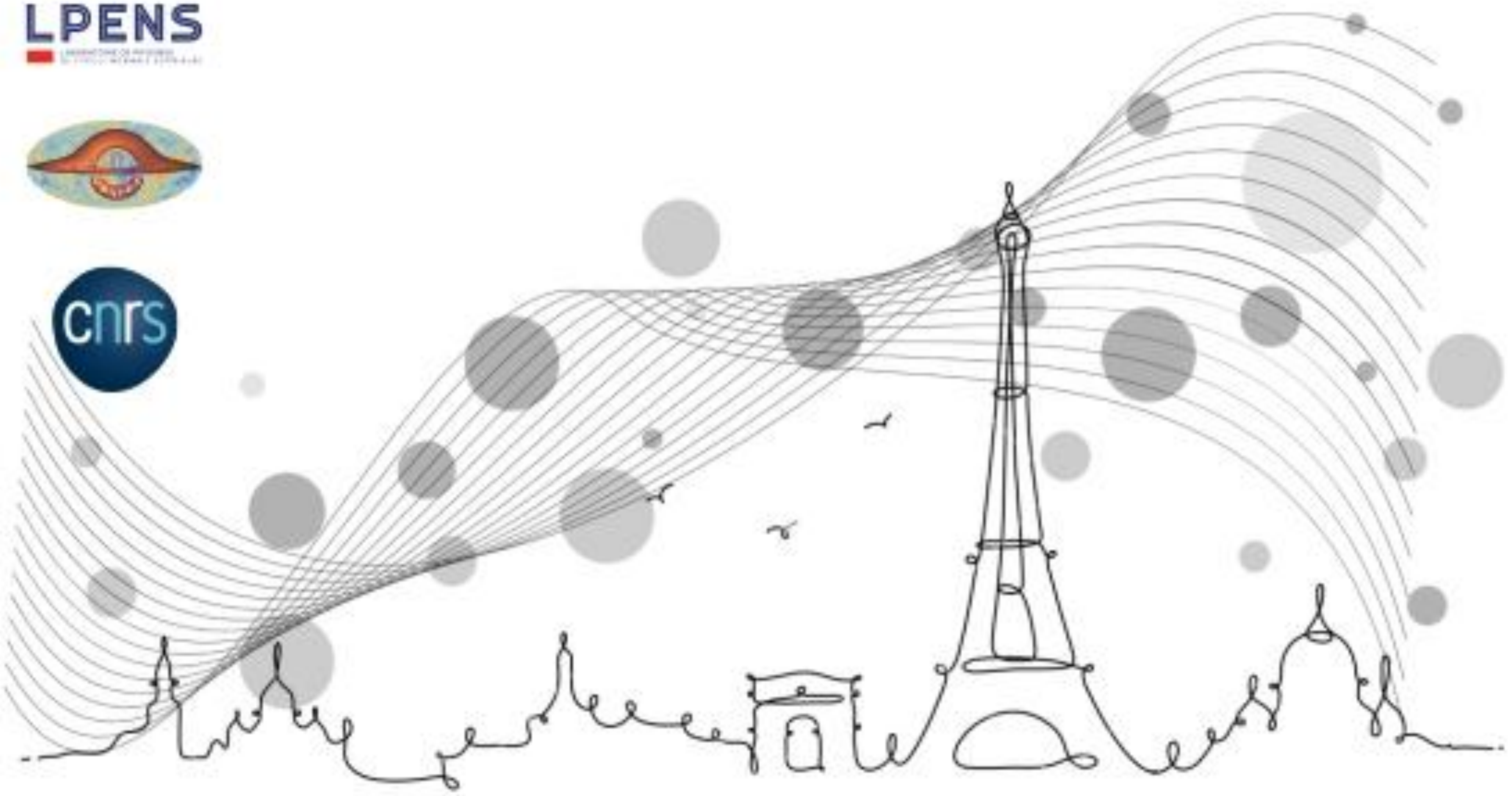
Primordial Black Holes from supercooled phase transitions

