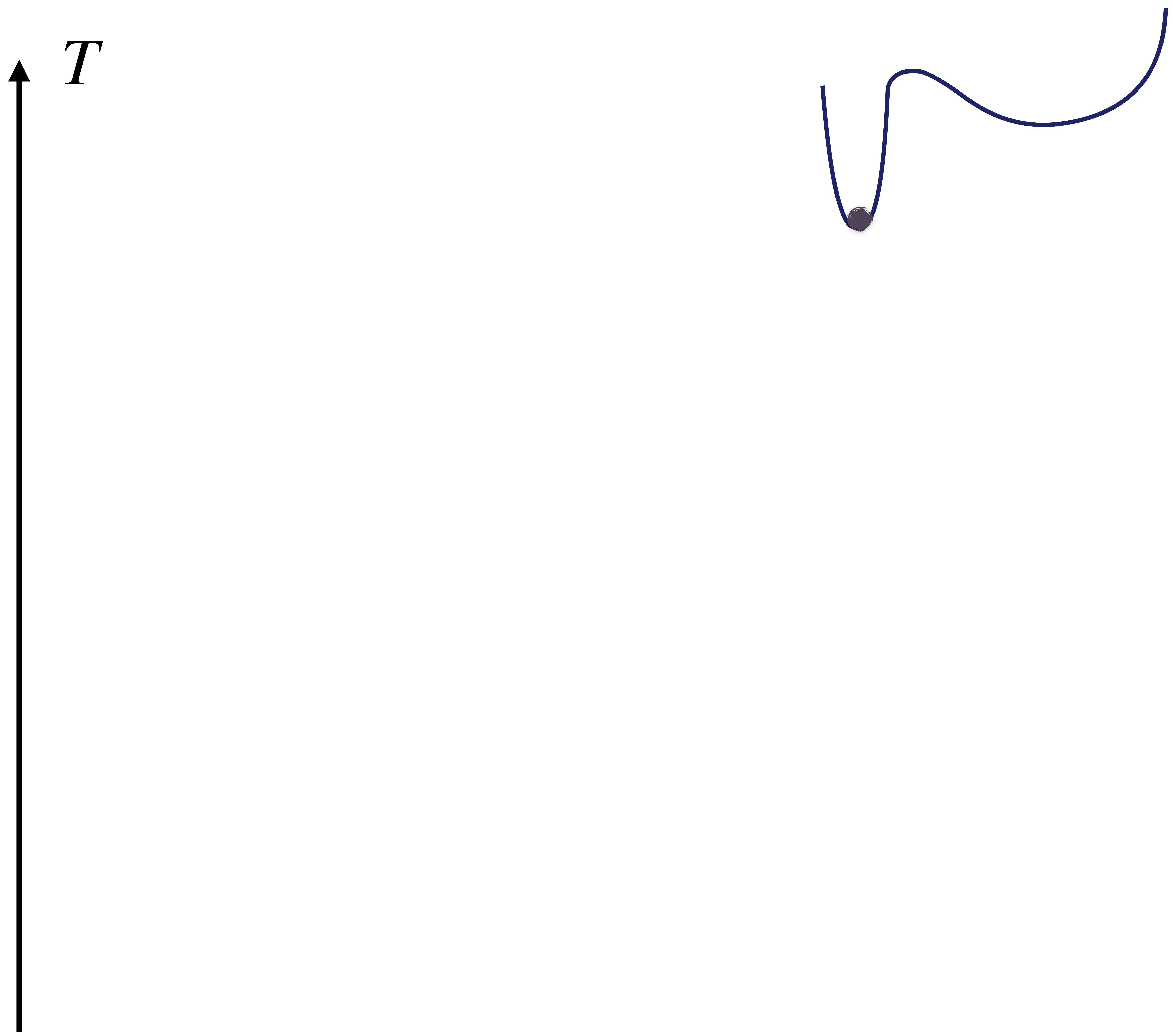


PBHs formation during supercooled phase transition

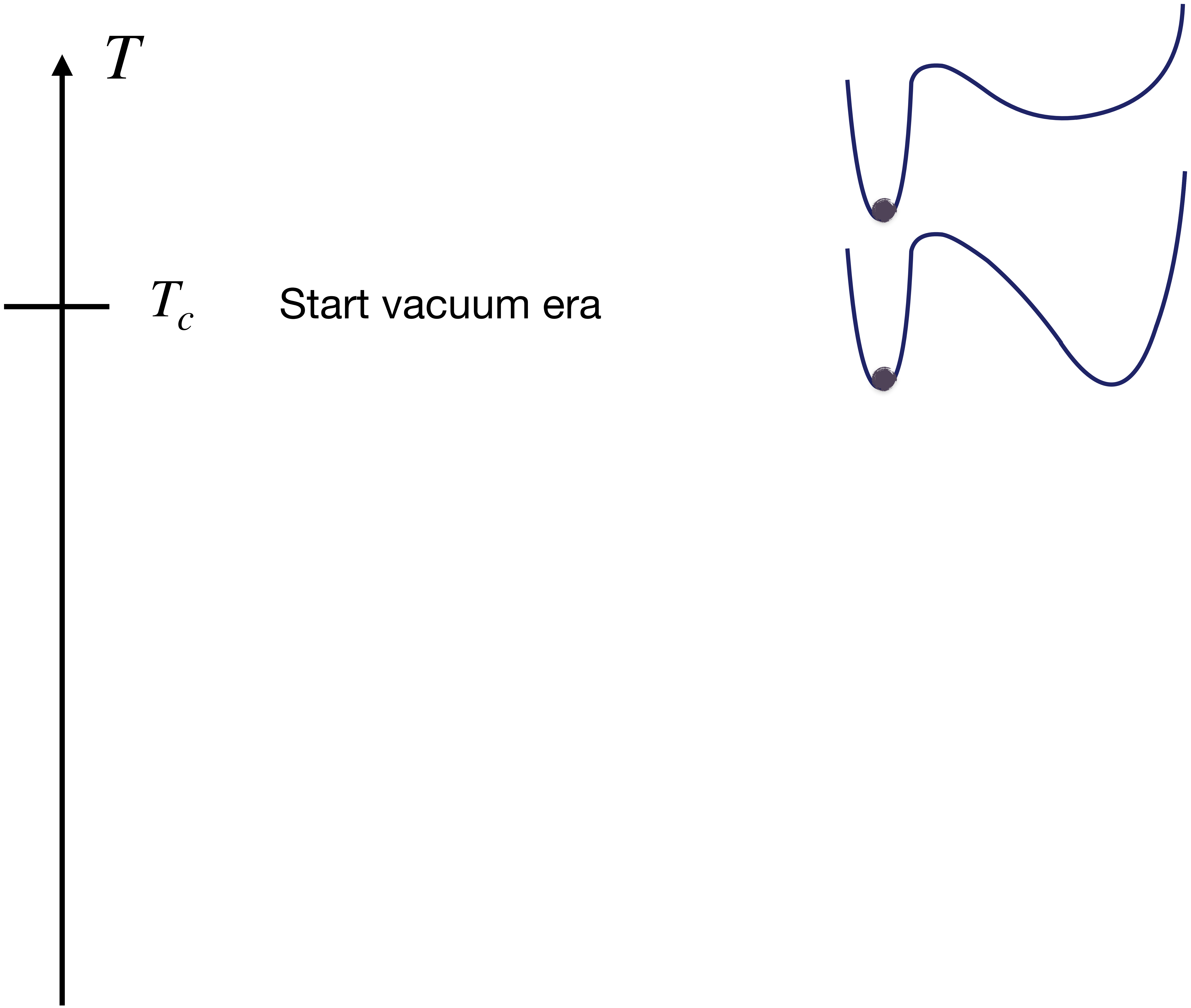
Guth 1980 "Old inflation idea"



Supercooled 1stOPT = delayed PT



Supercooled 1stOPT = delayed PT



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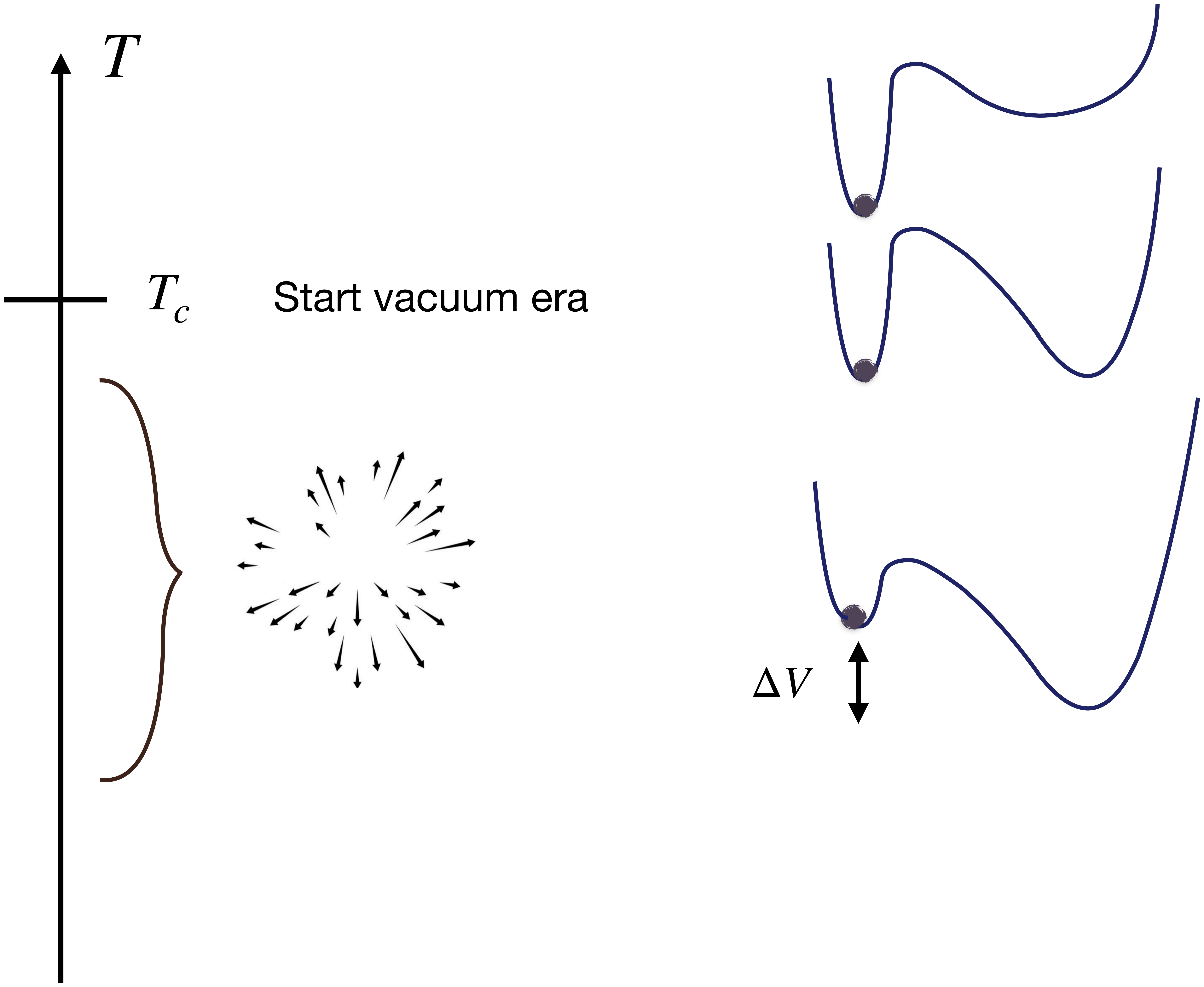

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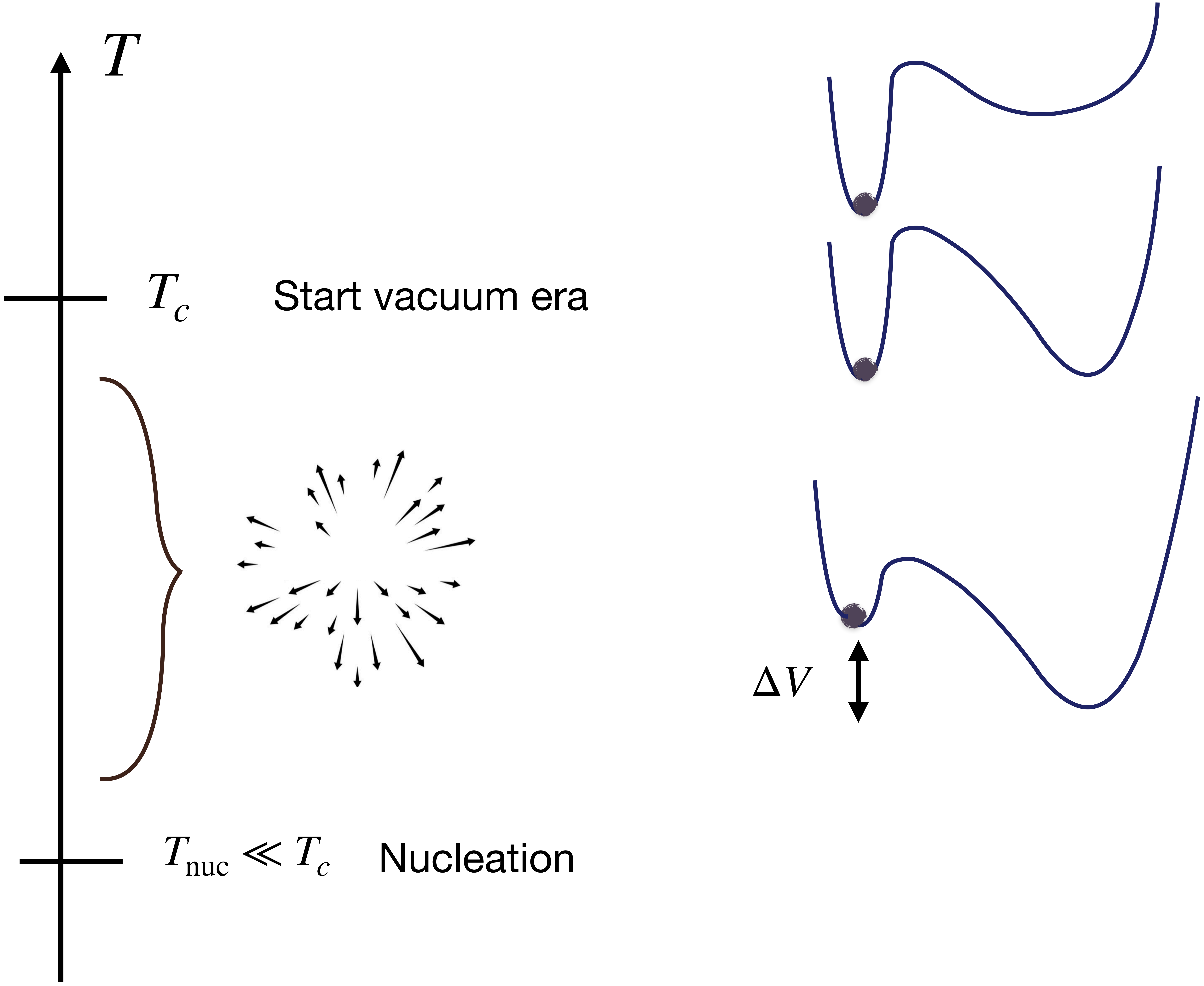

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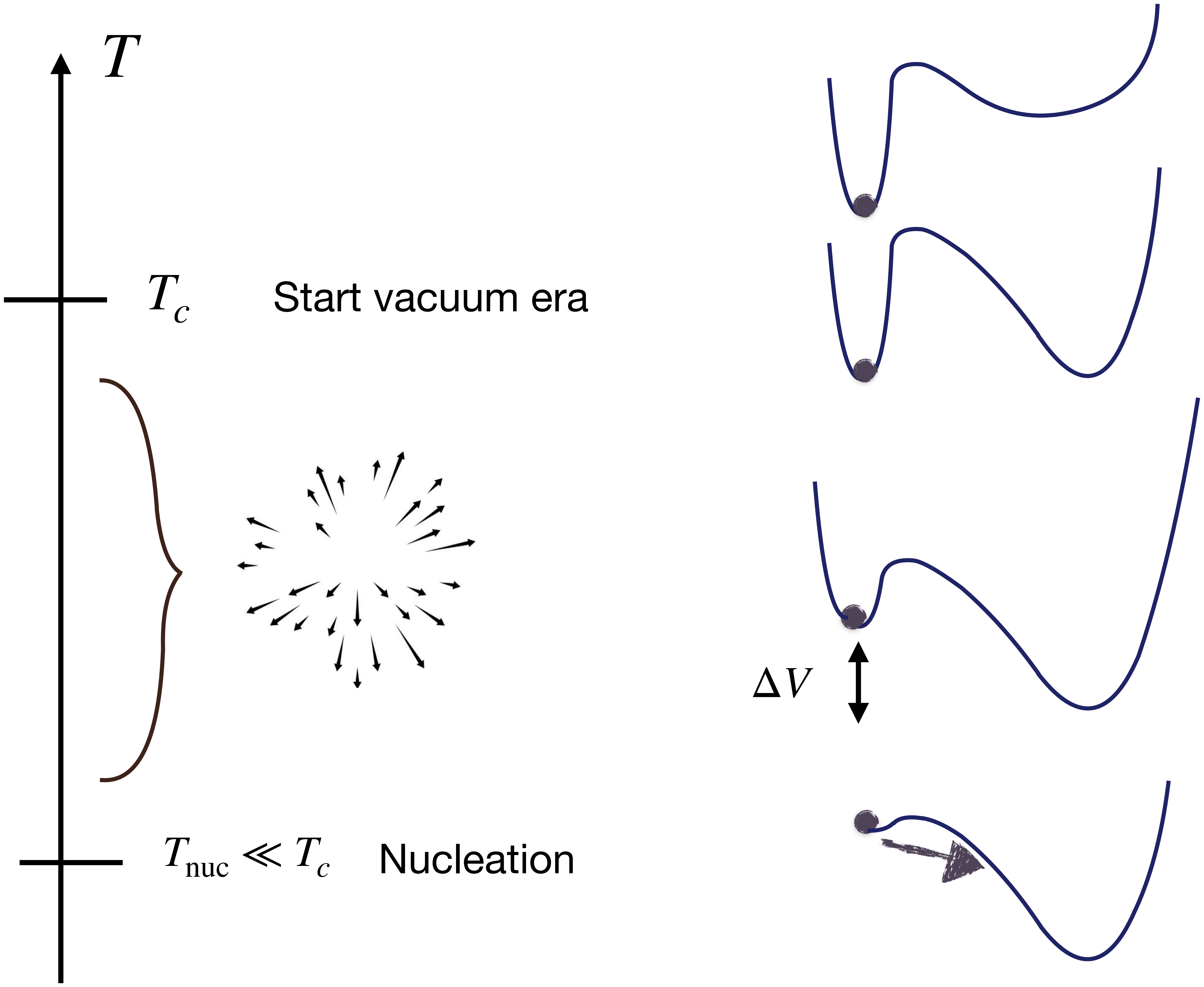

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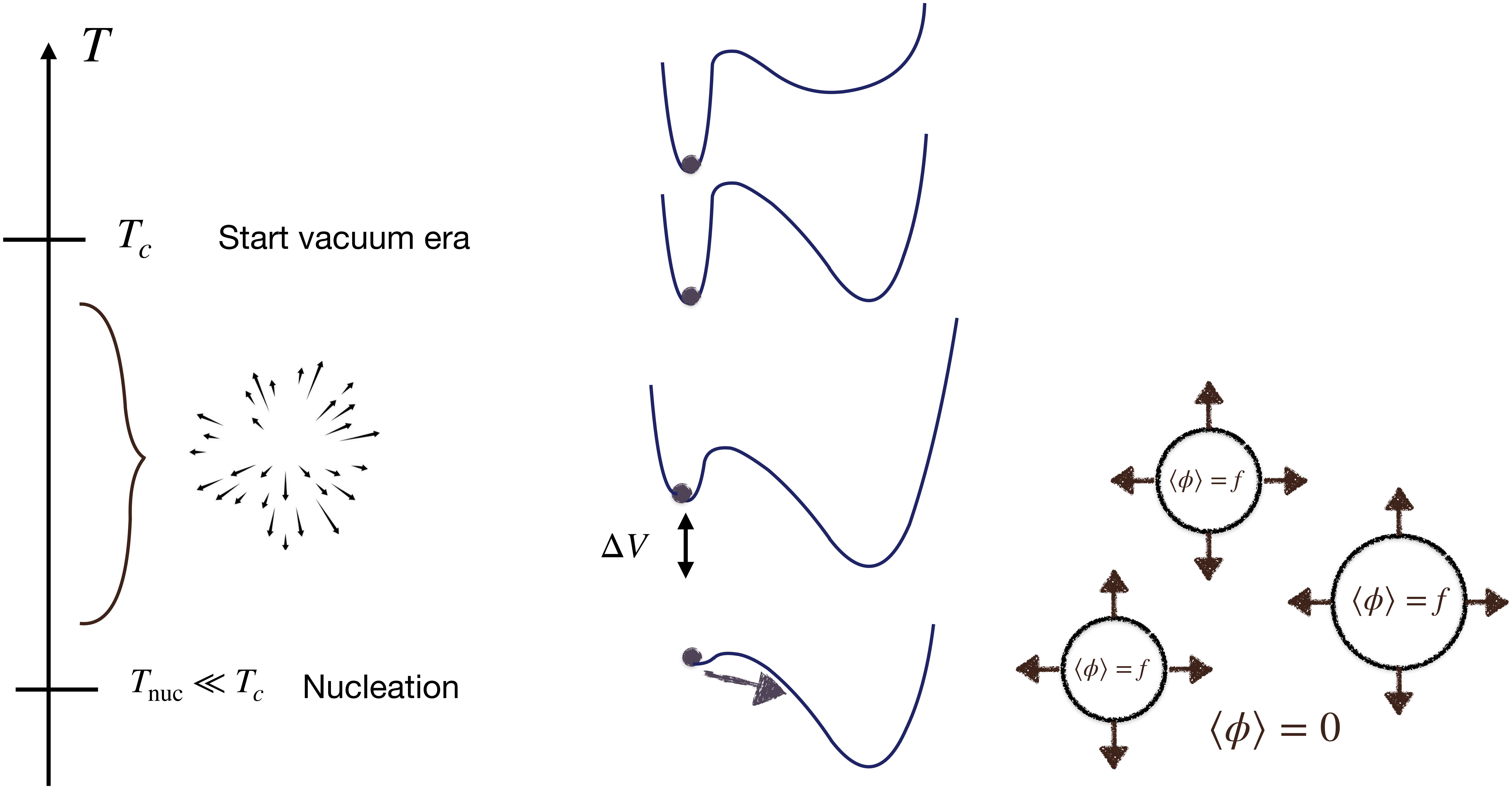
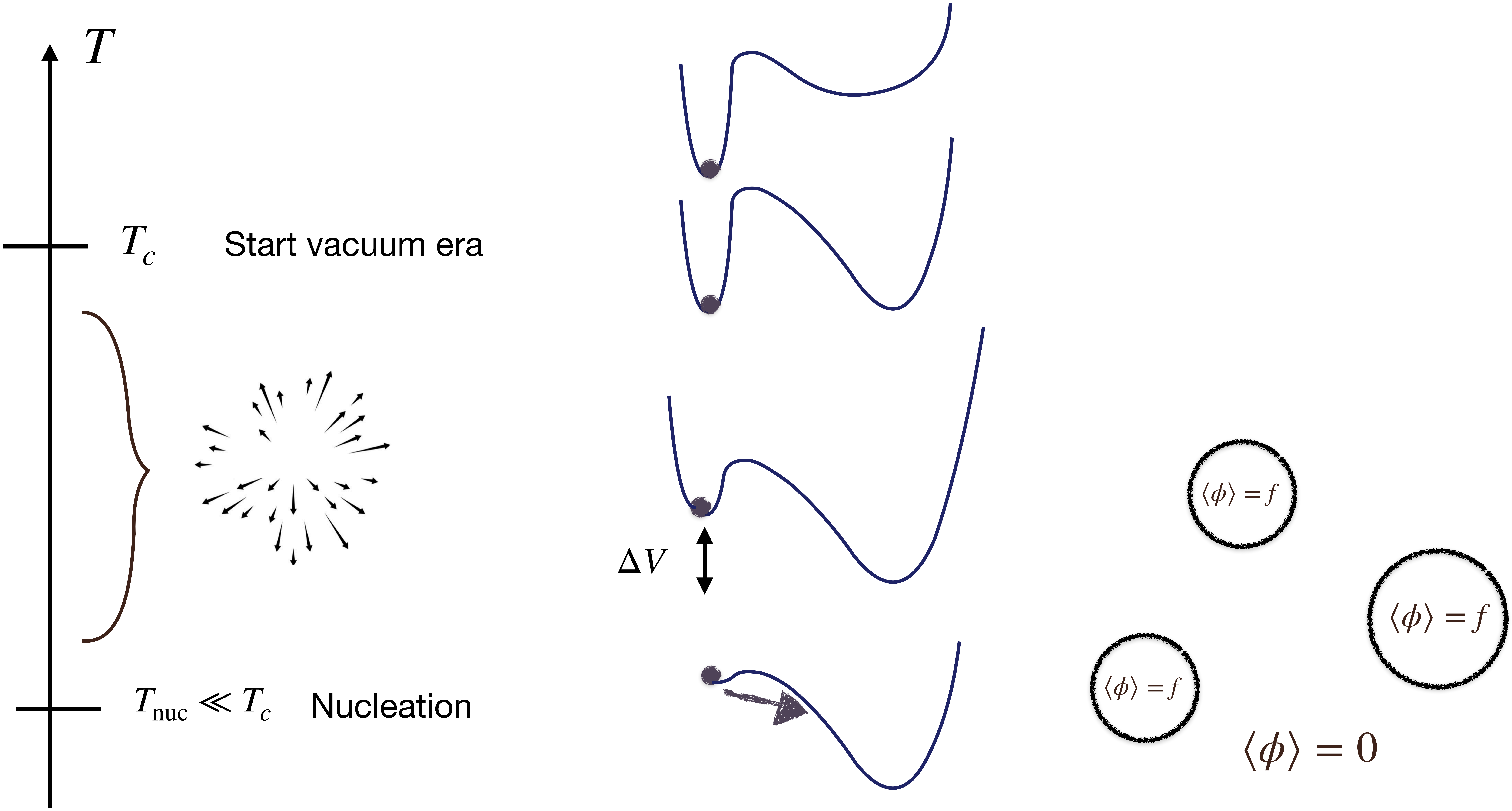
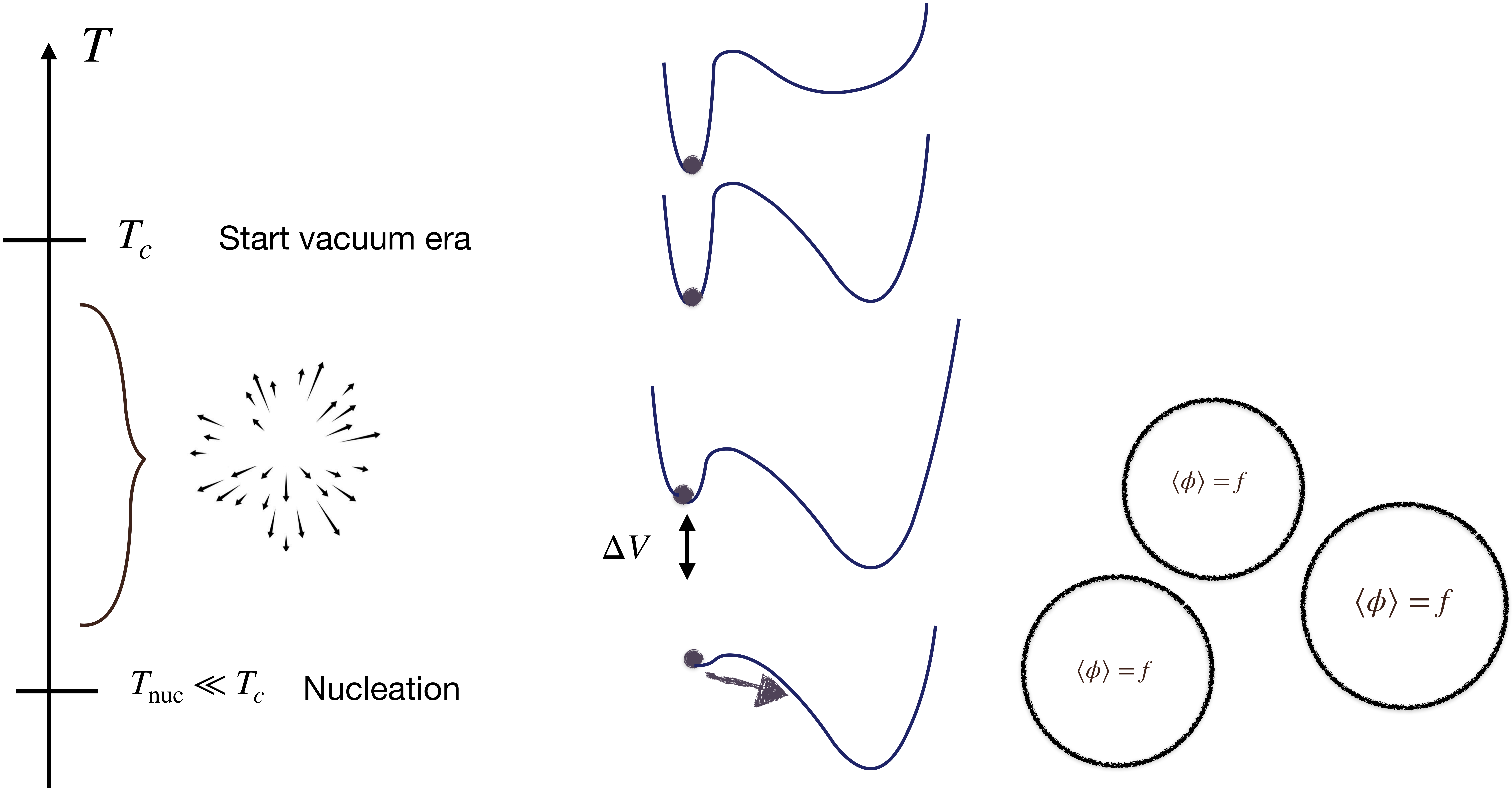