Yann Gouttenoire

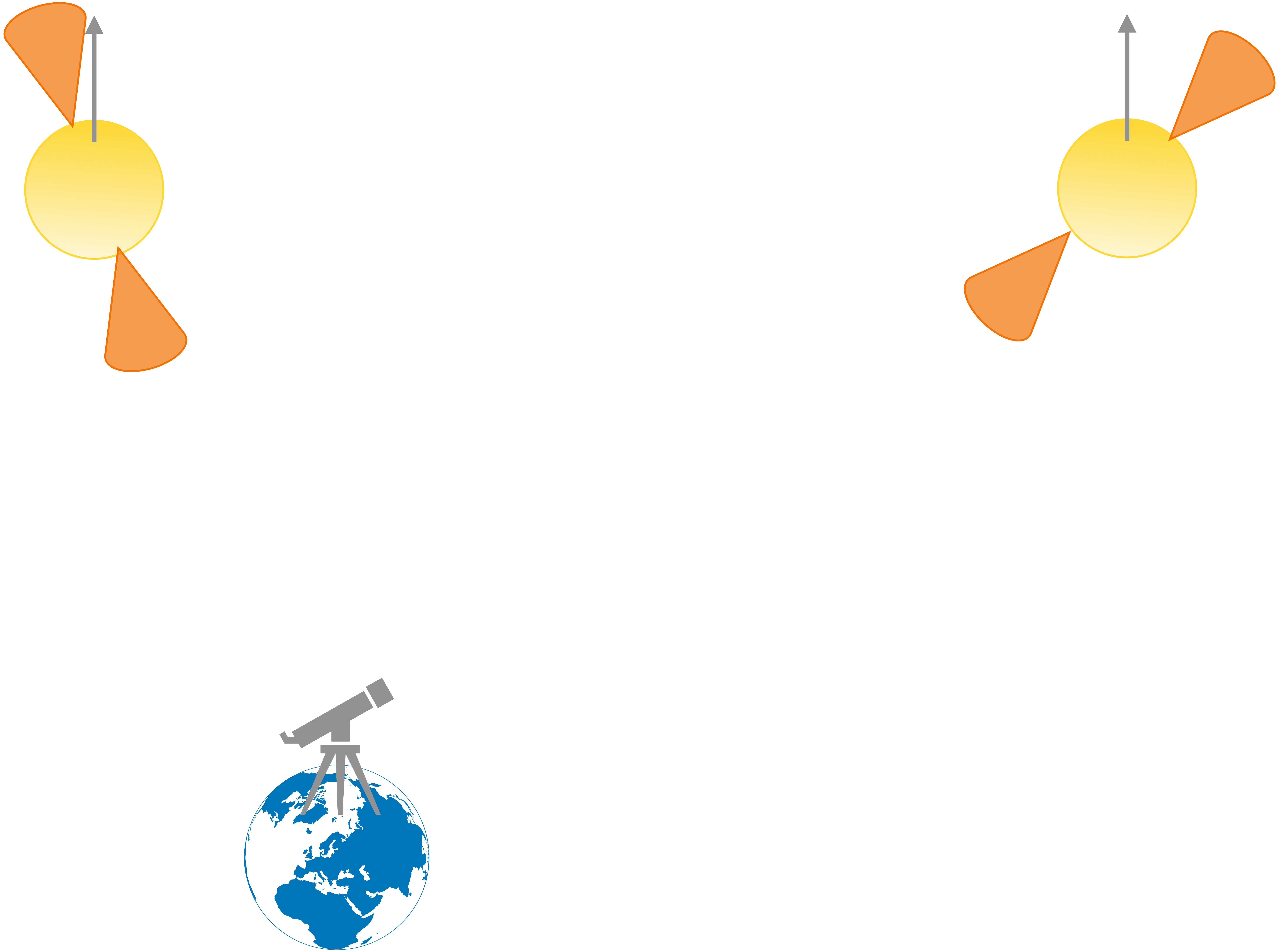
28th November 2023

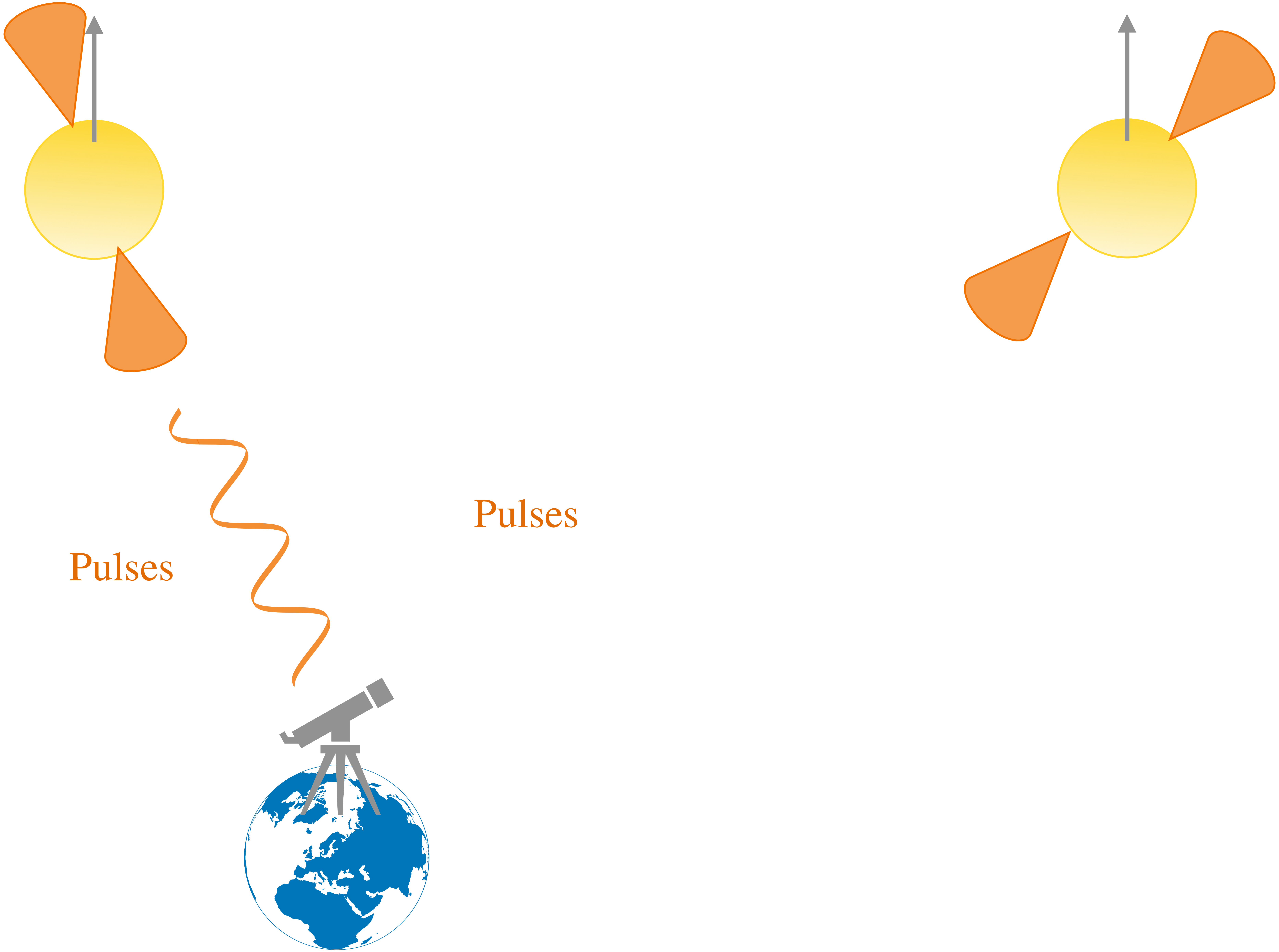


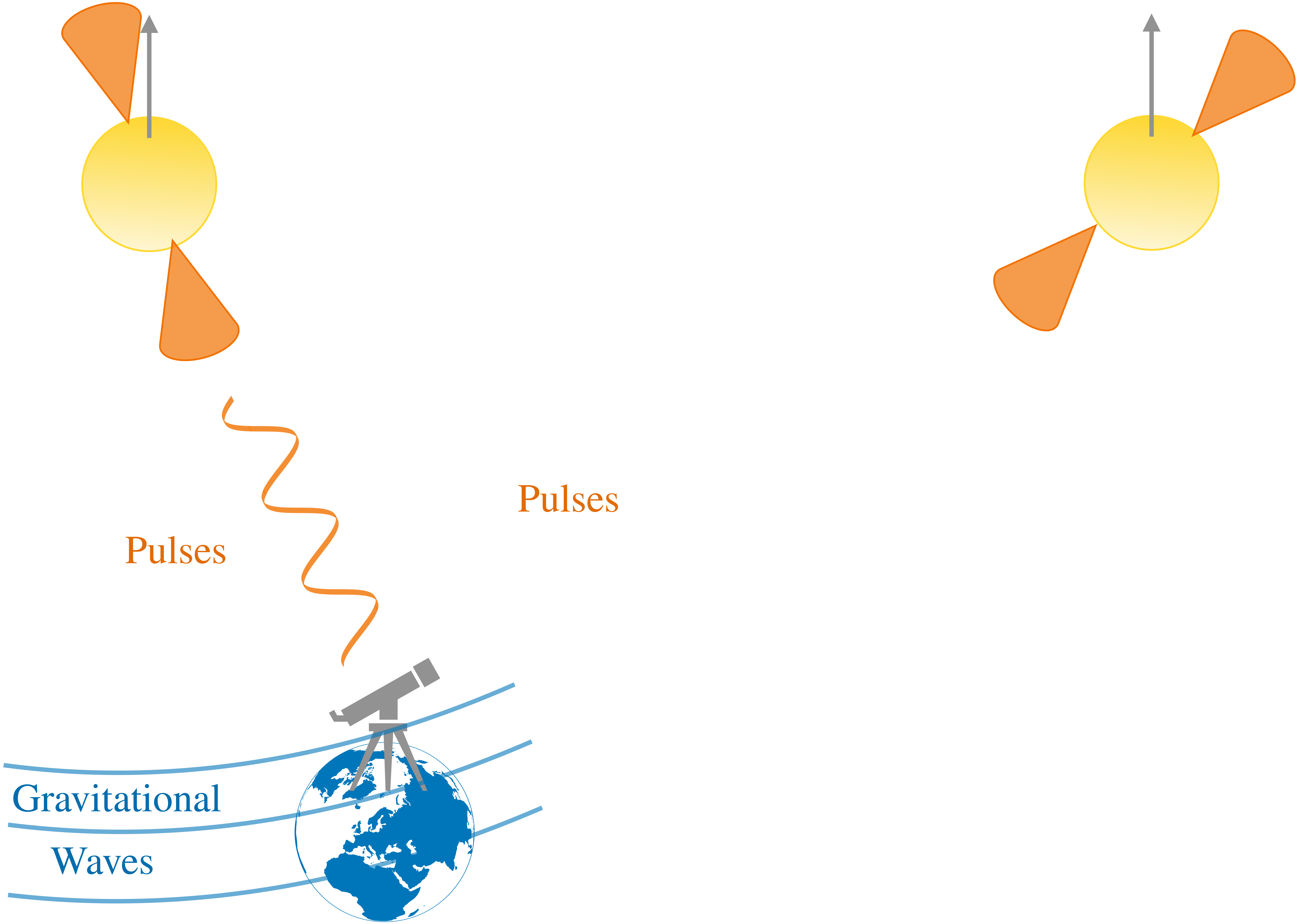
Paris workshop on primordial black holes and gravitational waves