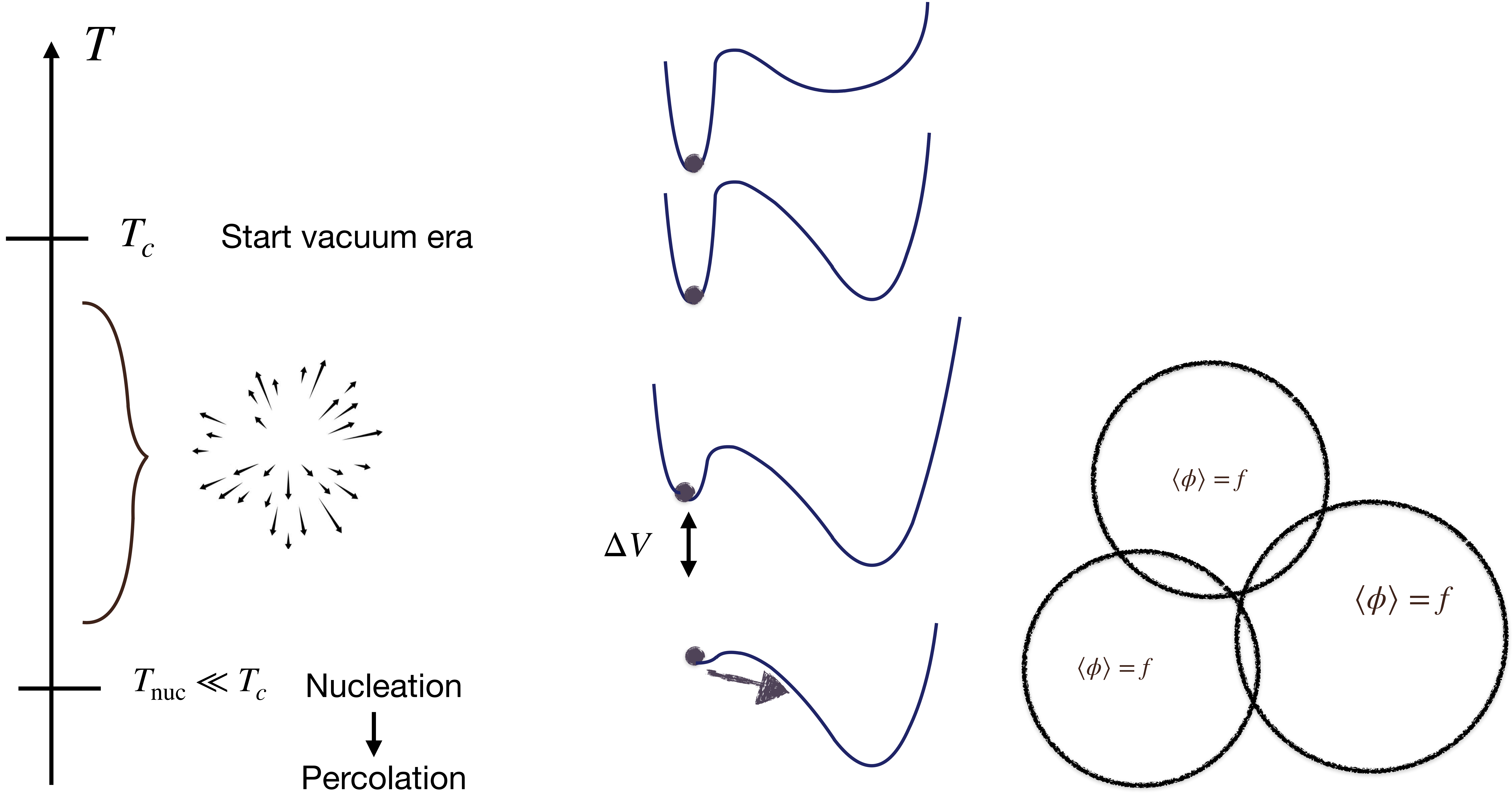
Supercooled 1stOPT = delayed PT



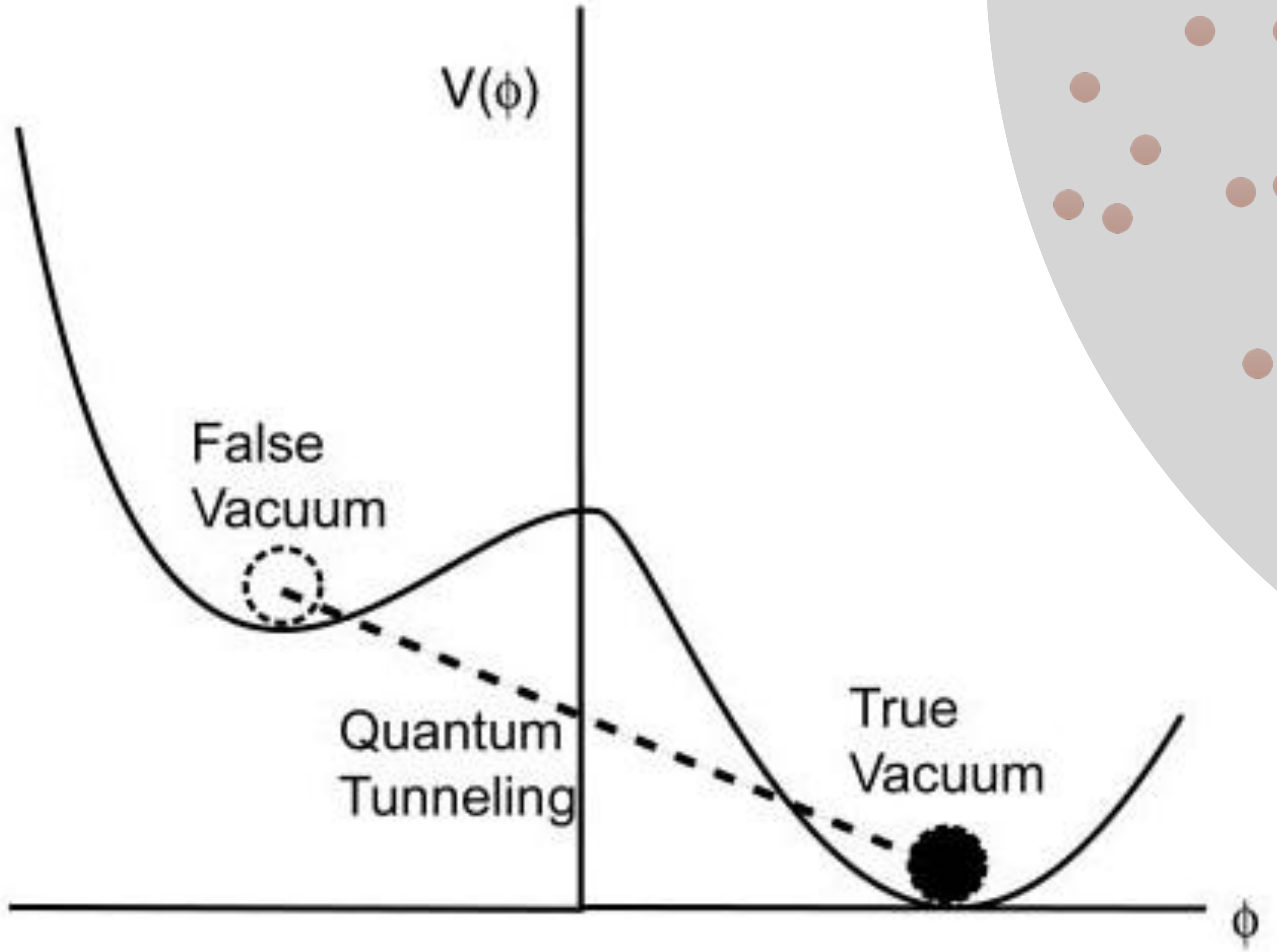
Supercooled 1stOPT = delayed PT

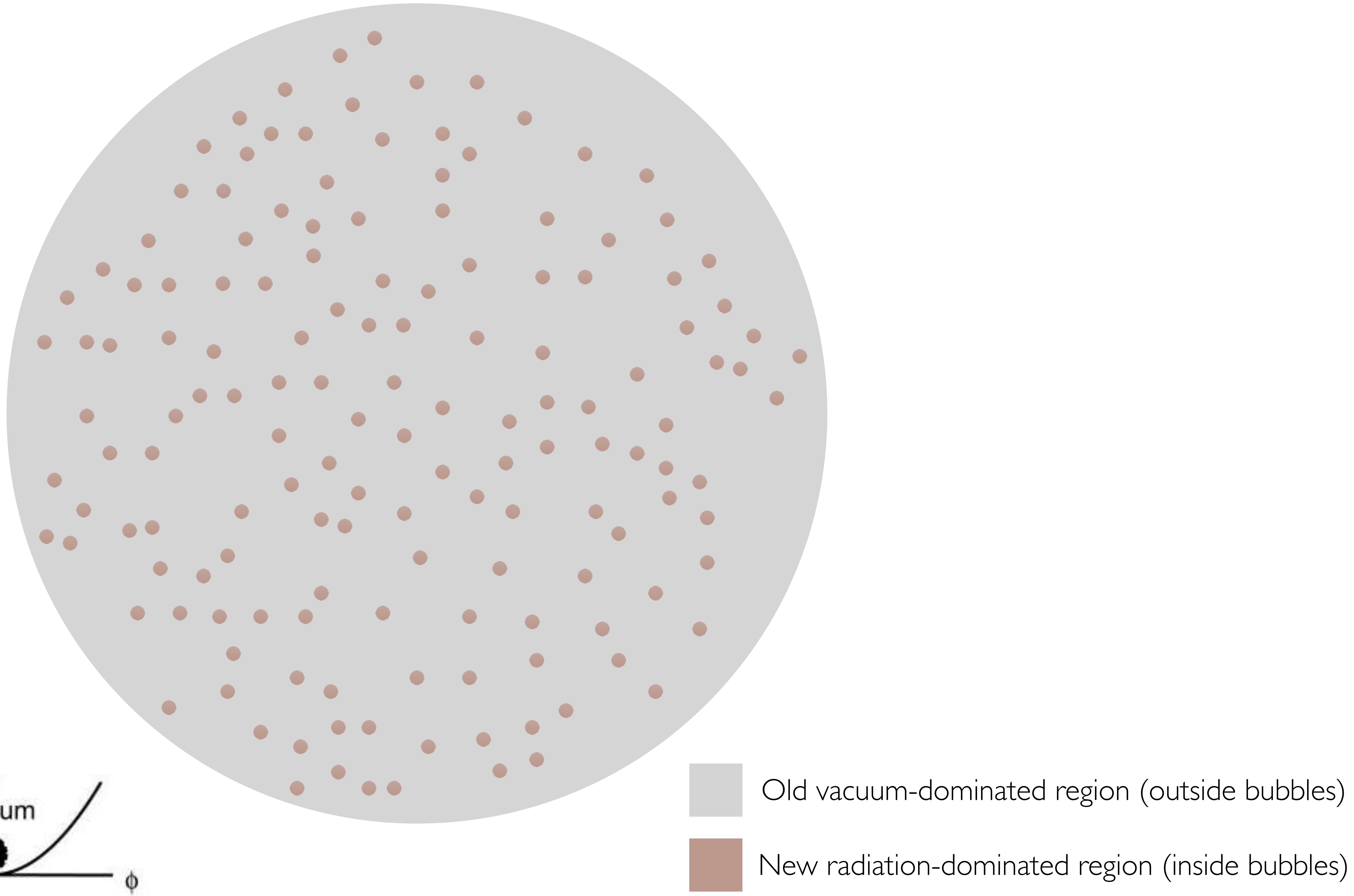


Supercooled 1stOPT = delayed PT



5) PBHs from delayed nucleation





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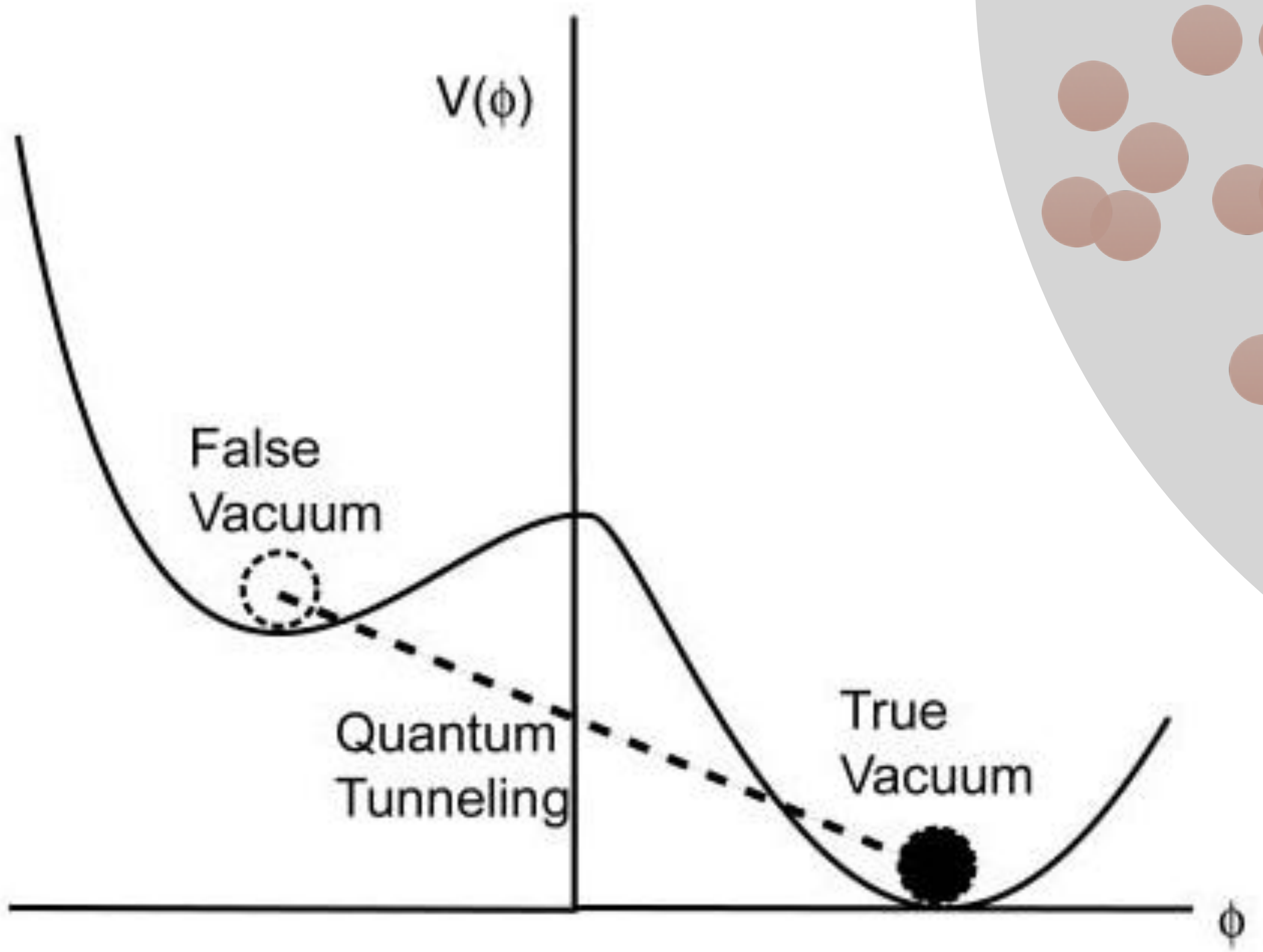

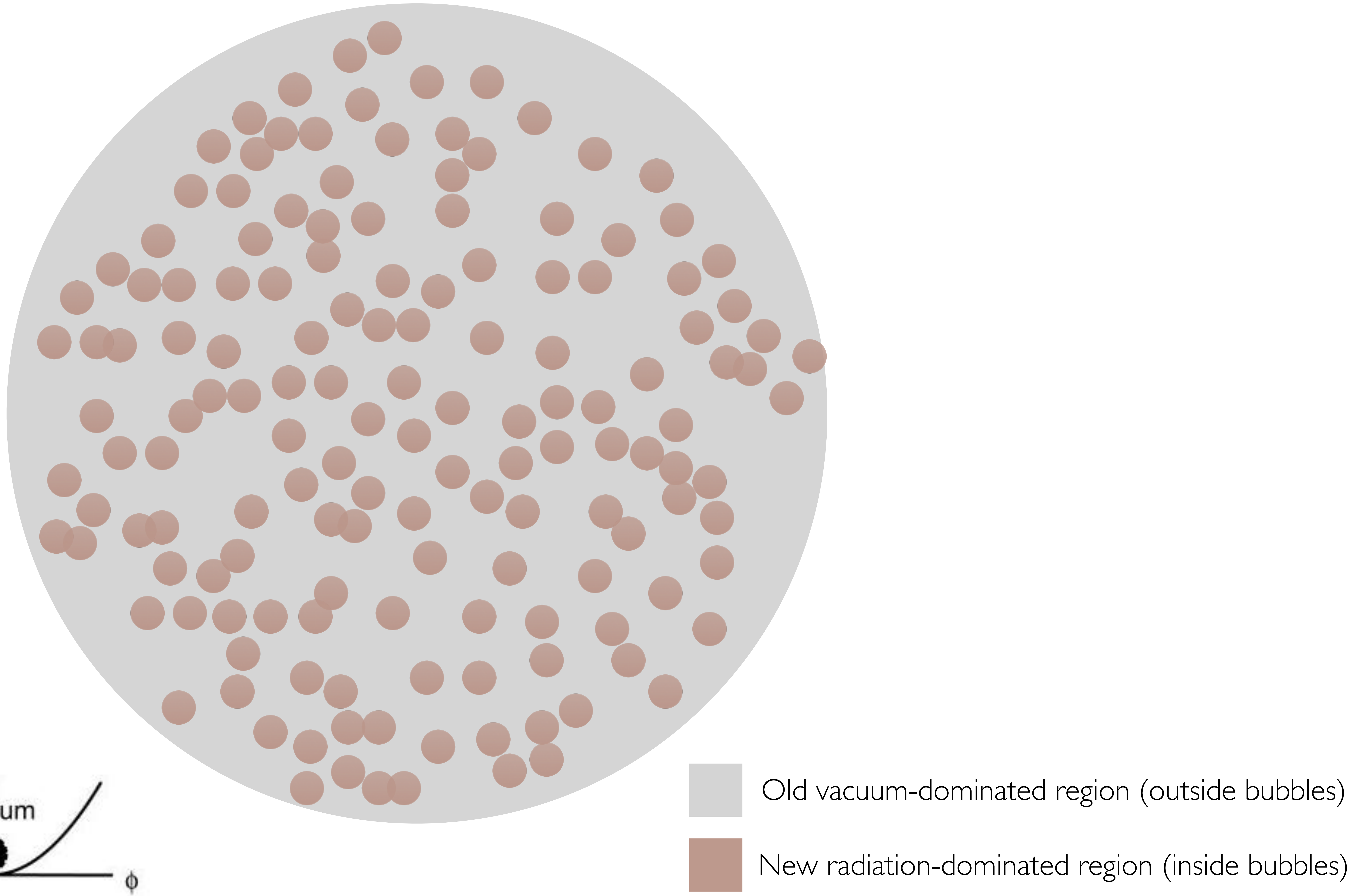

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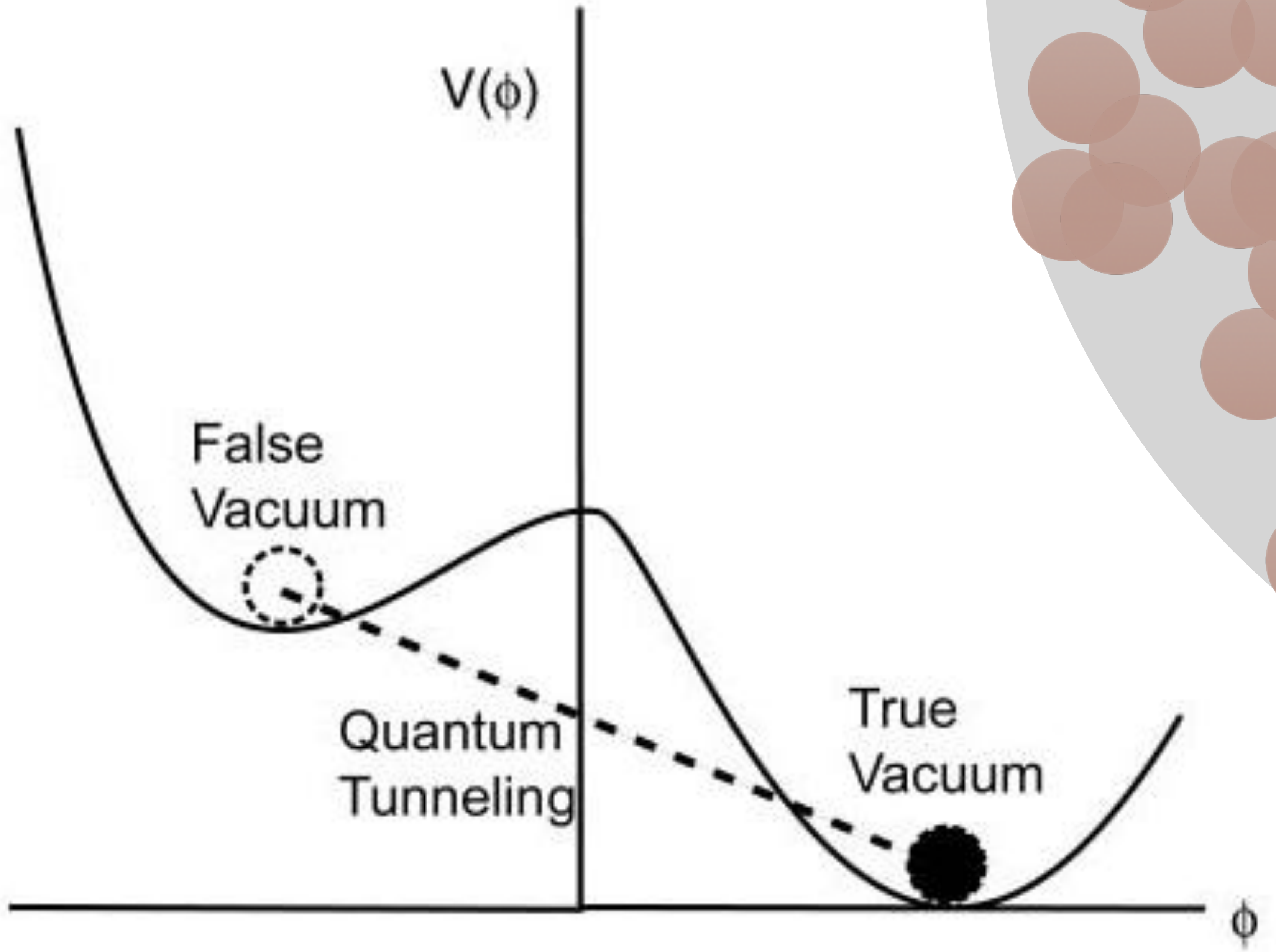

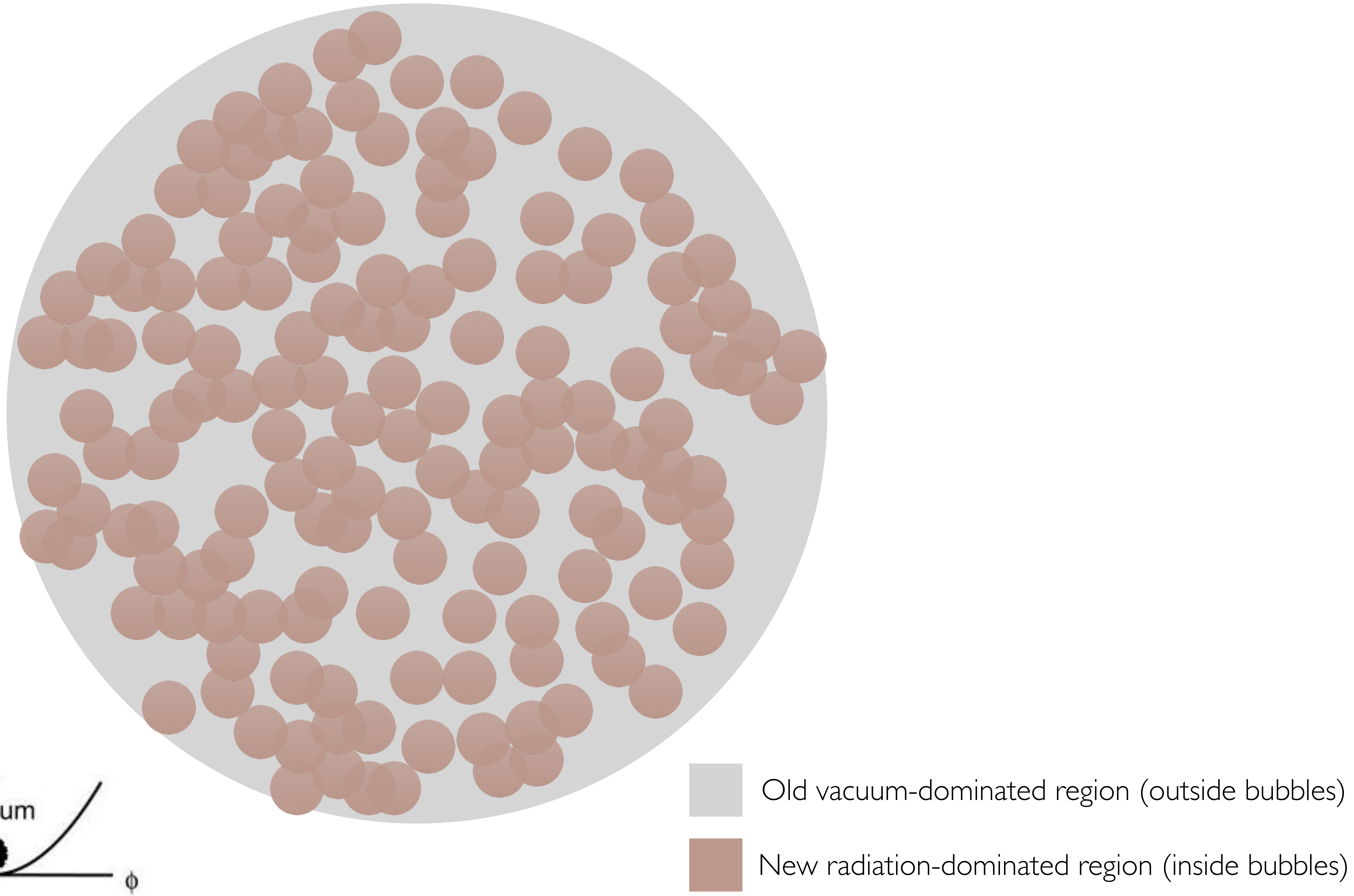

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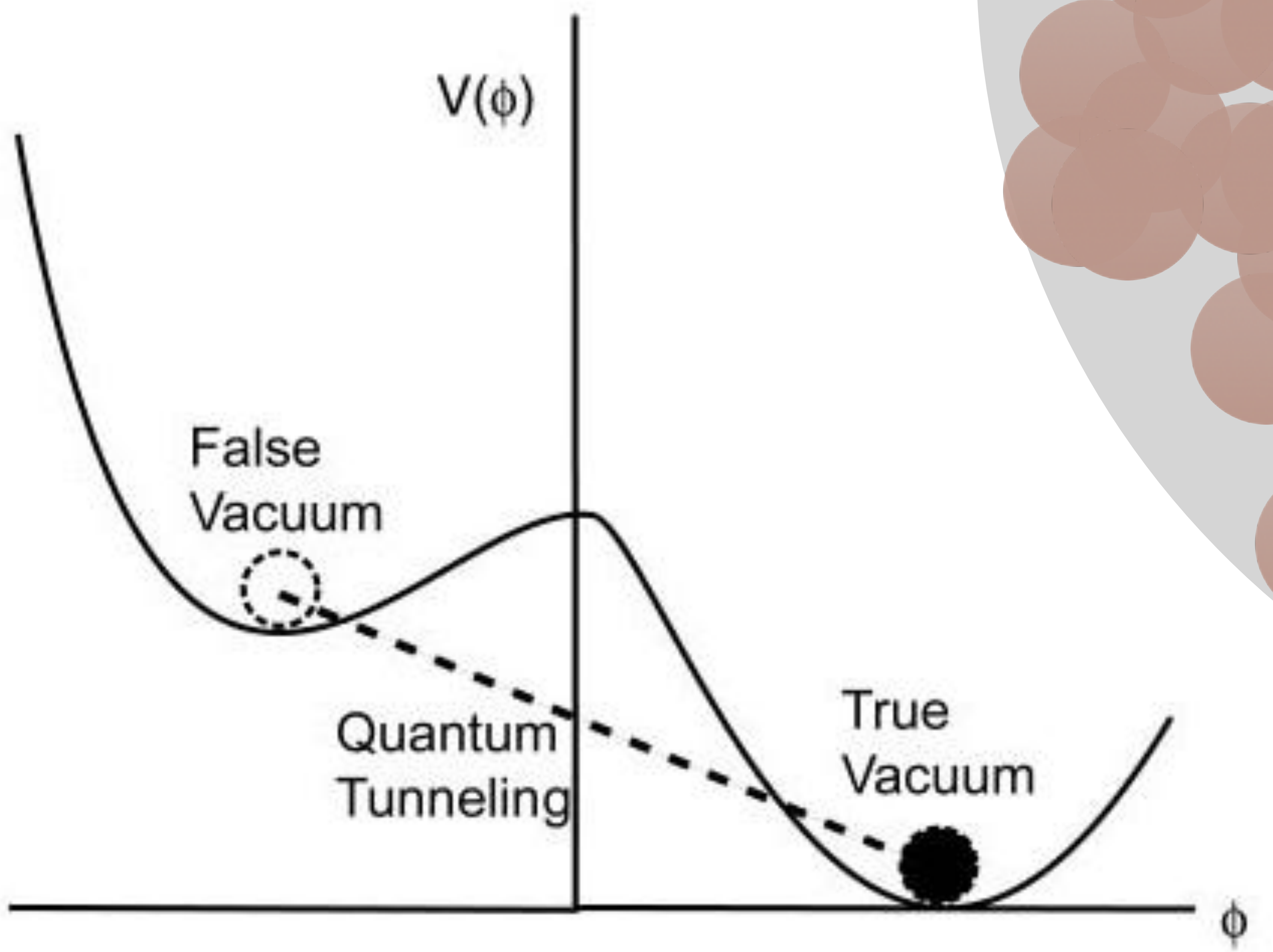

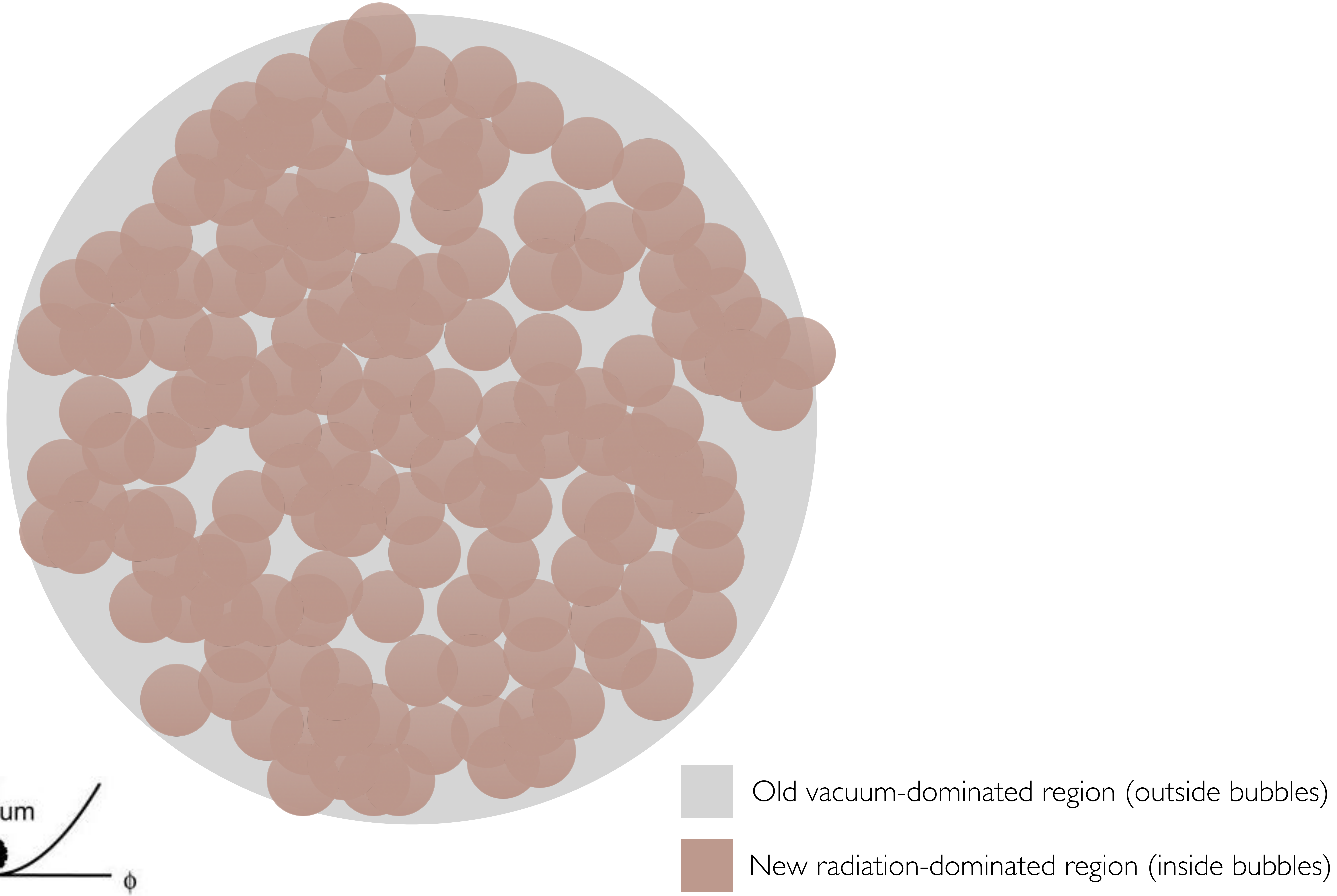

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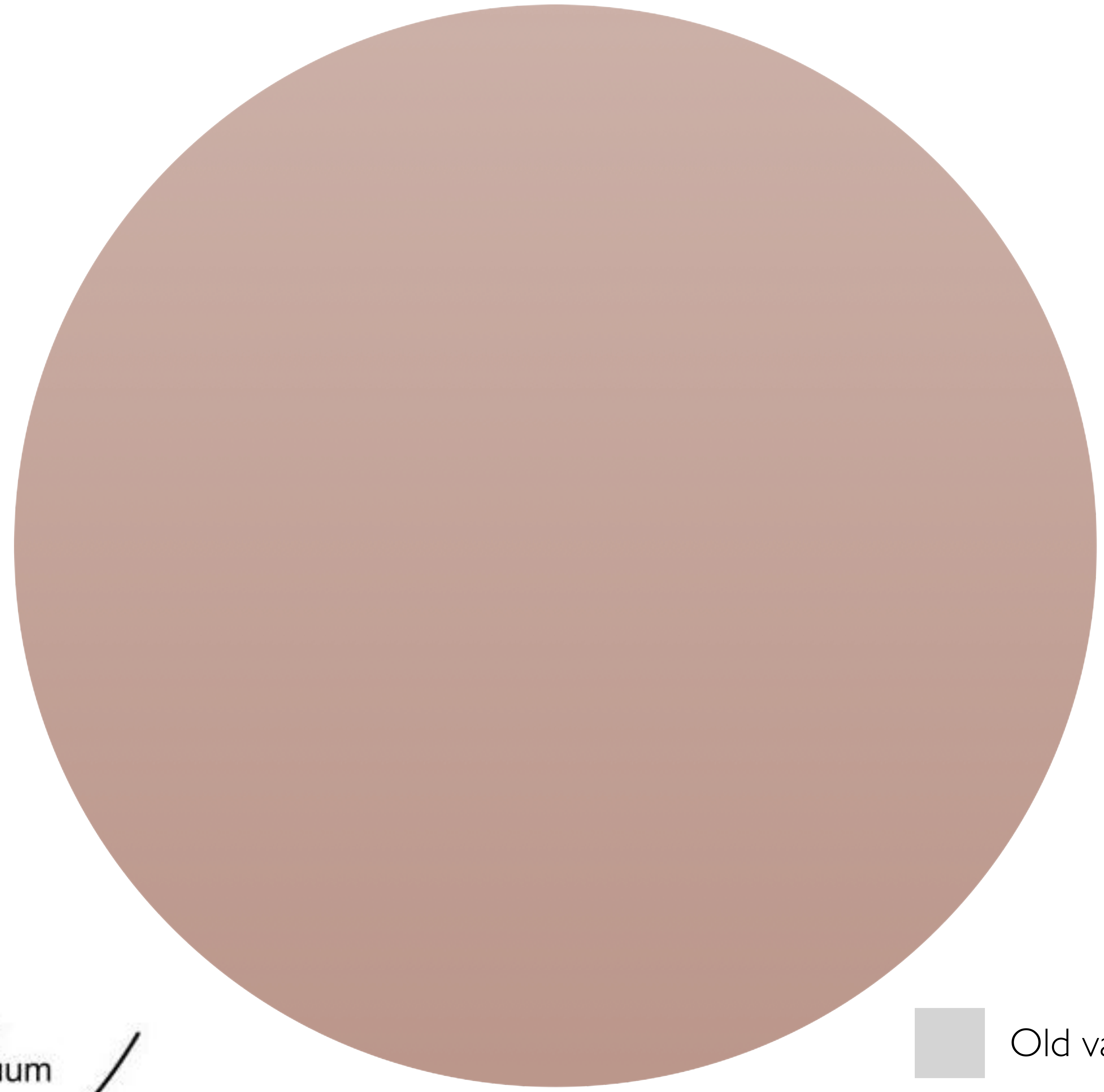
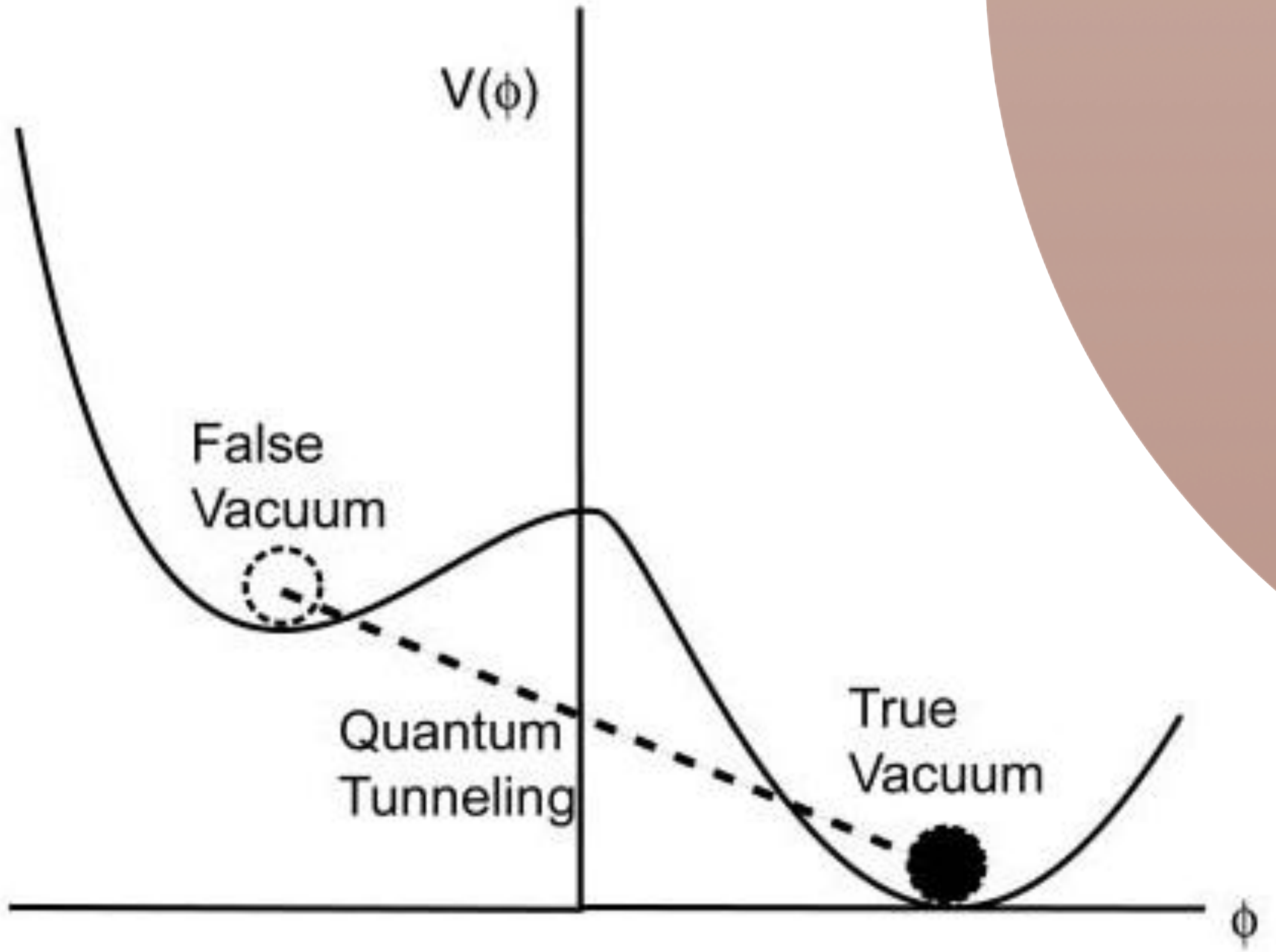
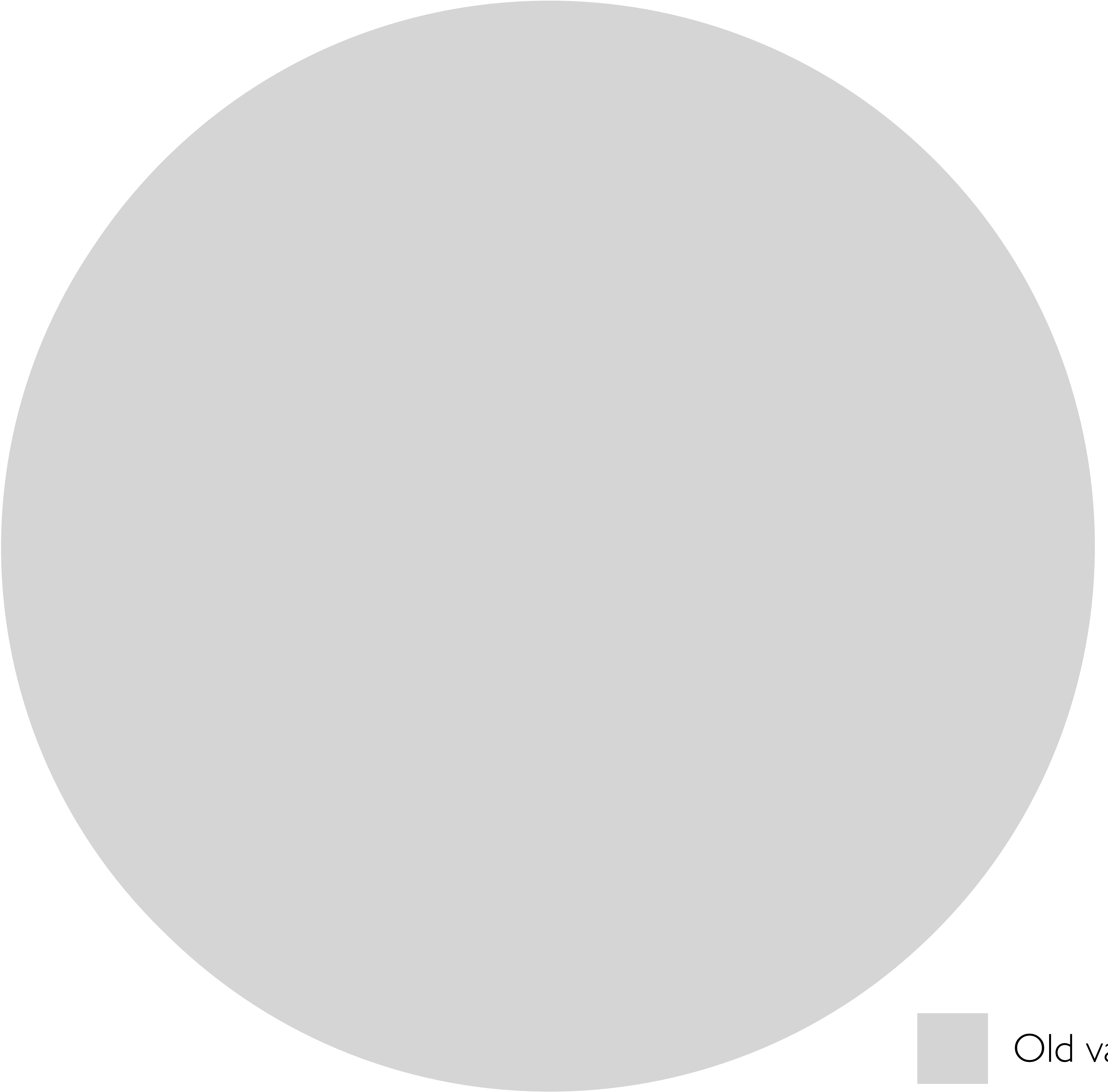


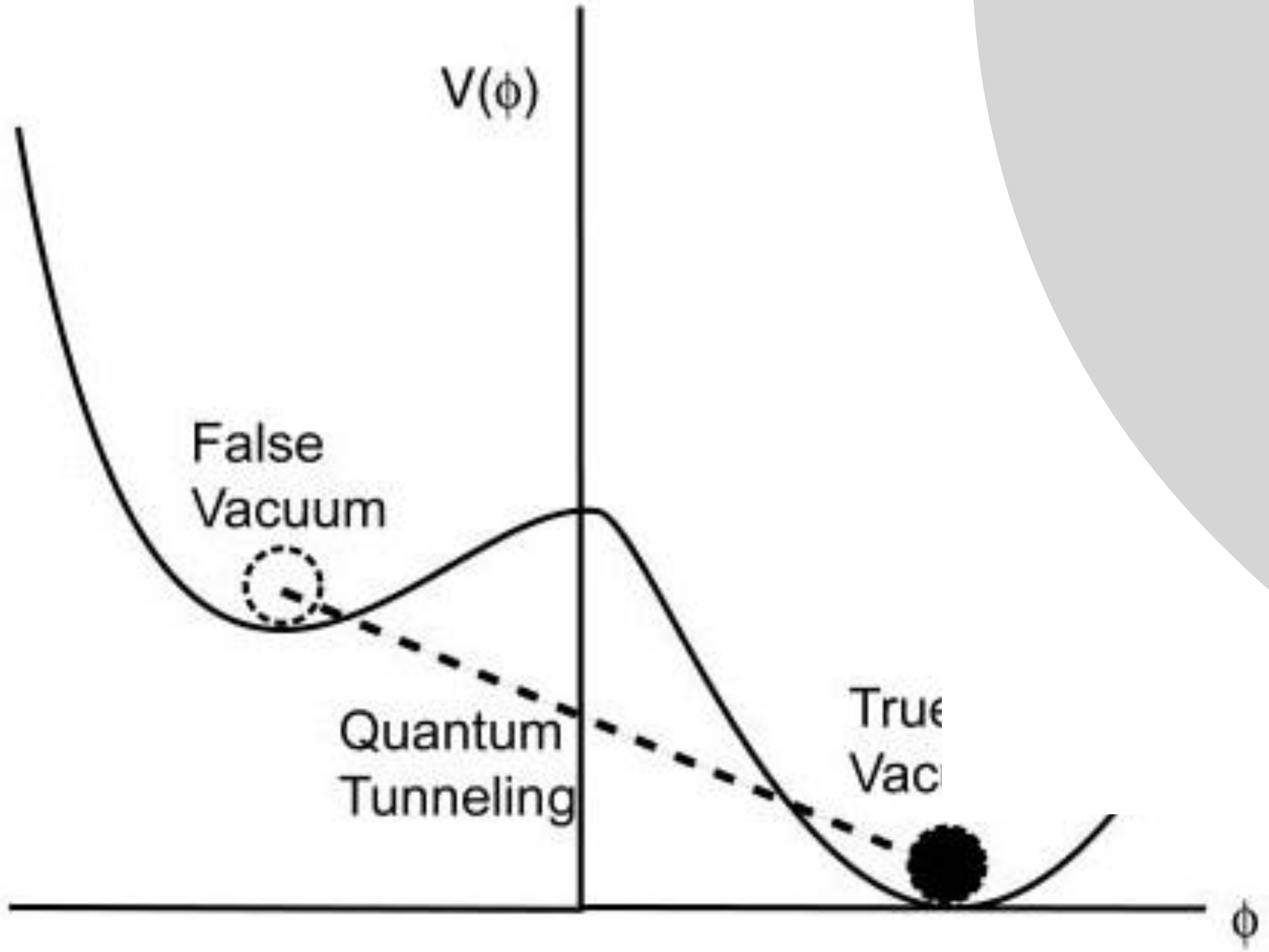


Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

5) PBHs from delayed nucleation





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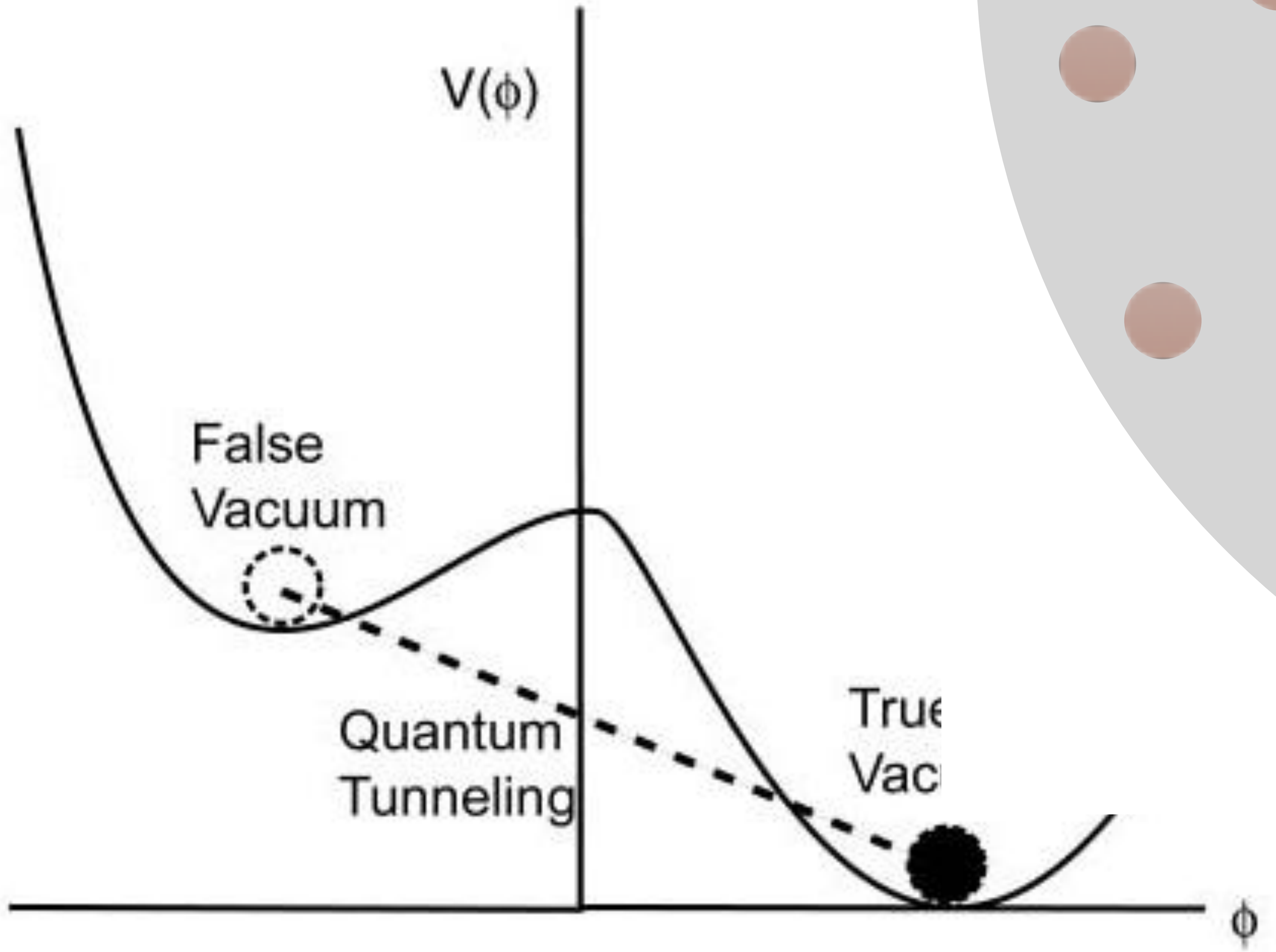