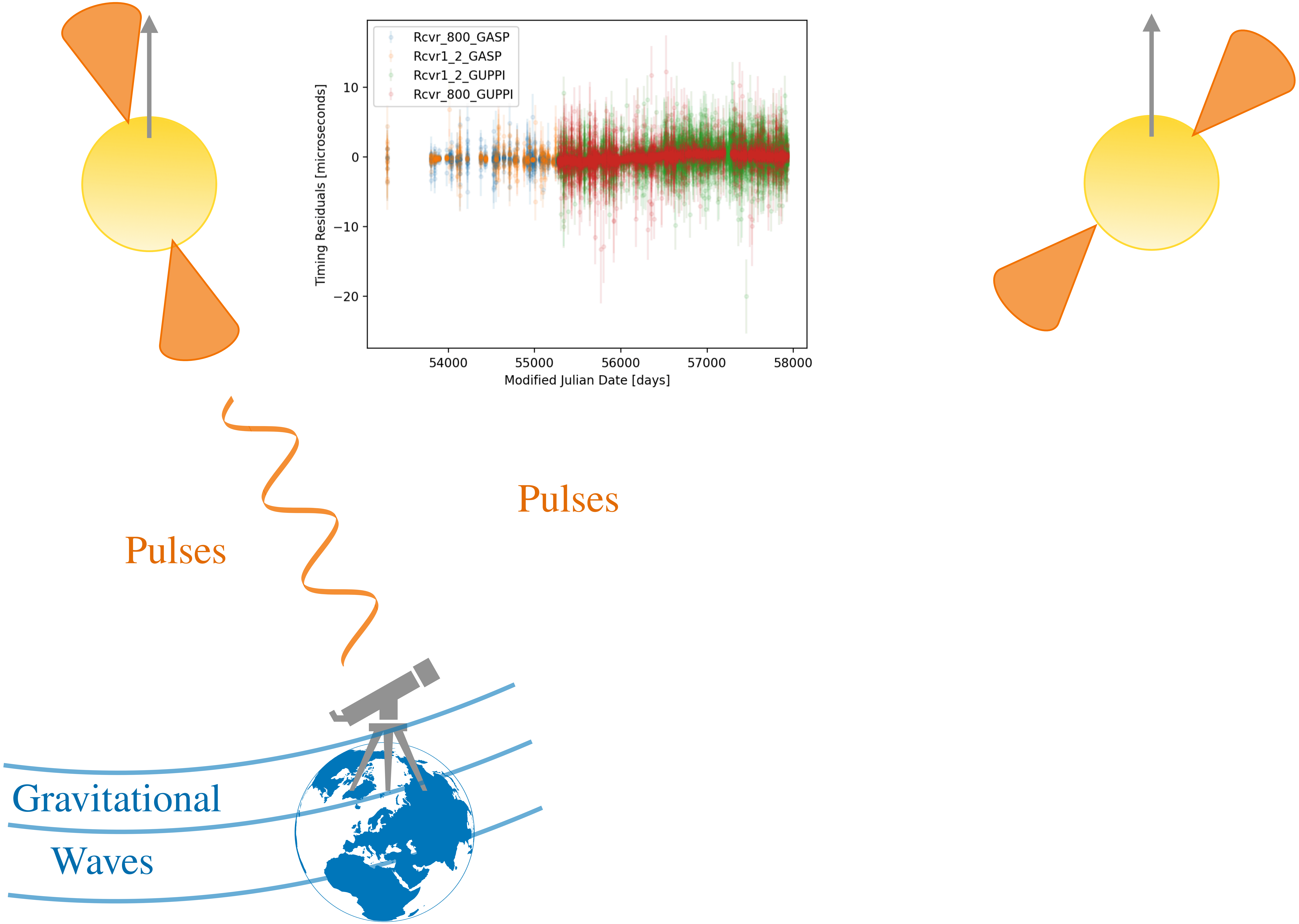
Postdoc in Tel Aviv U.