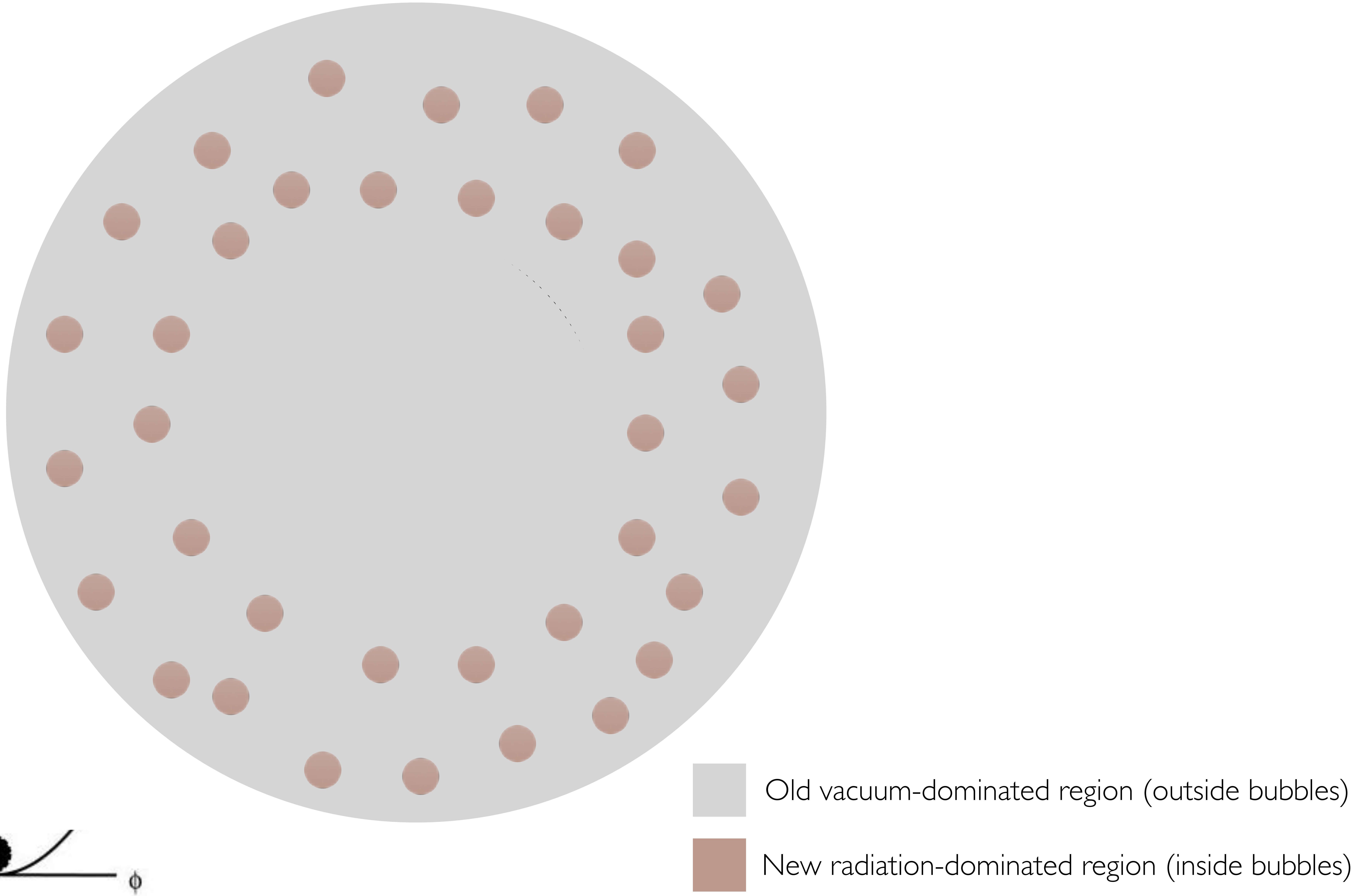

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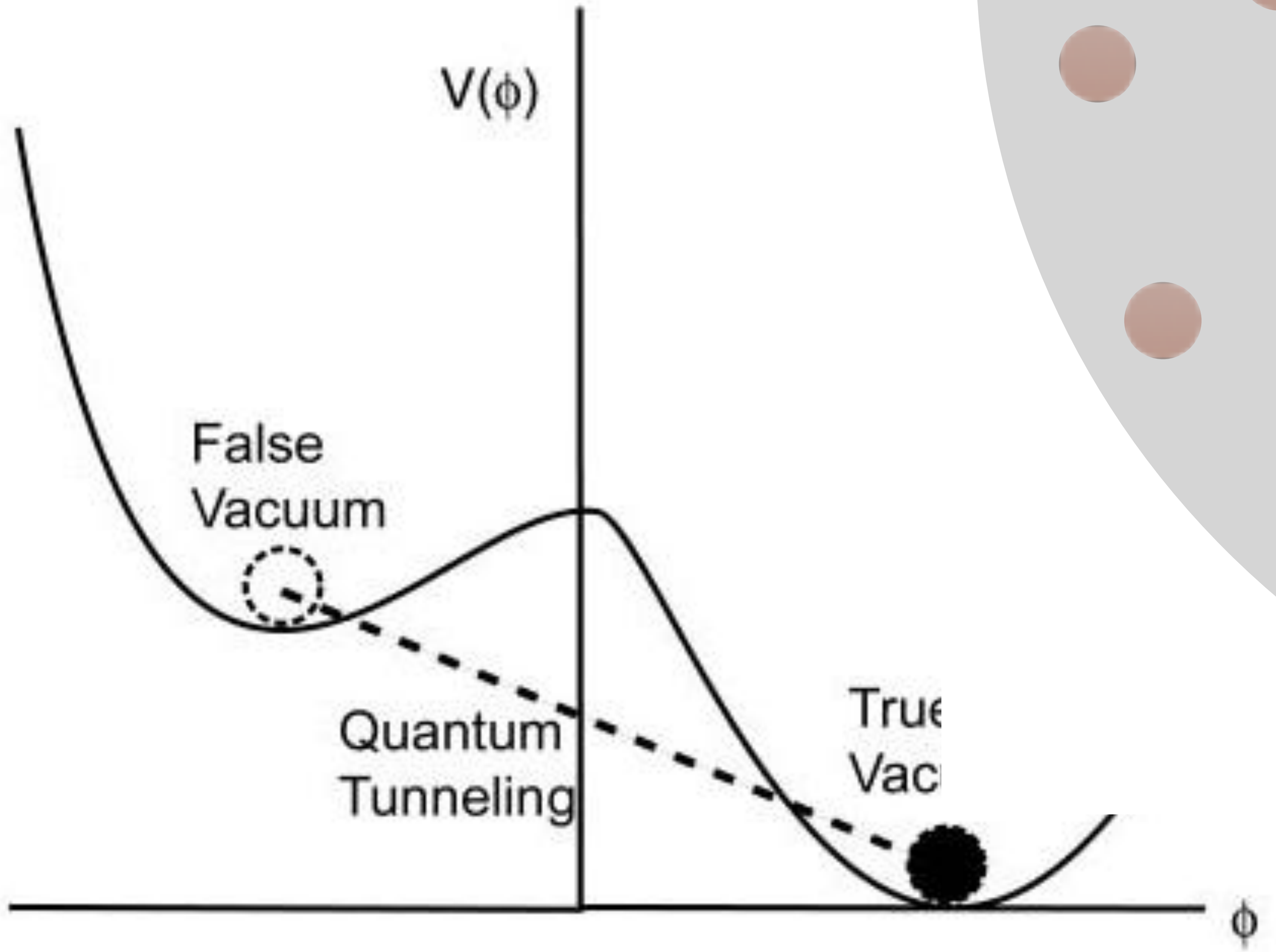

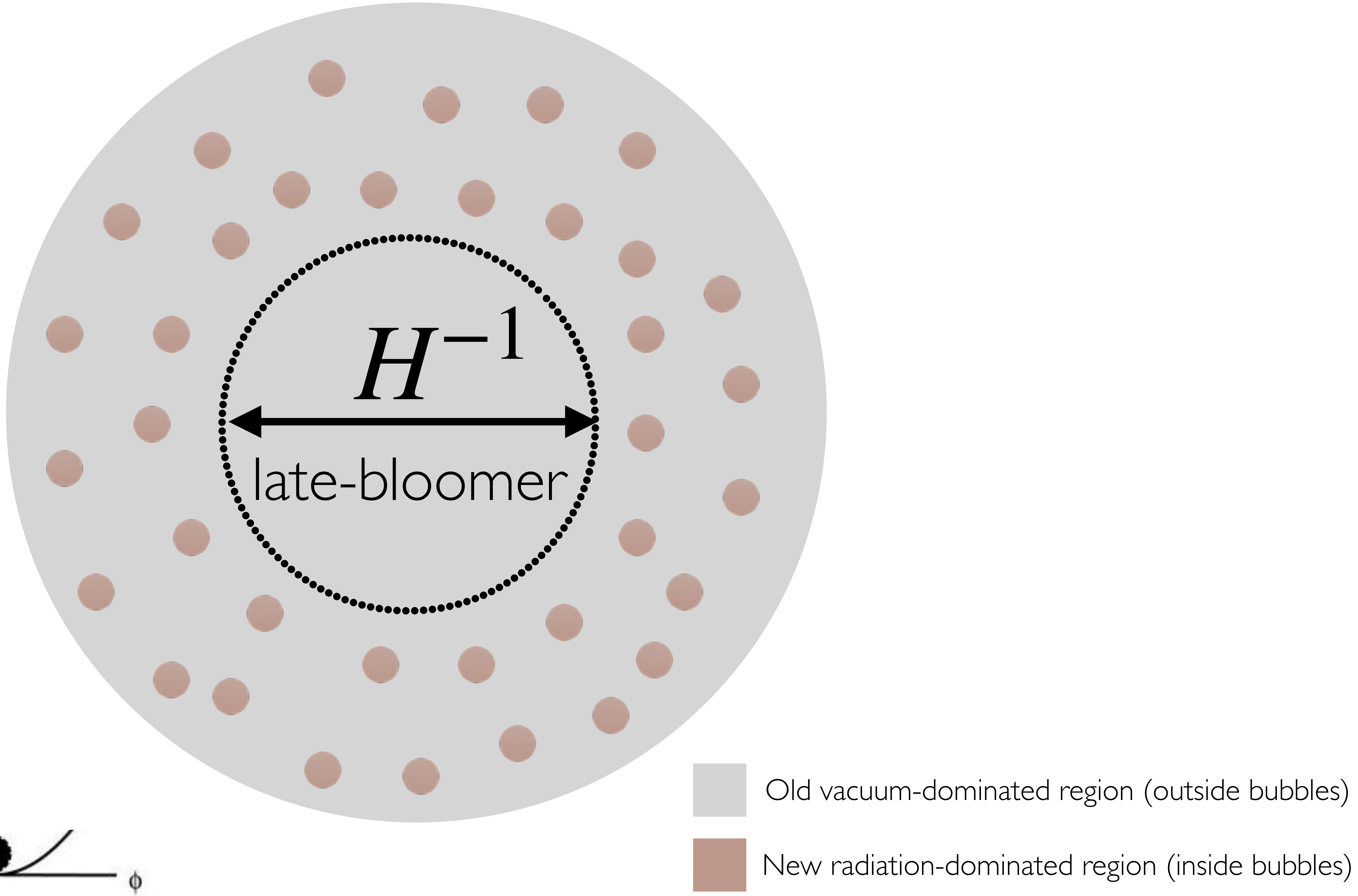

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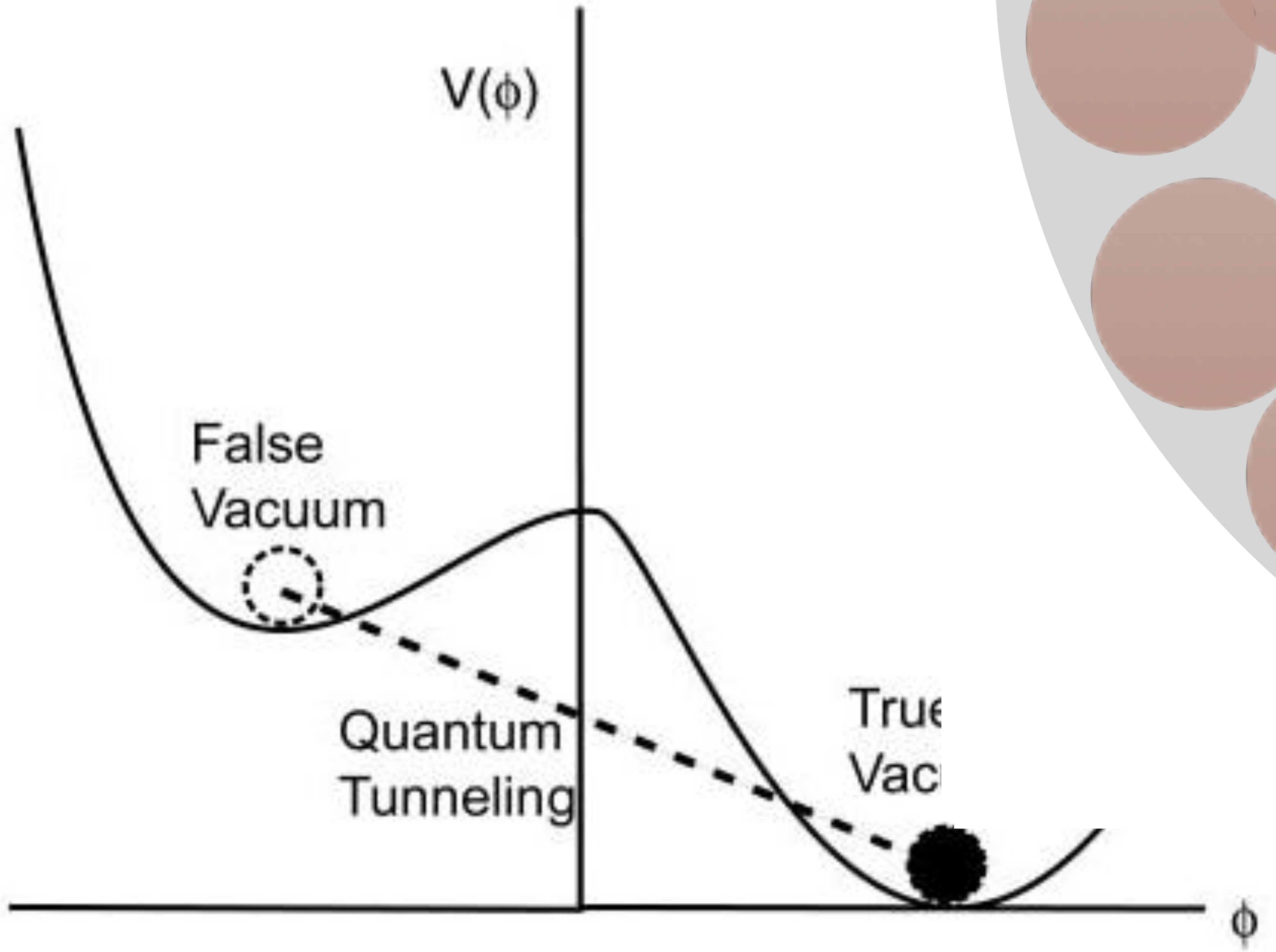

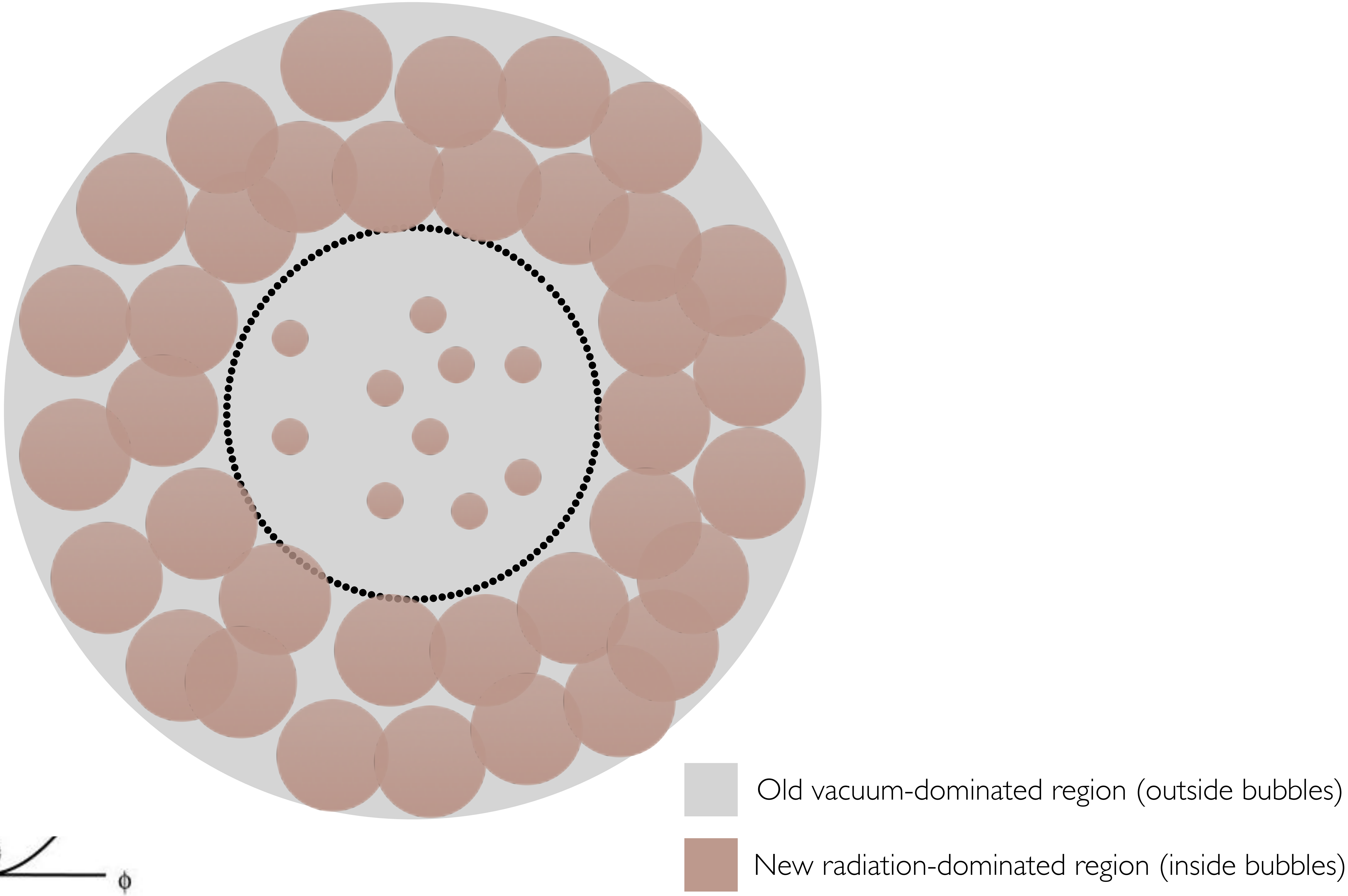

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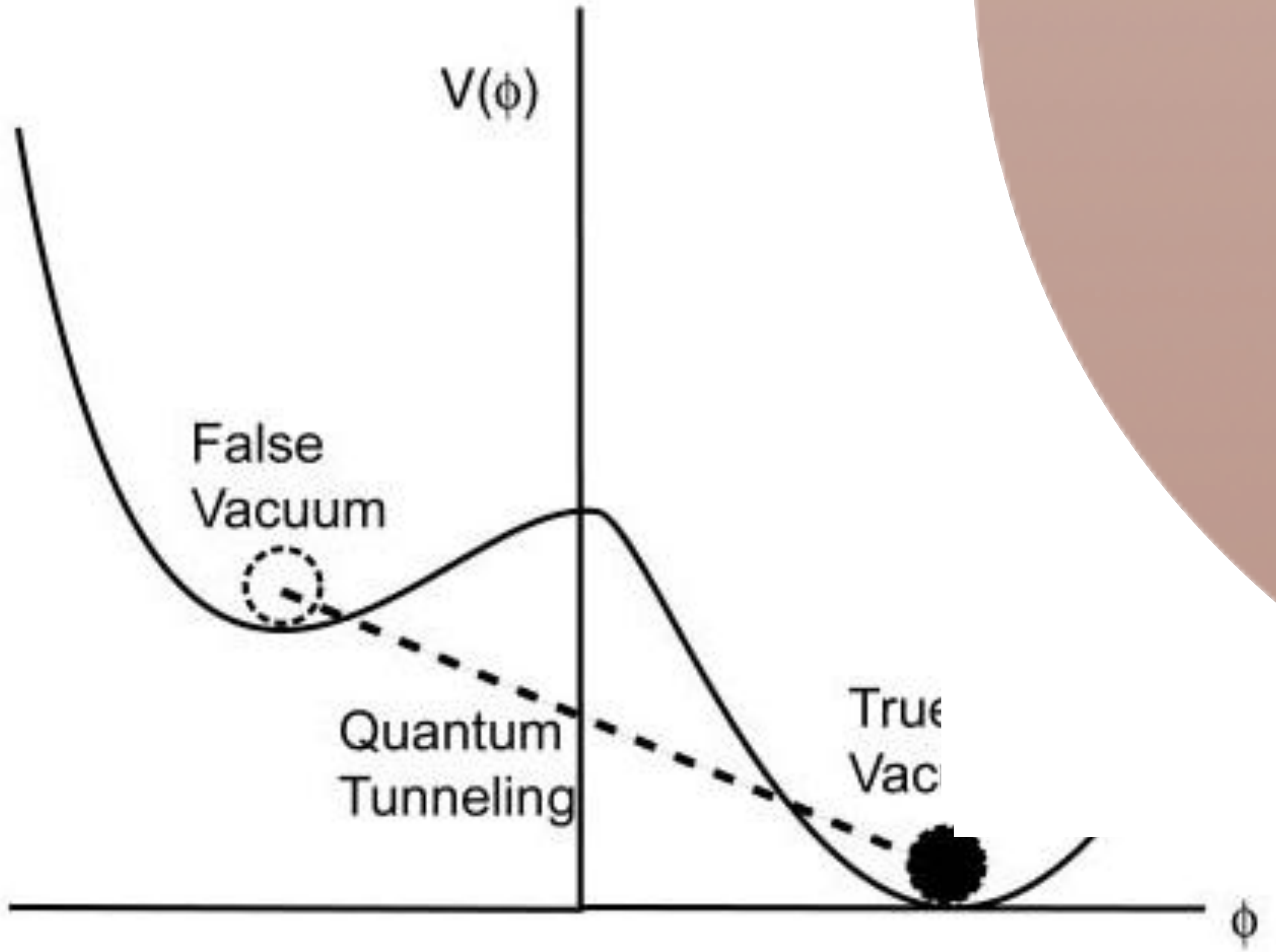