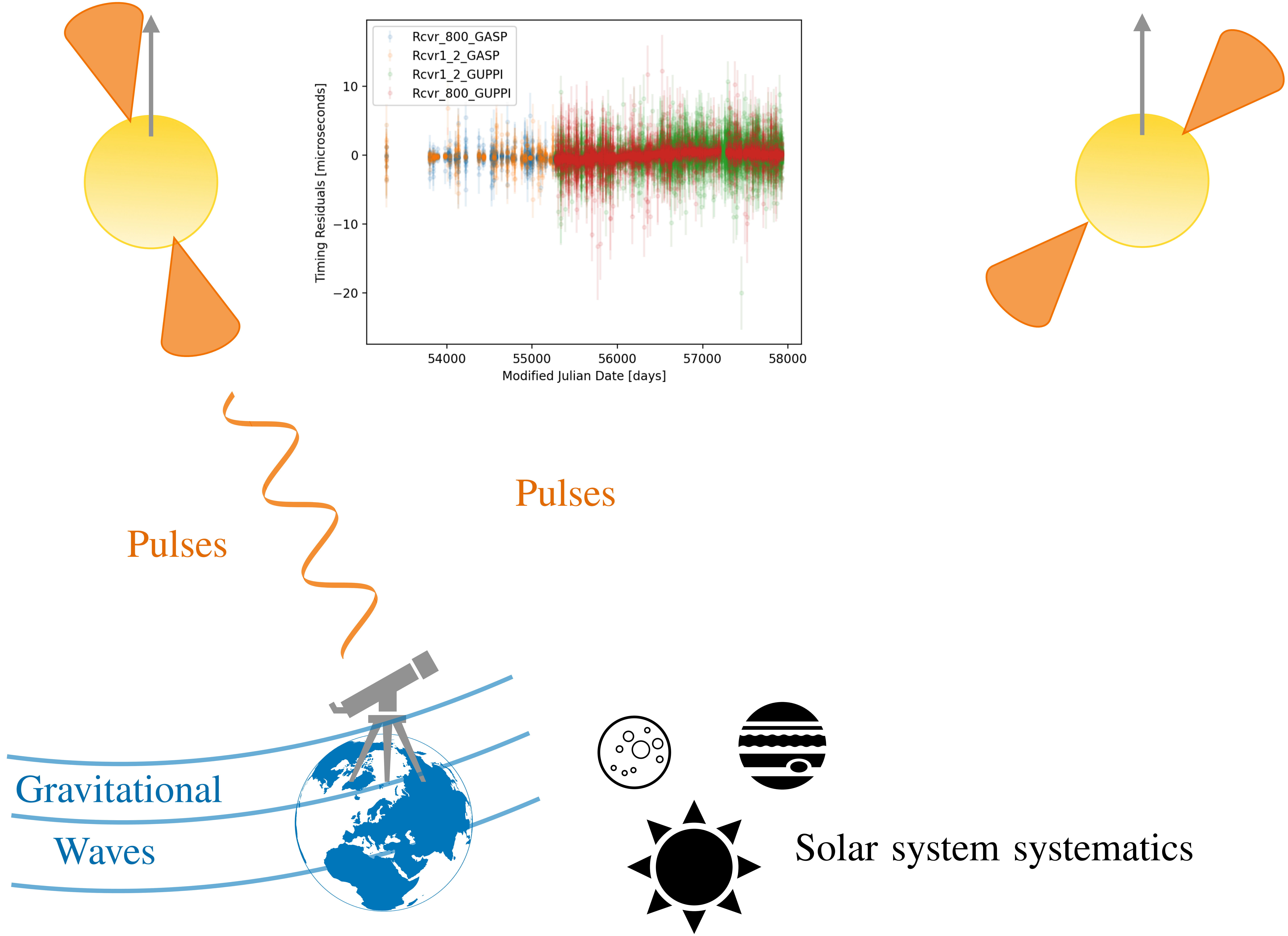
Azrieli International Postdoctoral Fellows

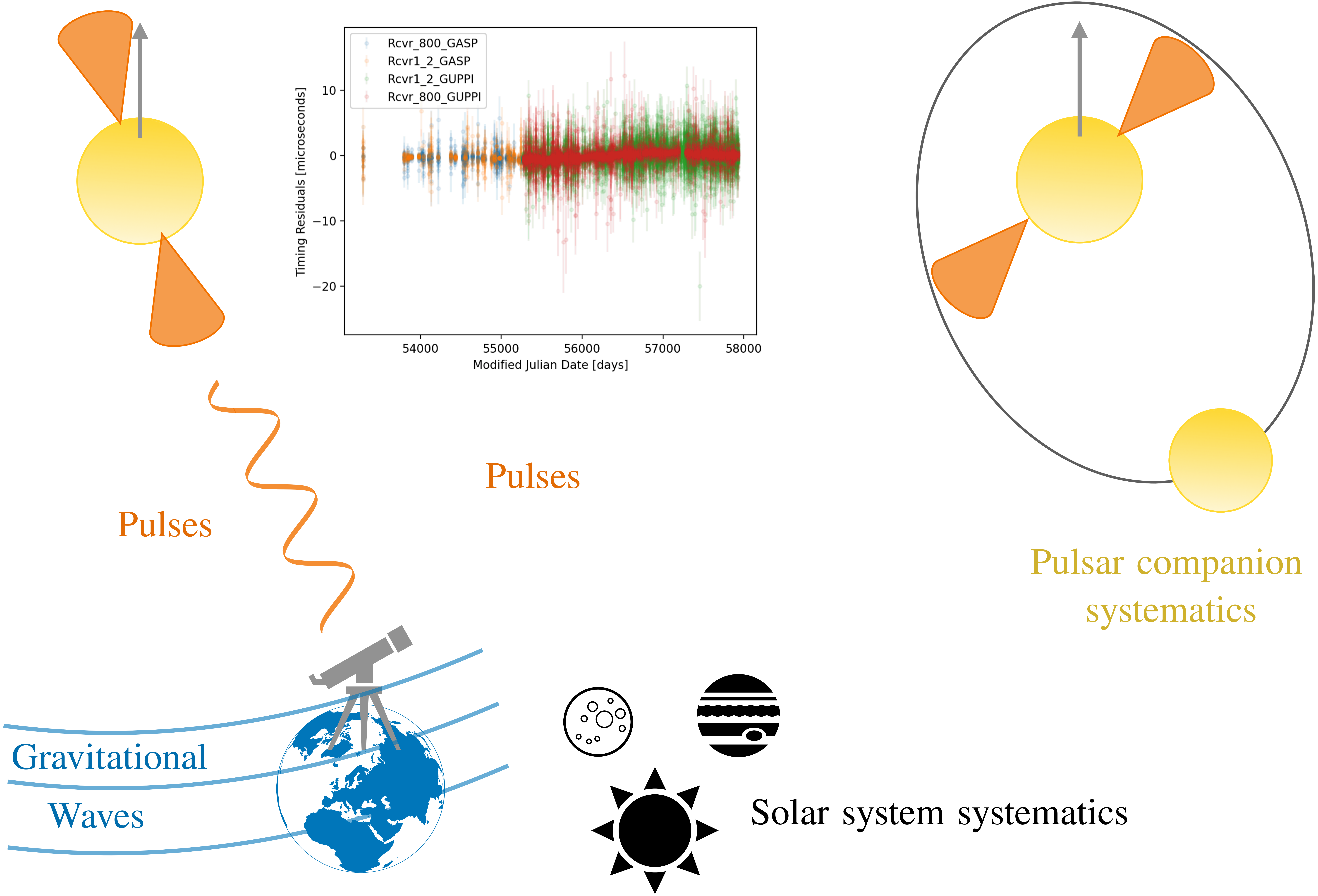



Pulses
Pulses

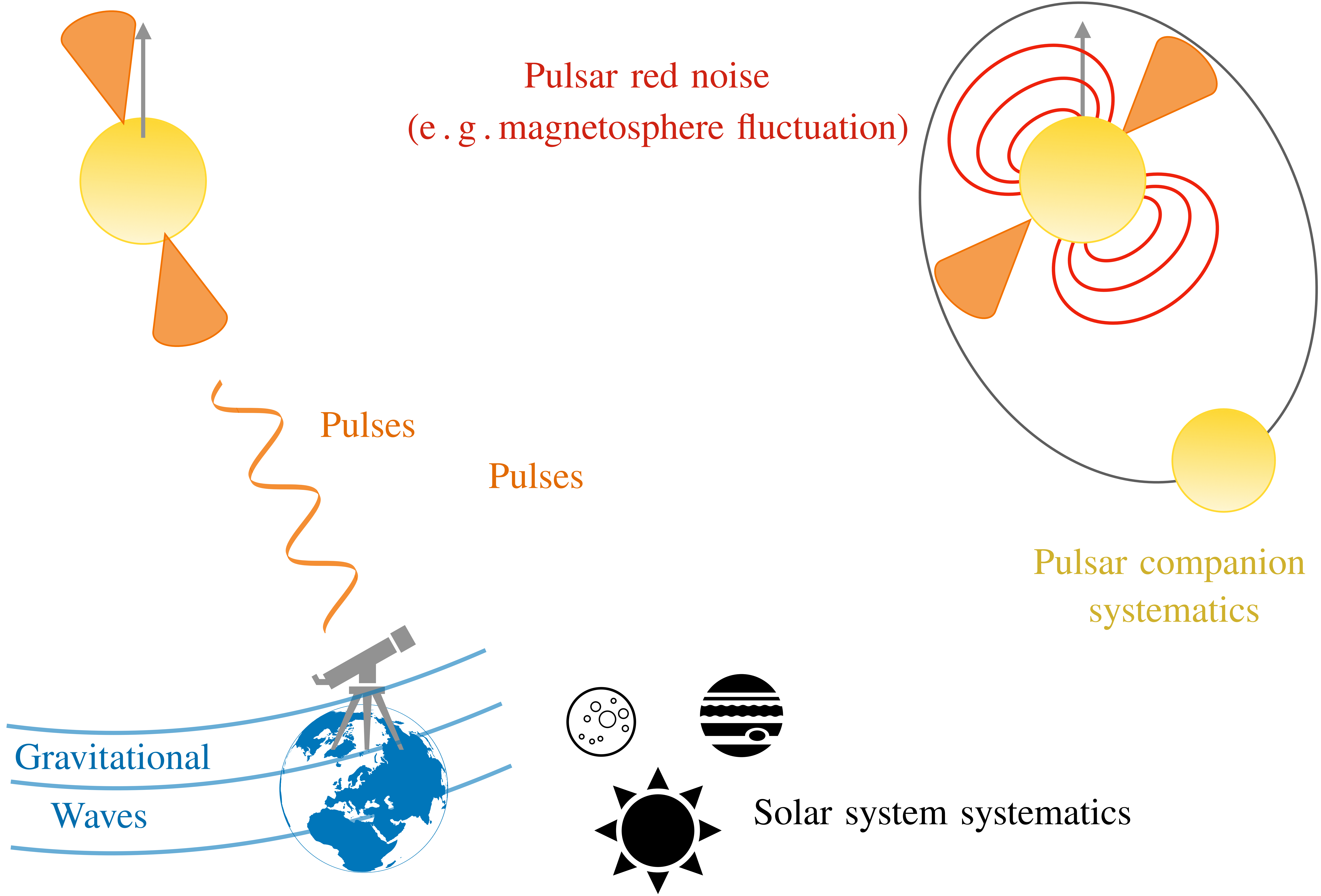

Pulses
Pulses
Gravitational
Waves


Rcvr_800_GASP
Rcvr1_2_GASP
Rcvr1_2_GUPPI
Rcvr_800_GUPPI
Timing Residuals [microseconds]
10
0
−10
−20
54000
55000
56000
57000
58000
Modified Julian Date [days]
Pulses
Pulses
Gravitational
Waves

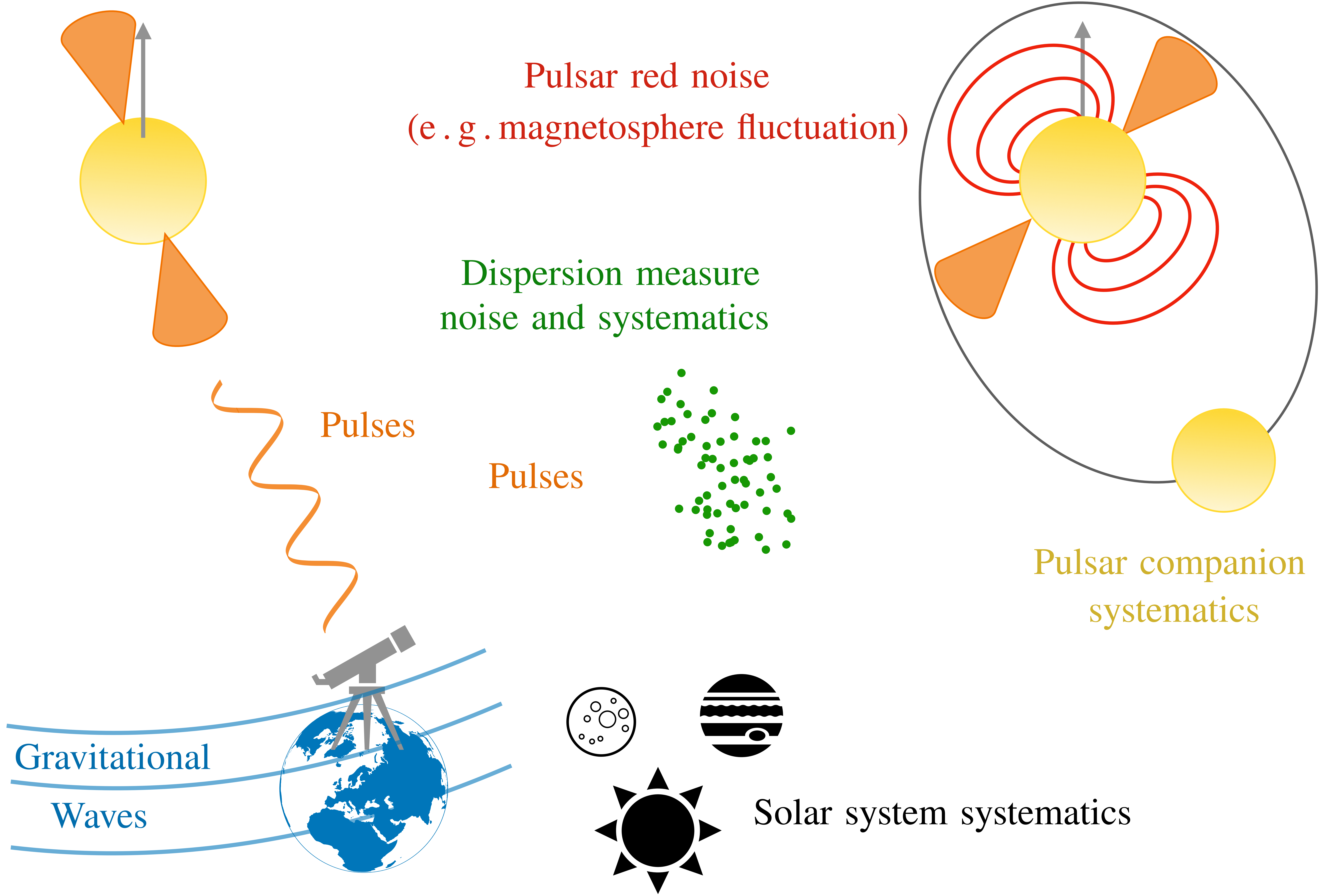

Rcvr_800_GASP
Rcvr1_2_GASP
Rcvr1_2_GUPPI
Rcvr_800_GUPPI
Timing Residuals [microseconds]
Modified Julian Date [days]
Pulses
Pulses
Gravitational
Waves
Solar system systematics