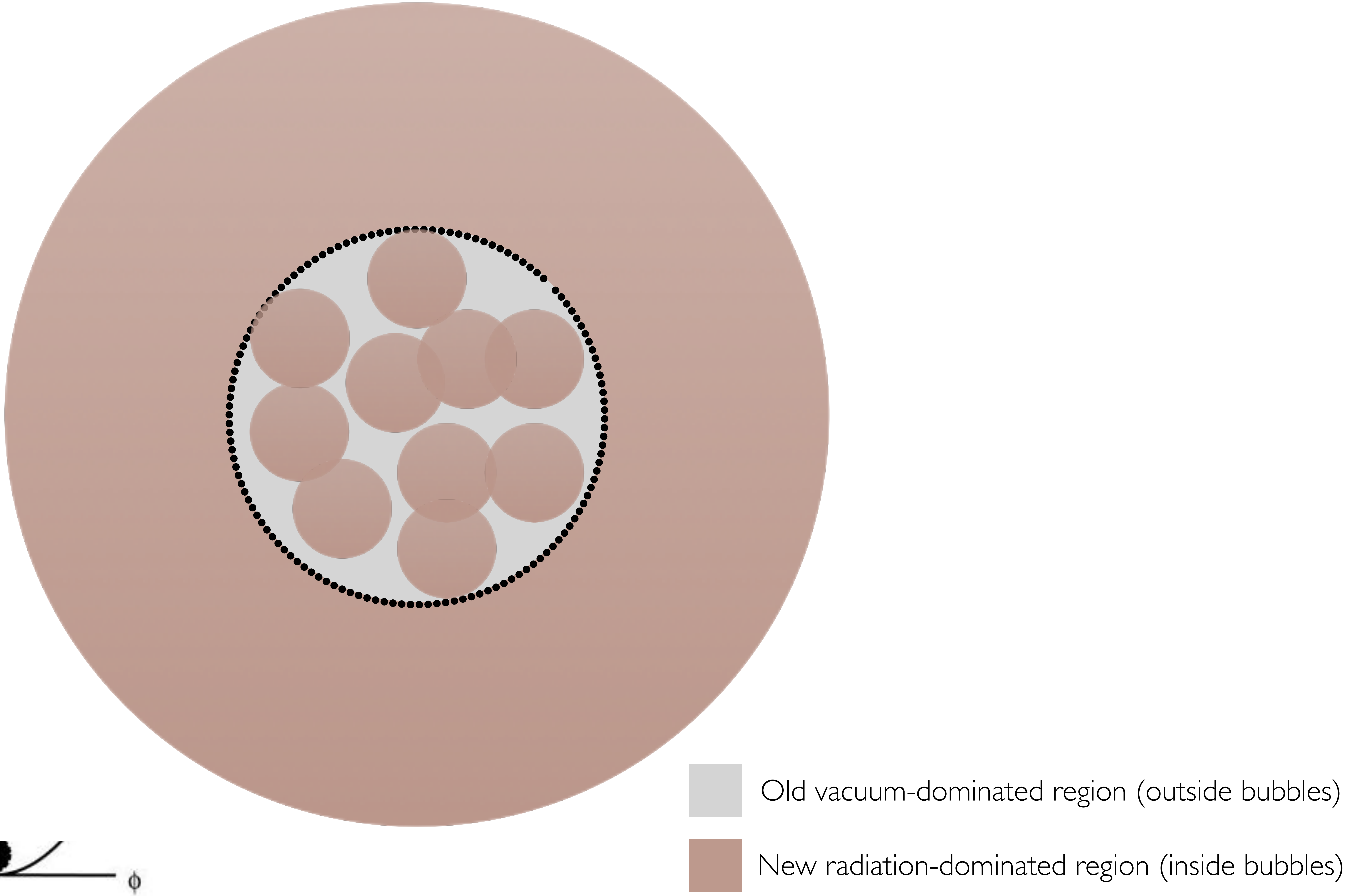

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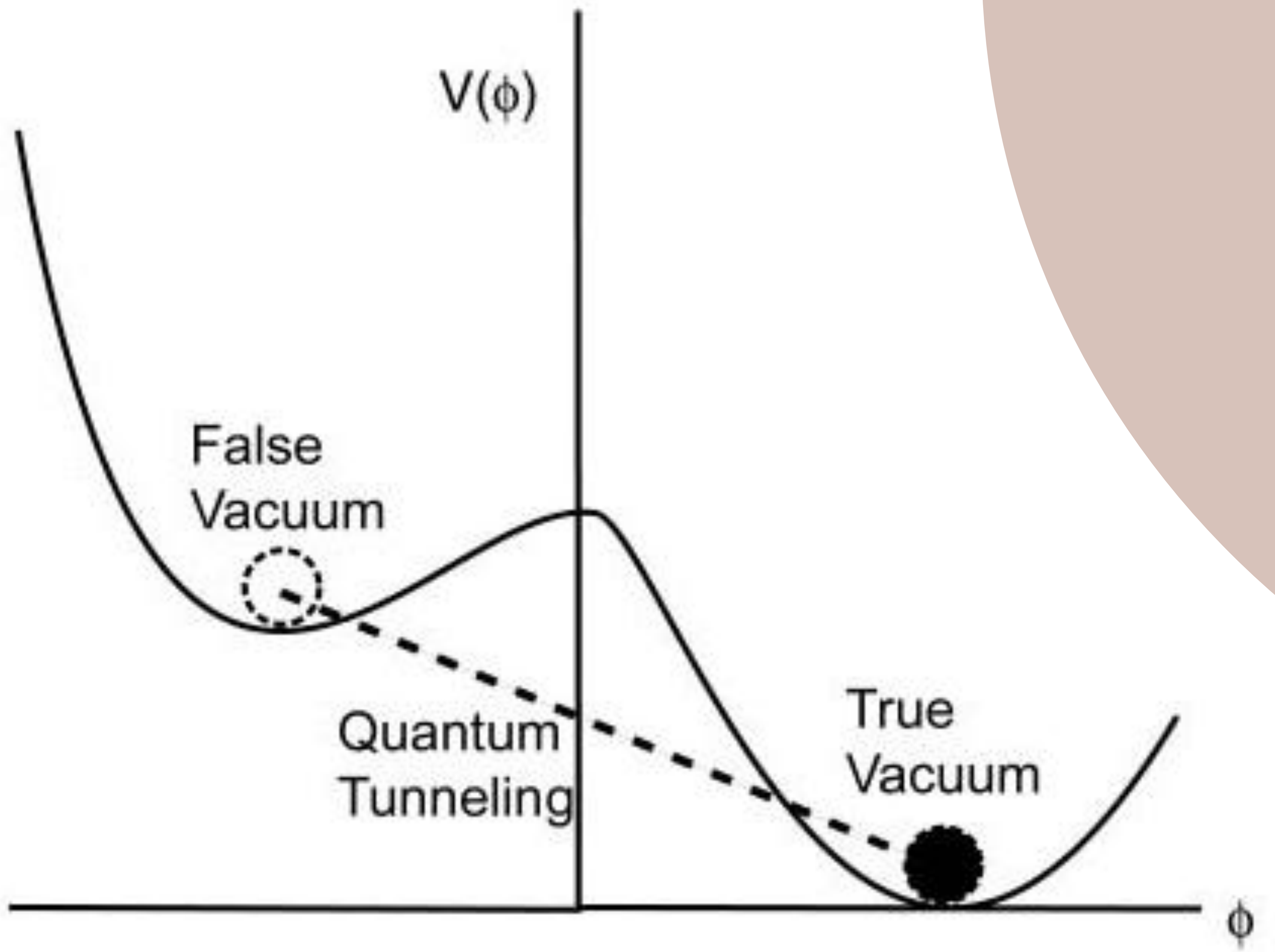

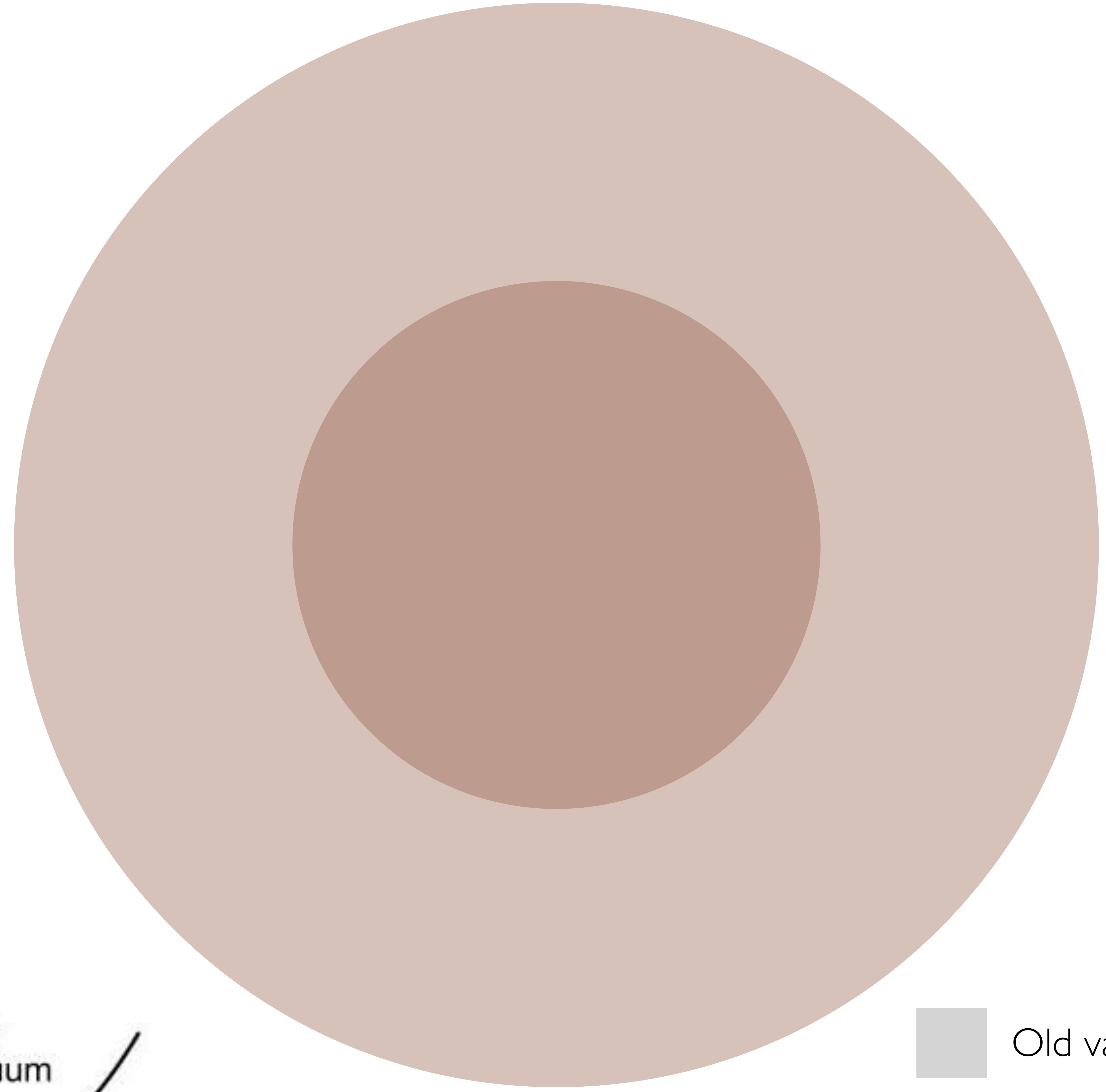

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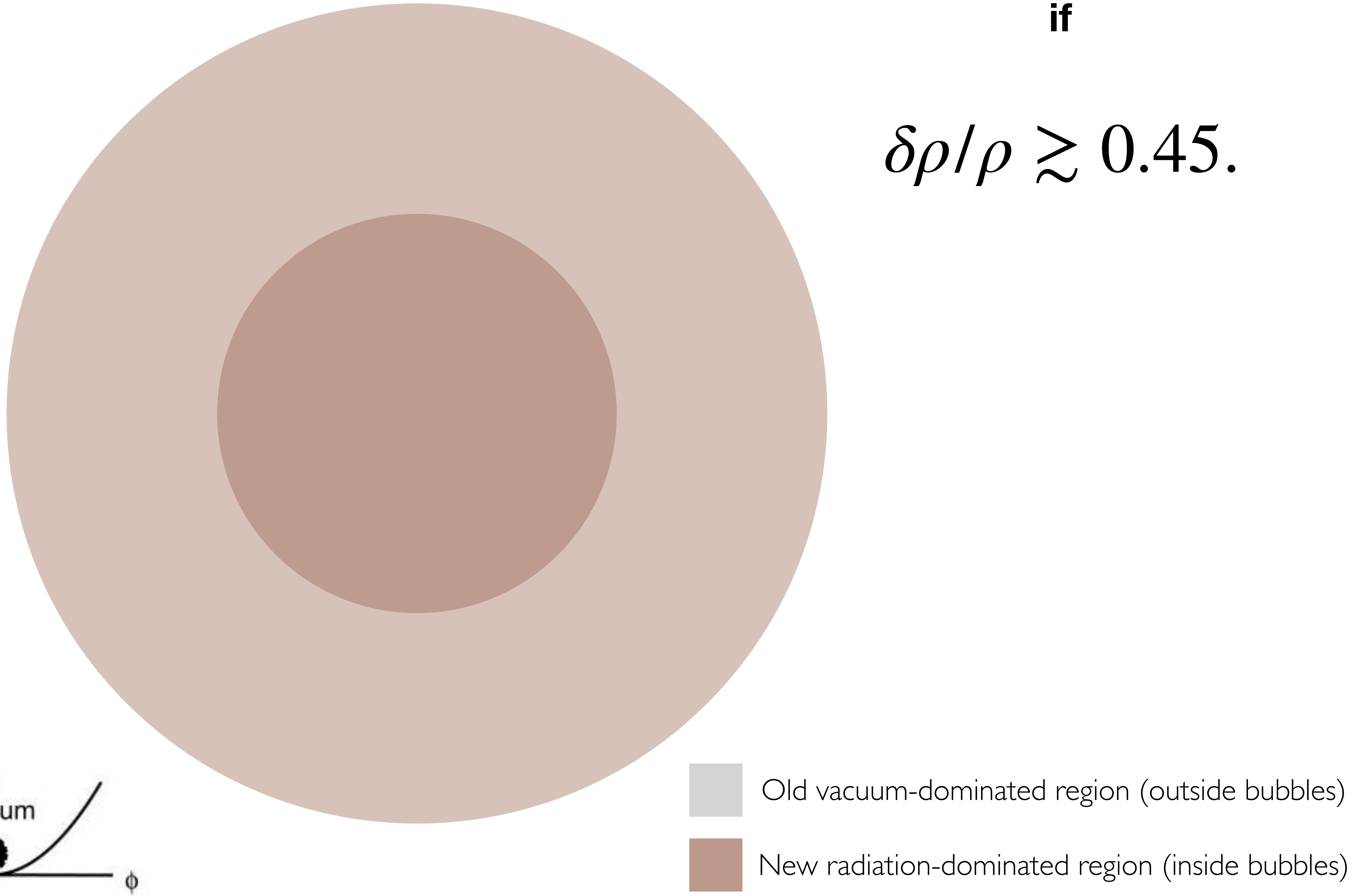
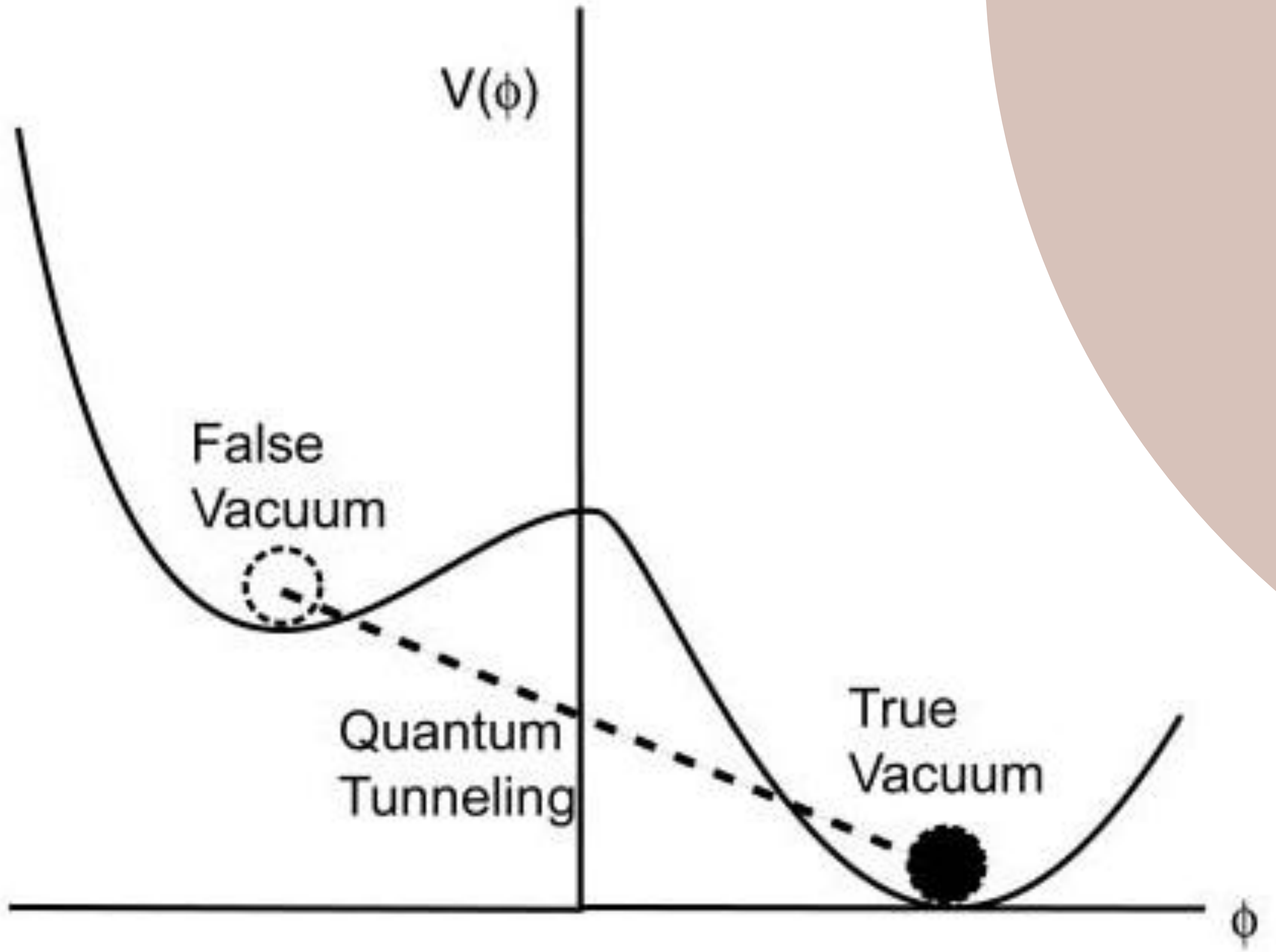


if

$$\delta\rho/\rho \gtrsim 0.45.$$



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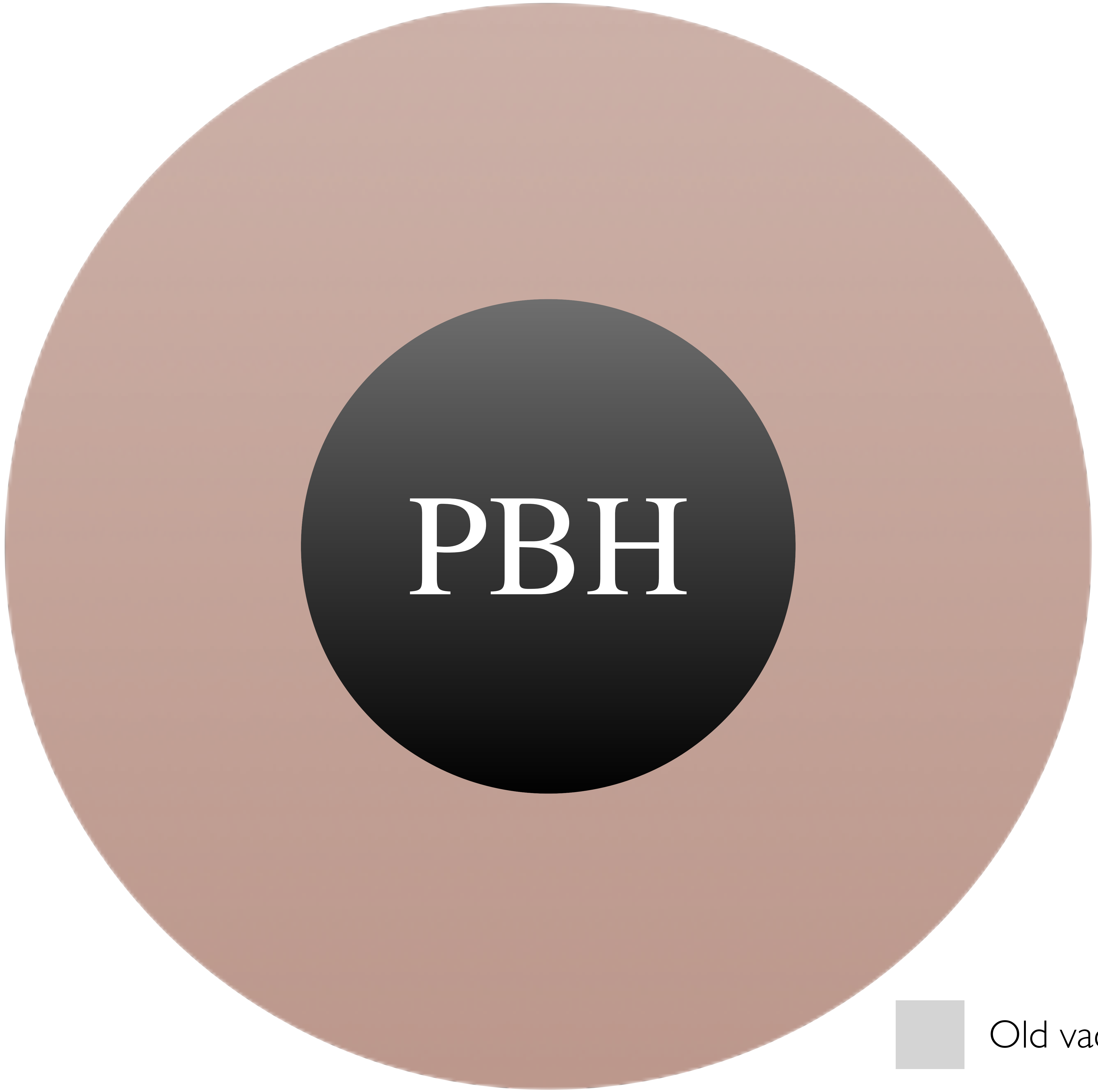
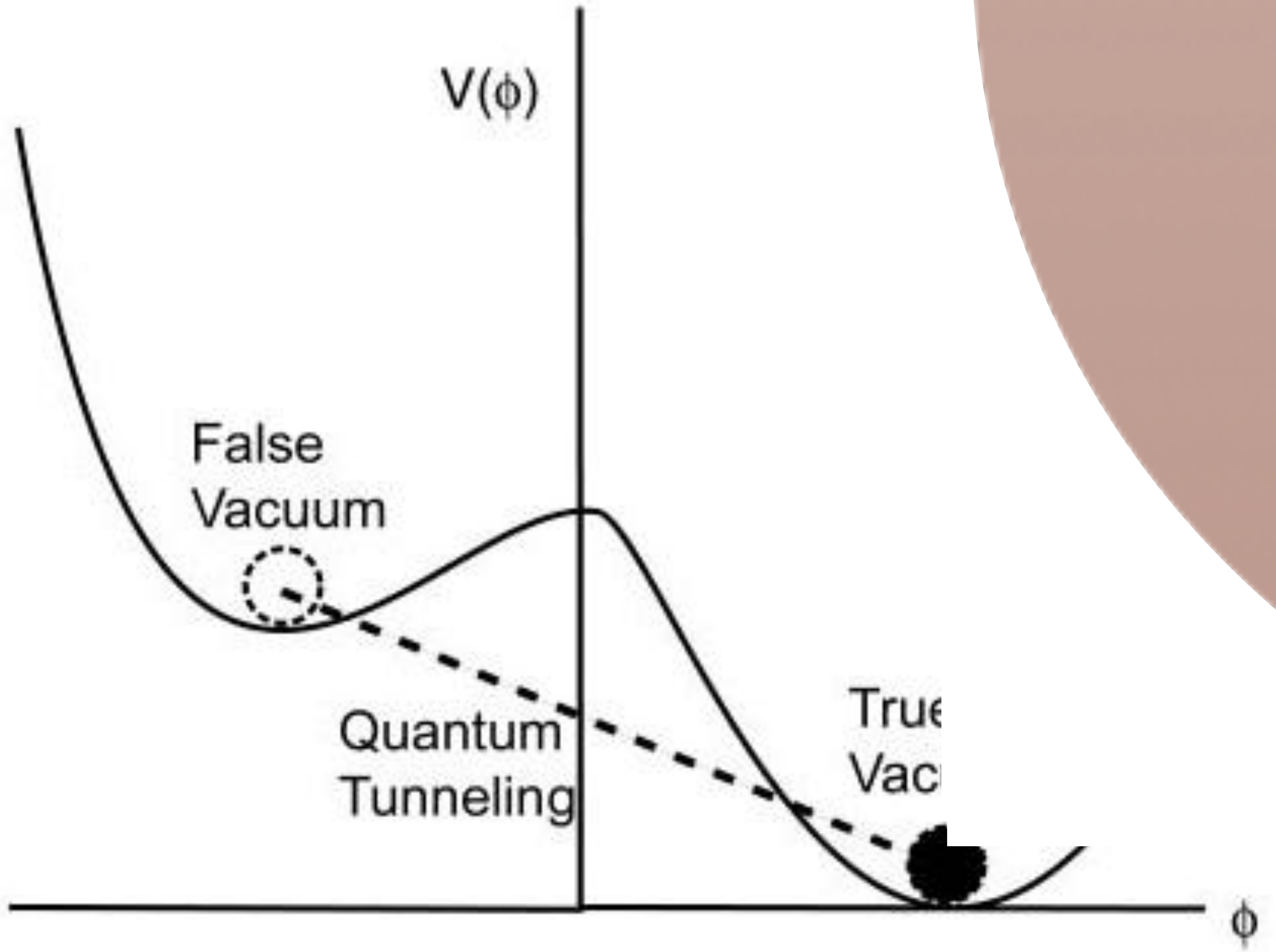


if

$$\delta\rho/\rho \gtrsim 0.45.$$

then

PBH



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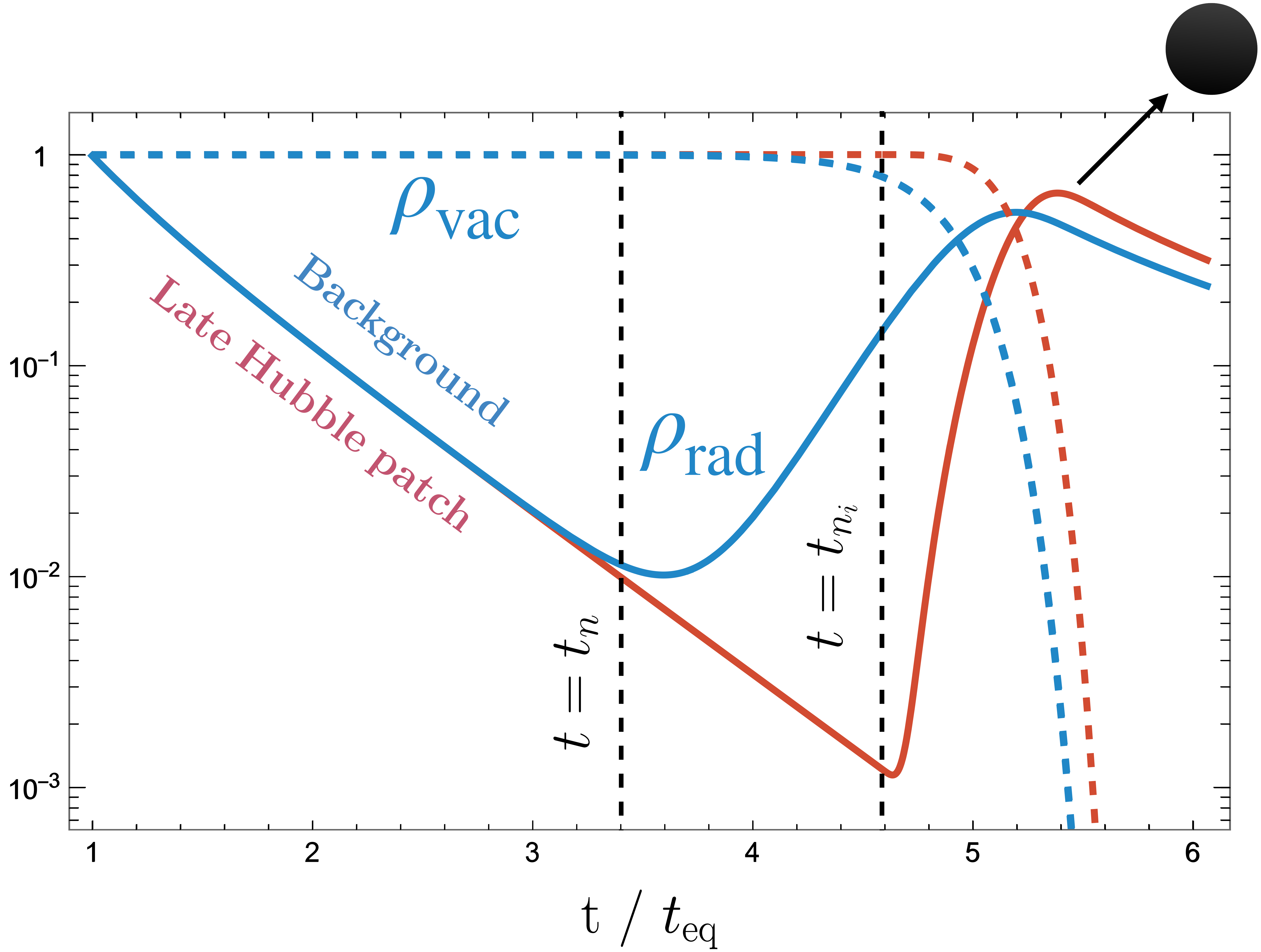


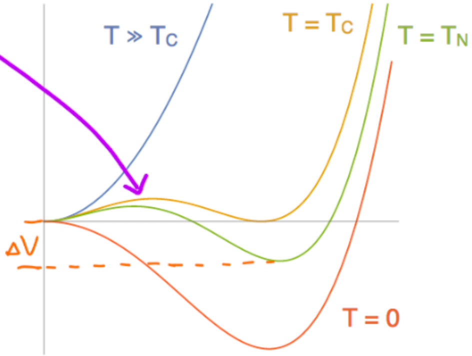
1
10^{-1}
10^{-2}
10^{-3}
1
2
3
4
5
6
$\rho_{\rm vac}$
$\rho_{\rm rad}$
Background
Late Hubble patch
$t = t_n$
$t = t_{n_i}$
t / $t_{\rm eq}$

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

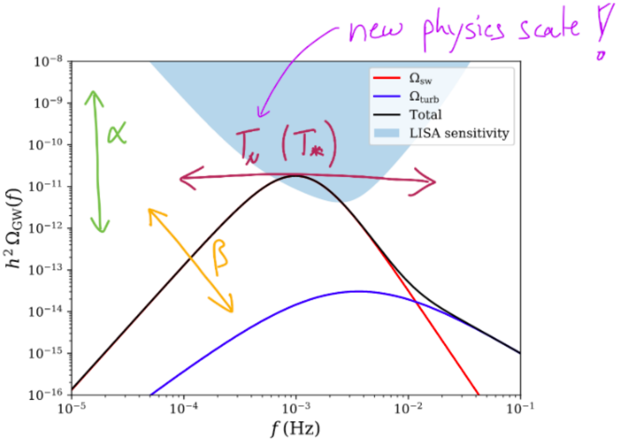
  ↓

  GWs
- Not in SM! Possible in BSM scenarios



Schwaller (Amsterdam (2019))

History of the Universe



Schwaller (Amsterdam, 2019)

History of the Universe

Strong CP Problem:

$$\frac{\theta}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \qquad \theta + \mathrm{Arg}[\mathrm{Det}(y_u y_d)] < 10^{-10}$$

Axion solution:

$$\theta \to \frac{a(x)}{f} \qquad \mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

[Peccei-Quinn '77 Weinberg-Wilczek '78]

- PQWW axion:
  Axion identified with the phase of the Higgs in a 2HDM ($f_a \sim V_{EW}$ was quickly ruled out long ago) [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

The need to require $f_a \gg V_{EW}$: "invisible axion"

- DSFZ Axion: SM quarks and Higgs charged under PQ.
  Requires 2HDM + 1 scalar singlet. SM leptons can also be charged. [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]
- KSVZ axion (or QCD axion, or hadronic axion):
  All SM fields are neutral under PQ. QCD anomaly is induced by new quarks, vectorlike under the SM, chiral under PQ.
  [Kim (1979), Shifman, Vainshtein, Sakharov (1980)]

History of the Universe

Slaying Axion-Like Particles via Gravitational Waves and Primordial Black Holes from Supercooled Phase Transition

Angela Conaci,[a,b] **Luigi Delle Rose,**[a,b] **P. S. Bhupal Dev,**[c] **Anish Ghoshal**[d]

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Washington University, St. Louis, Missouri 63130, USA
[d] Institute of Theoretical Physics, Faculty of Physics, University of Warsaw,
ul. Pasteura 5, 02-093 Warsaw, Poland

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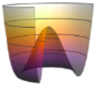
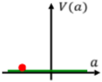
History of the Universe

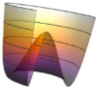
- **As long as $\Lambda_{QCD} < T < f_a$:**
  $U(1)_{PQ}$ broken only spontaneously,
  $m_a = 0$, $\langle a_0 \rangle = \theta_0 f_a \sim f_a$

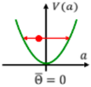




- **As soon as $T \sim \Lambda_{QCD}$:**
  $U(1)_{PQ}$ explicit breaking (instanton effects)
  $m_a(T)$ turns on. When $m_a(T) > H \sim 10^{-9}$ eV,
  $\langle a_0 \rangle \longrightarrow 0$ and starts oscillating undamped

$$\ddot{a} + 3H\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$





- **Energy stored in oscillations behaves as CDM**

History of the Universe

- Axion or ALP couplings to SM particles are always suppressed by inverse powers of $U(1)_{PQ}$ symmetry breaking scale f_a.
- Phenomenological scalar with complex singlet scalar Φ:

$$\Phi(x) = \frac{1}{\sqrt{2}}(f_a + \phi(x))e^{ia(x)/f_a} \quad (1)$$

- Spontaneous breaking of U(1) may lead to strong first-order phase transition at the f_a scale & generate GW signals to be detected at the current and future detectors.

History of the Universe

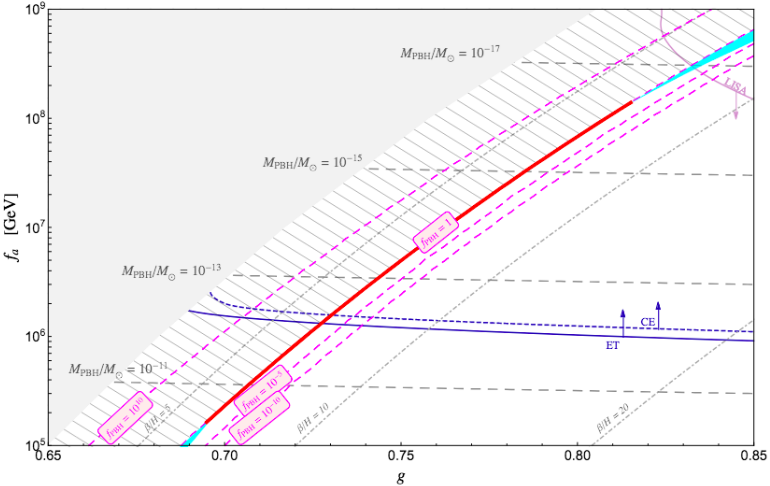
$$\mathcal{V}(\phi,T) = \mathcal{V}_0(\phi) + \mathcal{V}_{\rm CW}(\phi) + \mathcal{V}_T(\phi,T),$$

- Tree-level: $$\mathcal{V}_0 = -\mu^2|H|^2 + \lambda|H|^4 + \kappa|\Phi|^2|H|^2 + \lambda_a\left(|\Phi|^2 - \frac{1}{2}f_a^2\right)^2 . \\ = \frac{\lambda_a}{4}(\phi^2 - f_a^2)^2 + \left[\frac{\kappa}{2}\phi^2 - \mu^2\right]\left(\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right) \\ + \lambda\left[\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right]^2 .$$
- One-loop: $$\mathcal{V}_{\rm CW}(\phi) = \sum_i (-1)^F n_i \frac{m_i^4(\phi)}{64\pi^2}\left[\log\frac{m_i^2(\phi)}{\Lambda^2} - C_i\right] .$$
- Finite-temperature: $$\mathcal{V}_T(\phi,T) = \sum_i (-1)^F n_i \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m_i^2(\phi)}{T^2}\right),$$
- Temperature-dependent mass terms:

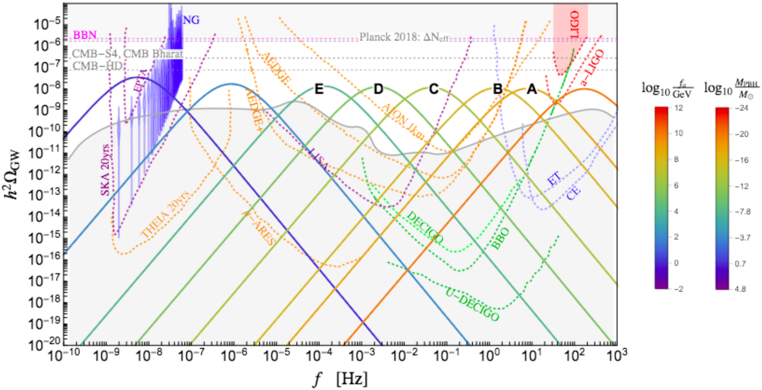
$$\Pi_h(T) = \Pi_{G_{0,\pm}}(T) = \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda + 4\kappa\right)T^2 ,$$
$$\Pi_\phi(T) = \frac{1}{3}(\kappa + 2\lambda_a)T^2 .$$

[Dolan, Jackiw (PRD '74); Arnold, Espinosa (PRD '93); Curtin, Meade, Ramani (EPJC '18)]