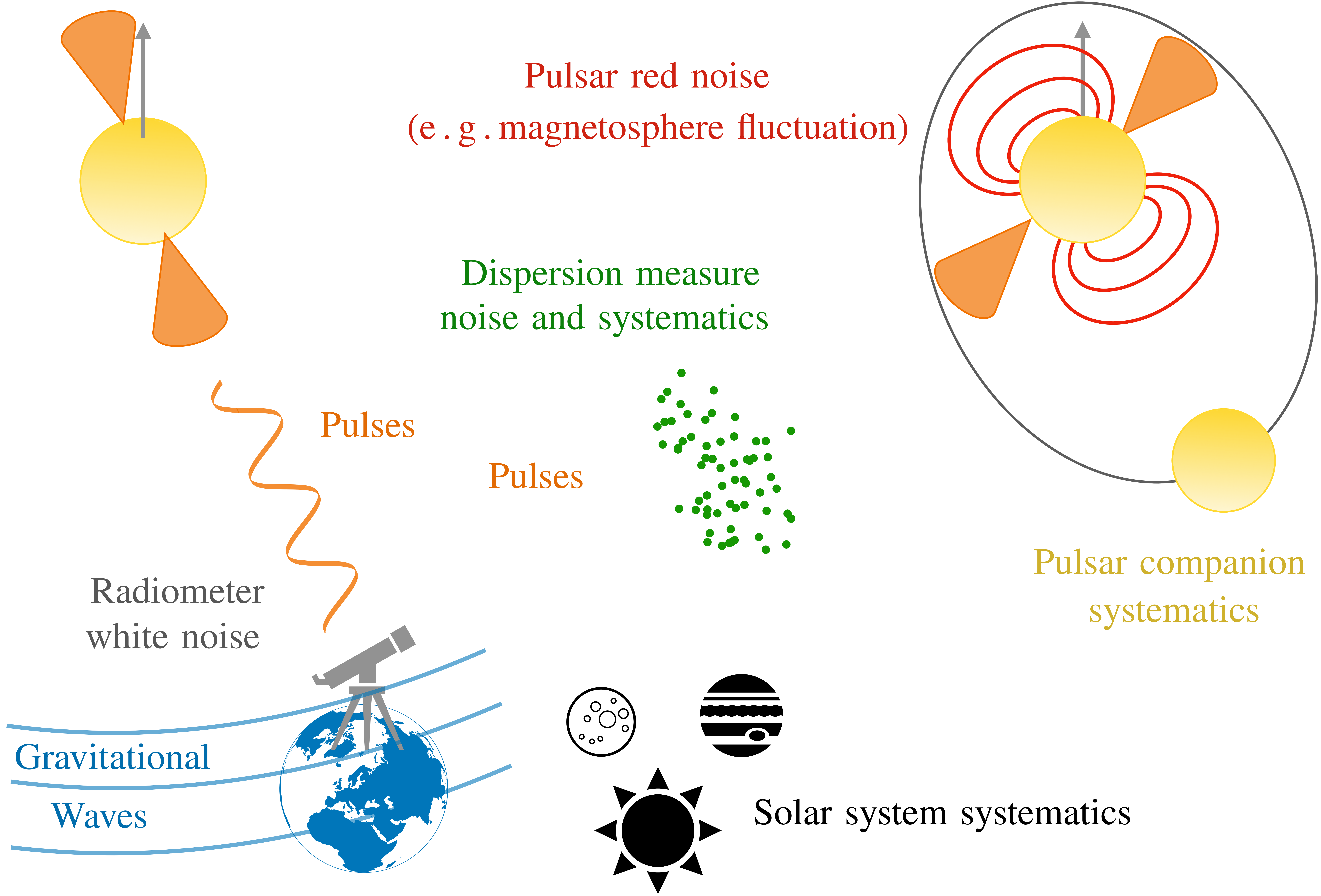
Rcvr_800_GASP
Rcvr1_2_GASP
Rcvr1_2_GUPPI
Rcvr_800_GUPPI
Timing Residuals [microseconds]
10
0
−10
−20
54000
55000
56000
57000
58000
Modified Julian Date [days]
Pulses
Pulses
Pulsar companion systematics
Gravitational Waves
Solar system systematics