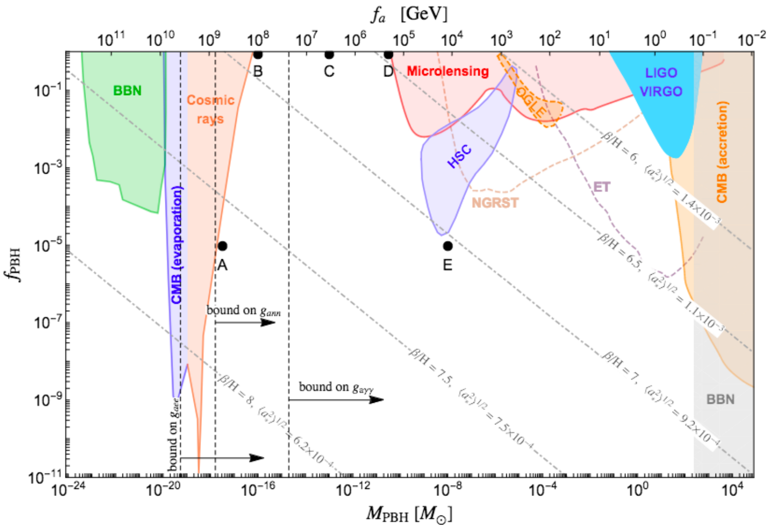
History of the Universe



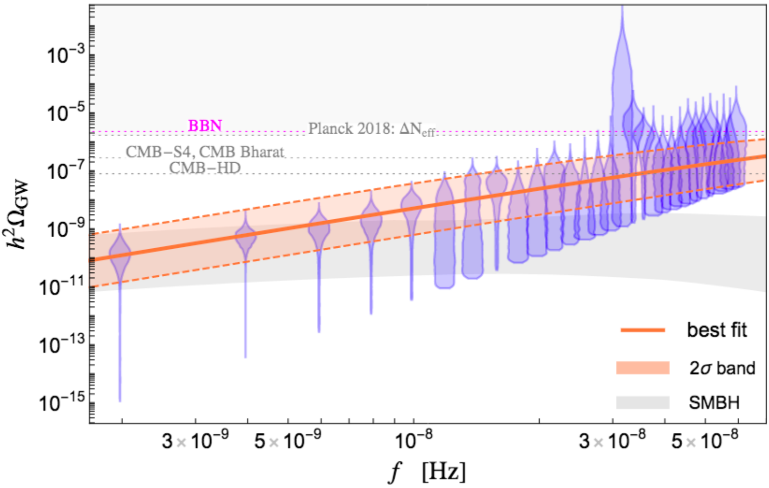
History of the Universe



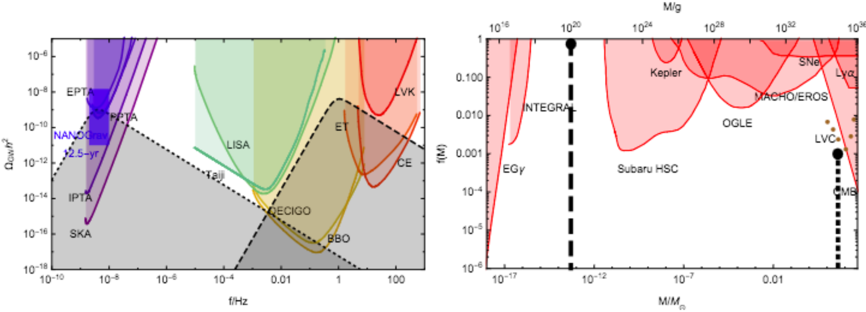
History of the Universe

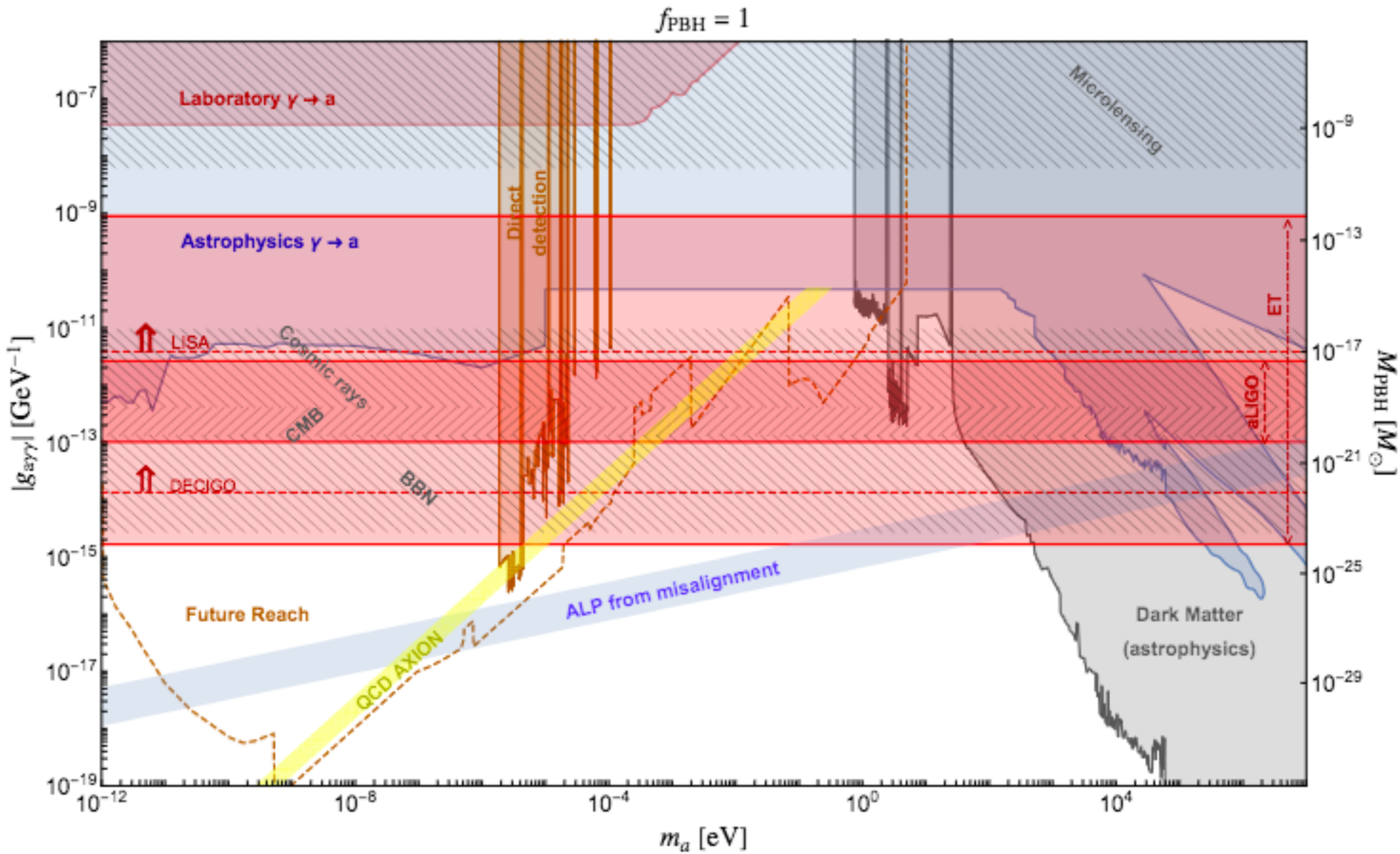


History of the Universe

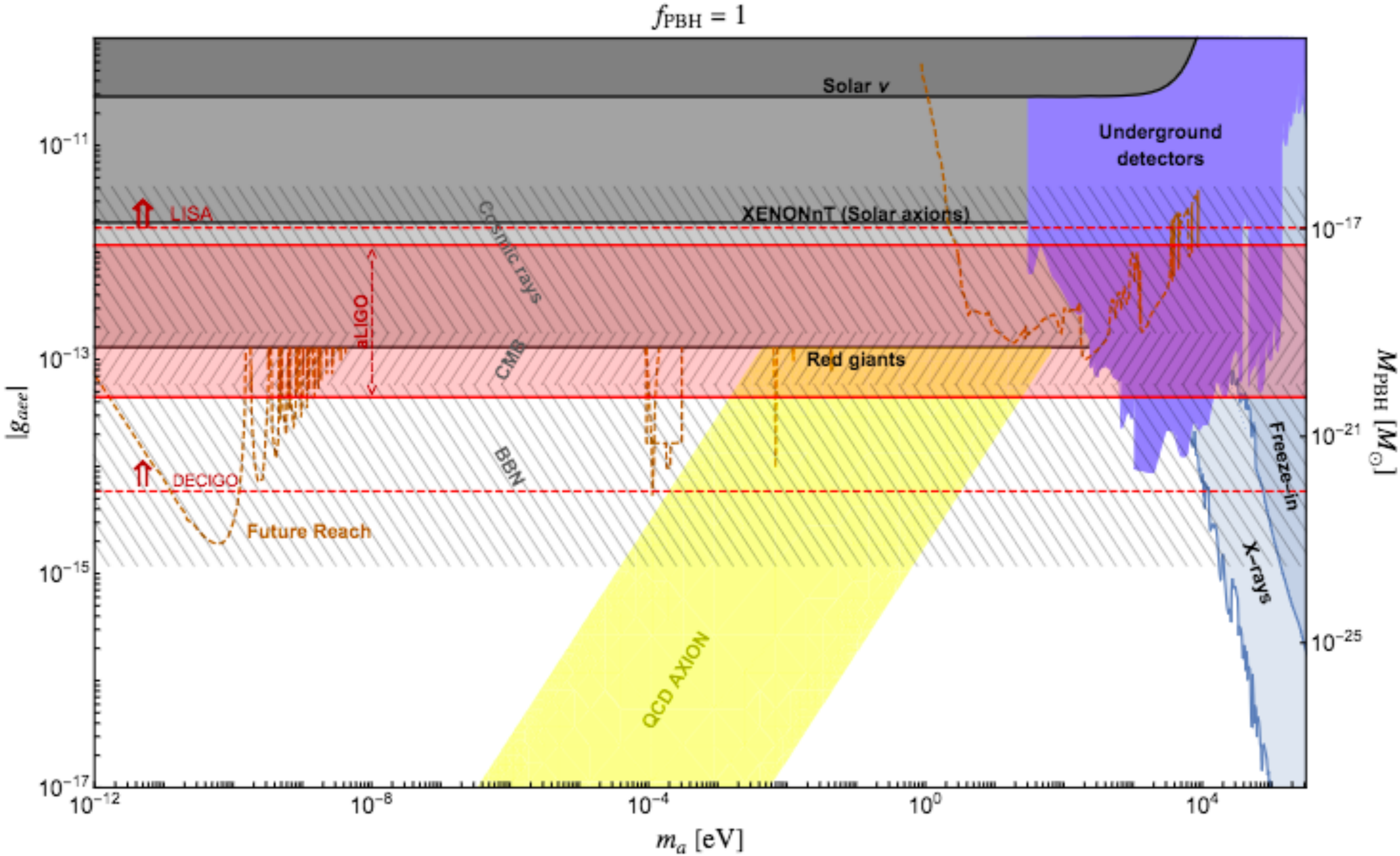


History of the Universe

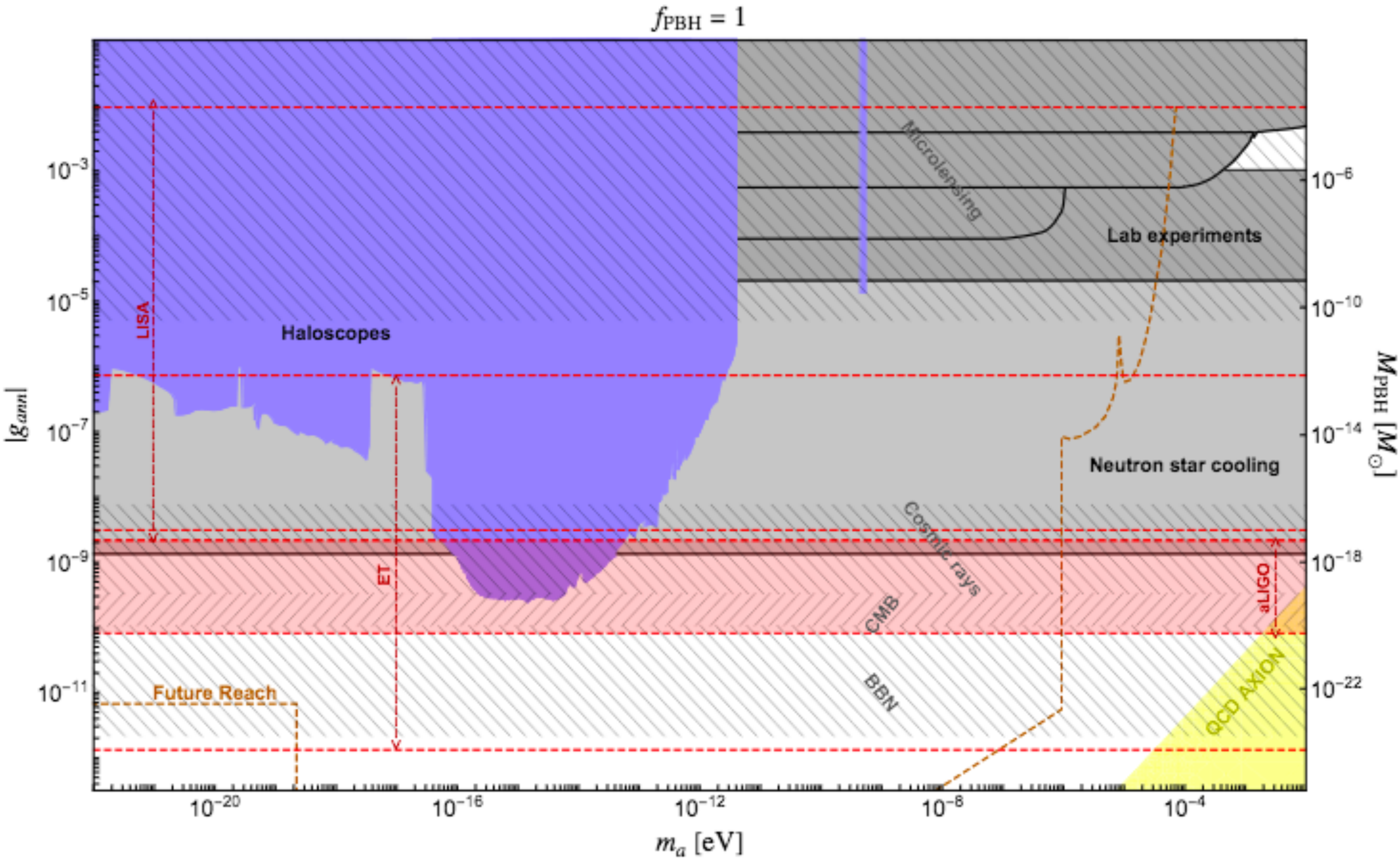




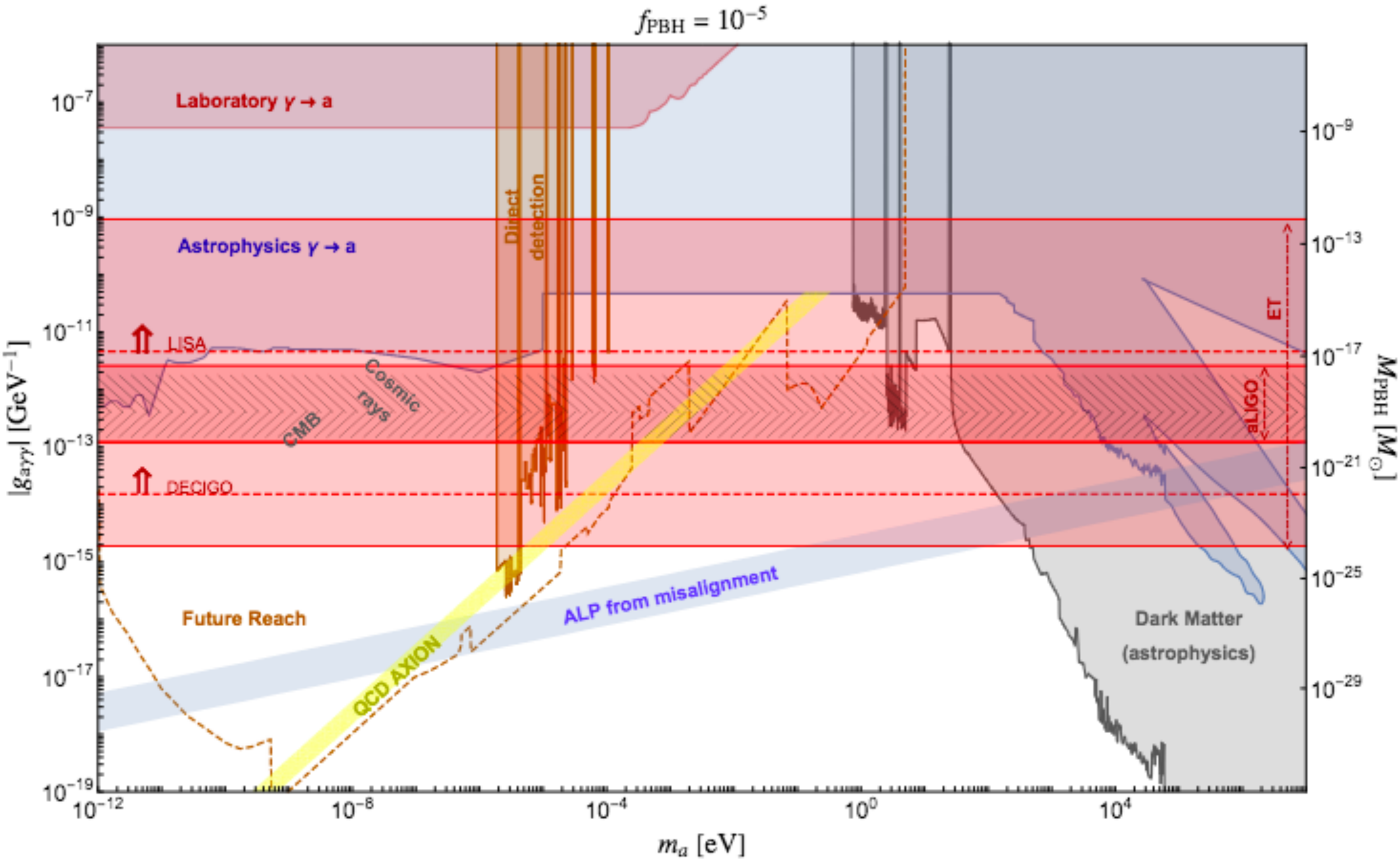
$f_{PBH} = 1$
Laboratory $\gamma \to a$
Astrophysics $\gamma \to a$
Microlensing
Direct detection
LISA
Cosmic rays
CMB
BBN
DECIGO
ET
aLIGO
Future Reach
ALP from misalignment
QCD AXION
Dark Matter (astrophysics)
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
M_{PBH} [$M_\odot$]
m_a [eV]



$f_{\rm PBH} = 1$
Solar ν
Underground detectors
XENONnT (Solar axions)
LISA
Cosmic rays
aLIGO
CMB
Red giants
BBN
DECIGO
Future Reach
QCD AXION
Freeze-in
X-rays
$|g_{aee}|$
10^{-11}
10^{-13}
10^{-15}
10^{-17}
m_a [eV]
10^{-12}
10^{-8}
10^{-4}
10^{0}
10^{4}
$M_{\rm PBH}$ [$M_\odot$]
10^{-17}
10^{-21}
10^{-25}



$f_{\rm PBH} = 1$
Haloscopes
LISA
ET
Microlensing
Lab experiments
Neutron star cooling
Cosmic rays
CMB
BBN
aLIGO
QCD AXION
Future Reach
$|g_{ann}|$
$M_{\rm PBH}$ [$M_\odot$]
m_a [eV]



$f_{\rm PBH} = 10^{-5}$
Laboratory γ → a
Astrophysics γ → a
Direct detection
LISA
Cosmic rays
CMB
DECIGO
Future Reach
QCD AXION
ALP from misalignment
Dark Matter (astrophysics)
ET
aLIGO
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
$M_{\rm PBH}$ [$M_\odot$]

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.

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

ICTS INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

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Organizers:

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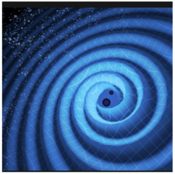
Subhendra Mohanty (IIT-Kanpur)

Tathagata Ghosh (HRI, Prayagraj)

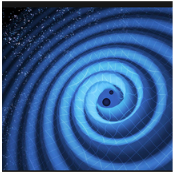
Anish Ghoshal (University of Warsaw, Poland)

Gravitational Waves Workshop in ICTS

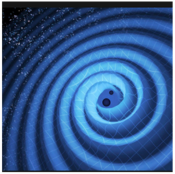
You are welcome, registration to open soon !!



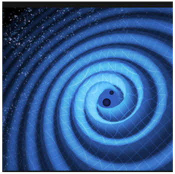
Day 1-3: Phase Transitions GW



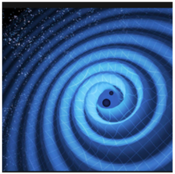
Day 4: Topological Defects GW



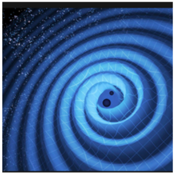
Day 5-7: Inflationary Sources GW



Day 8: Field Theory aspects GW



Day 9-10: GW experiments + PTA session



Week 1: Pedagogical Lectures

Thank You