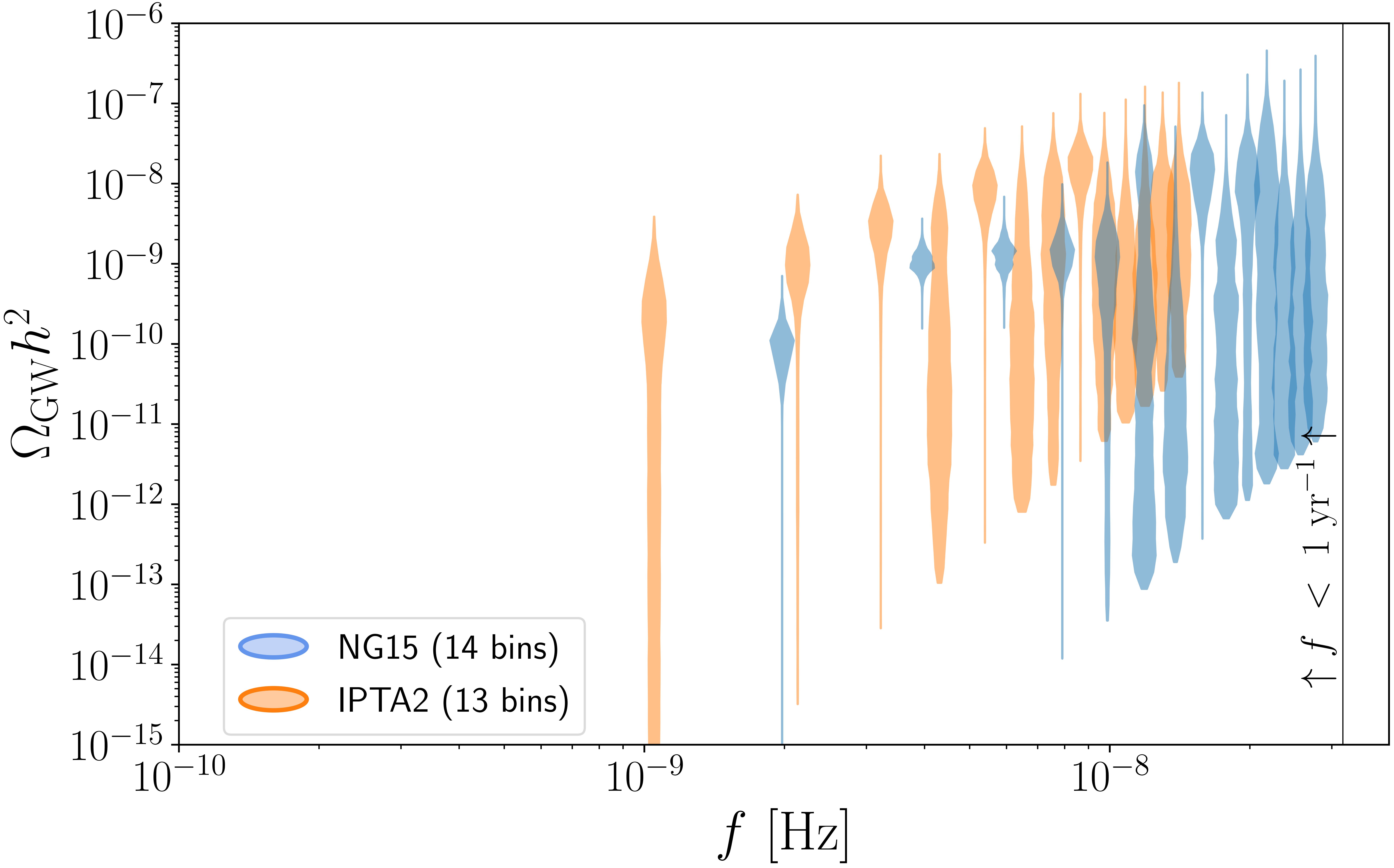


Pulsar red noise
(e.g. magnetosphere fluctuation)
Pulses
Pulses
Pulsar companion
systematics
Gravitational
Waves
Solar system systematics

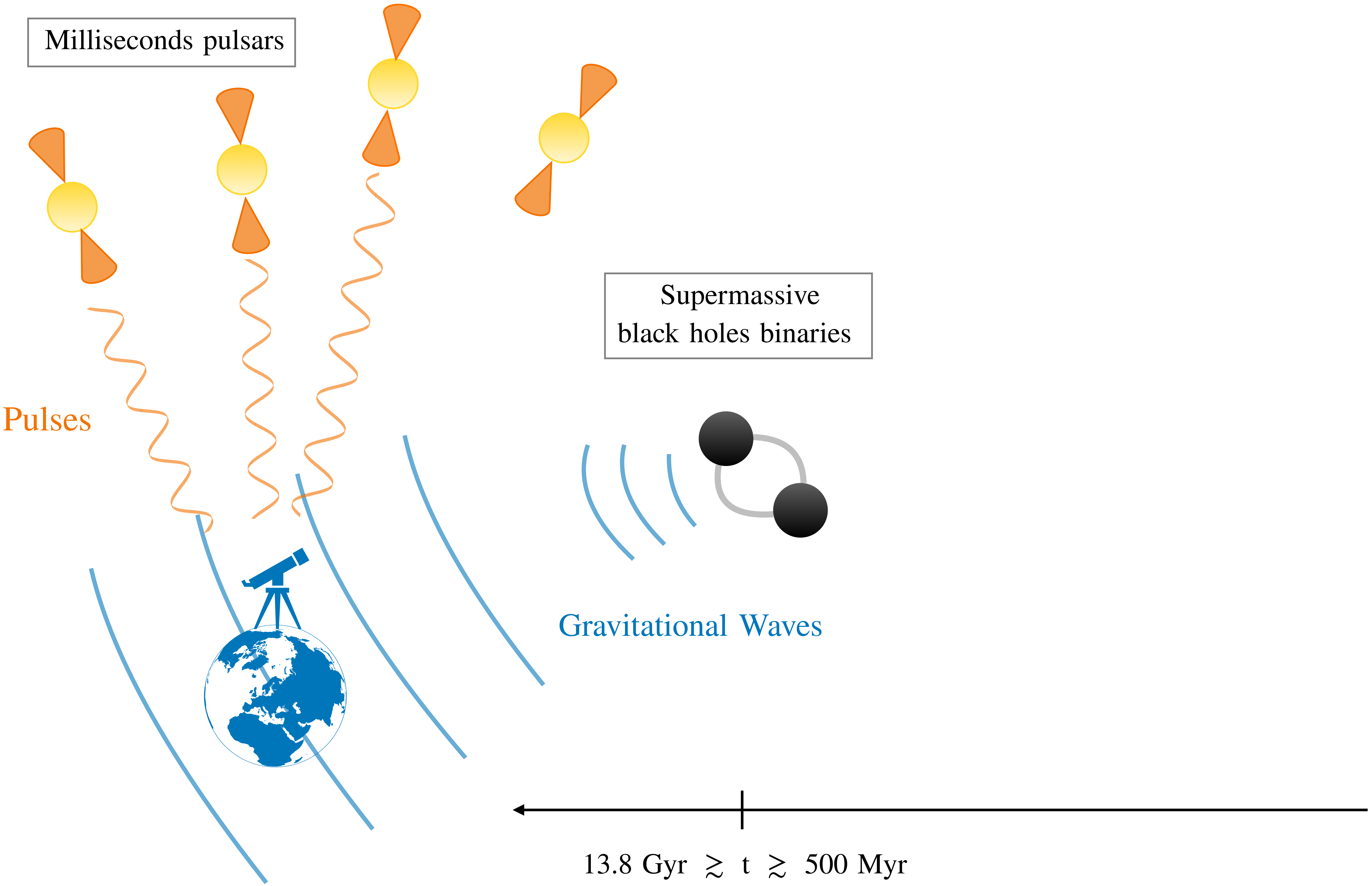


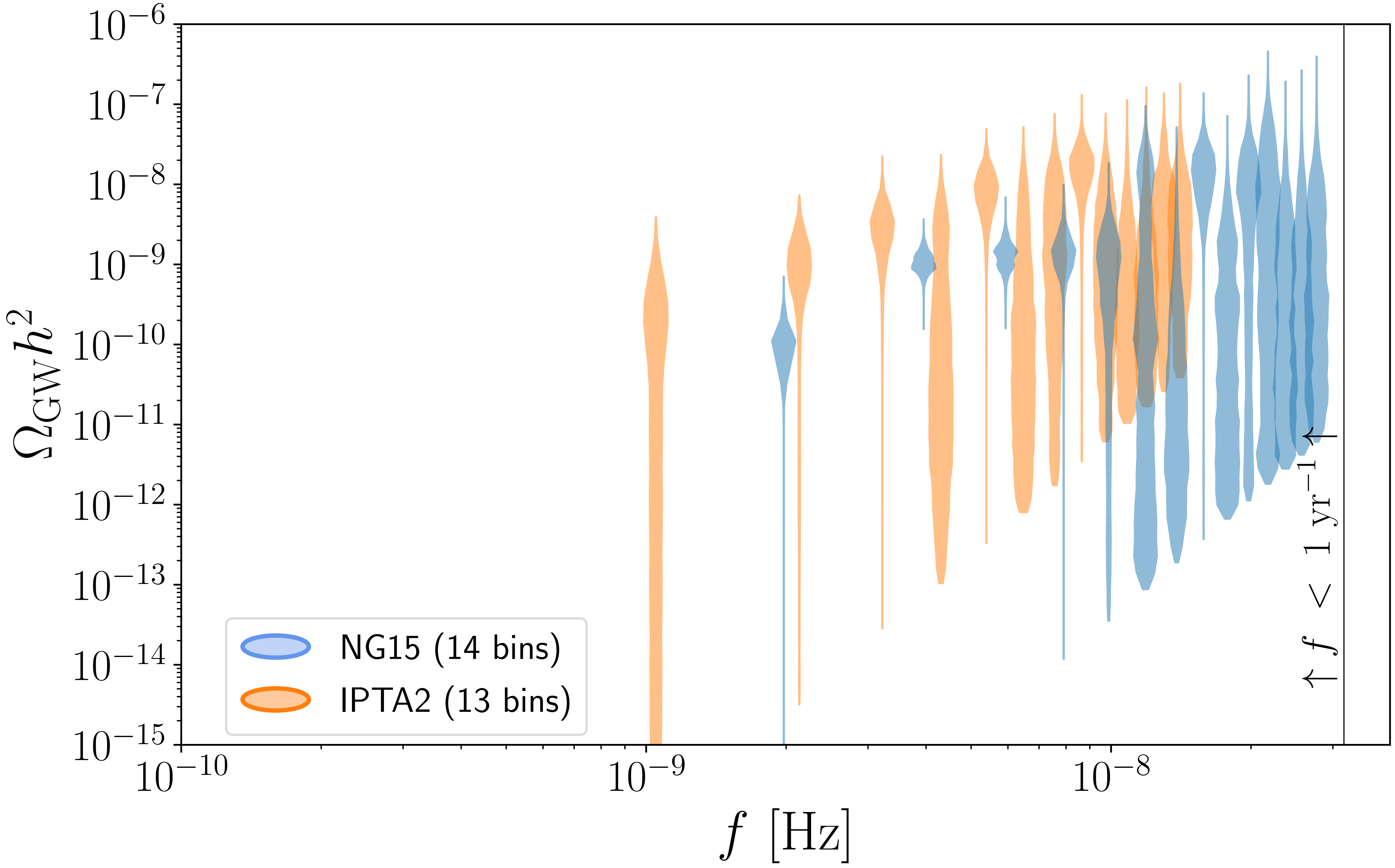
Pulsar red noise
(e.g. magnetosphere fluctuation)
Dispersion measure
noise and systematics
Pulses
Pulses
Pulsar companion
systematics
Gravitational
Waves
Solar system systematics


Pulsar red noise
(e.g. magnetosphere fluctuation)
Dispersion measure
noise and systematics
Pulses
Pulses
Pulsar companion
systematics
Radiometer
white noise
Gravitational
Waves
Solar system systematics



$\Omega_{\rm GW}h^2$
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
13.8 Gyr ≳ t ≳ 500 Myr



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$\Omega_{\rm GW} h^2$
10^{-10}
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10^{-8}
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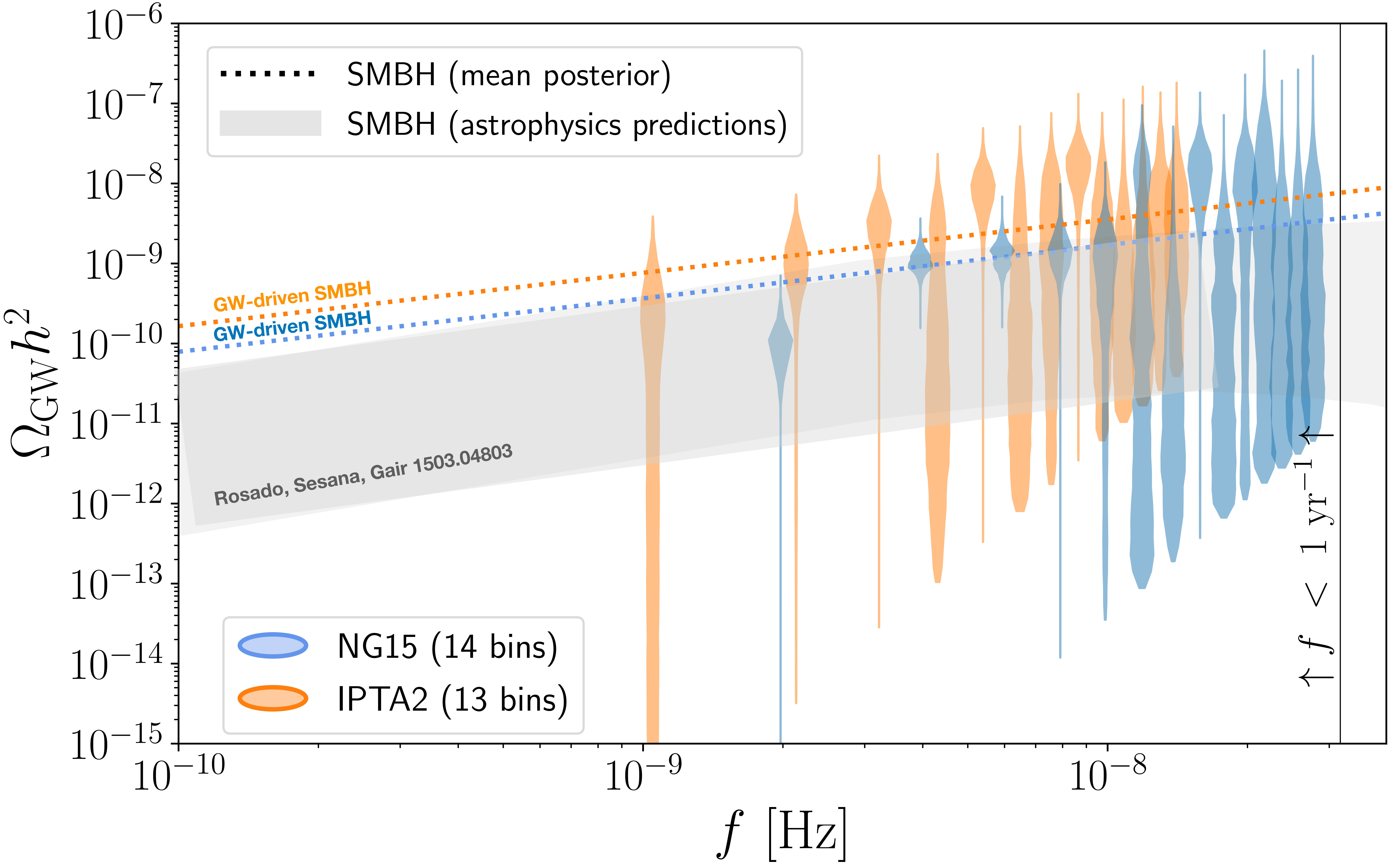
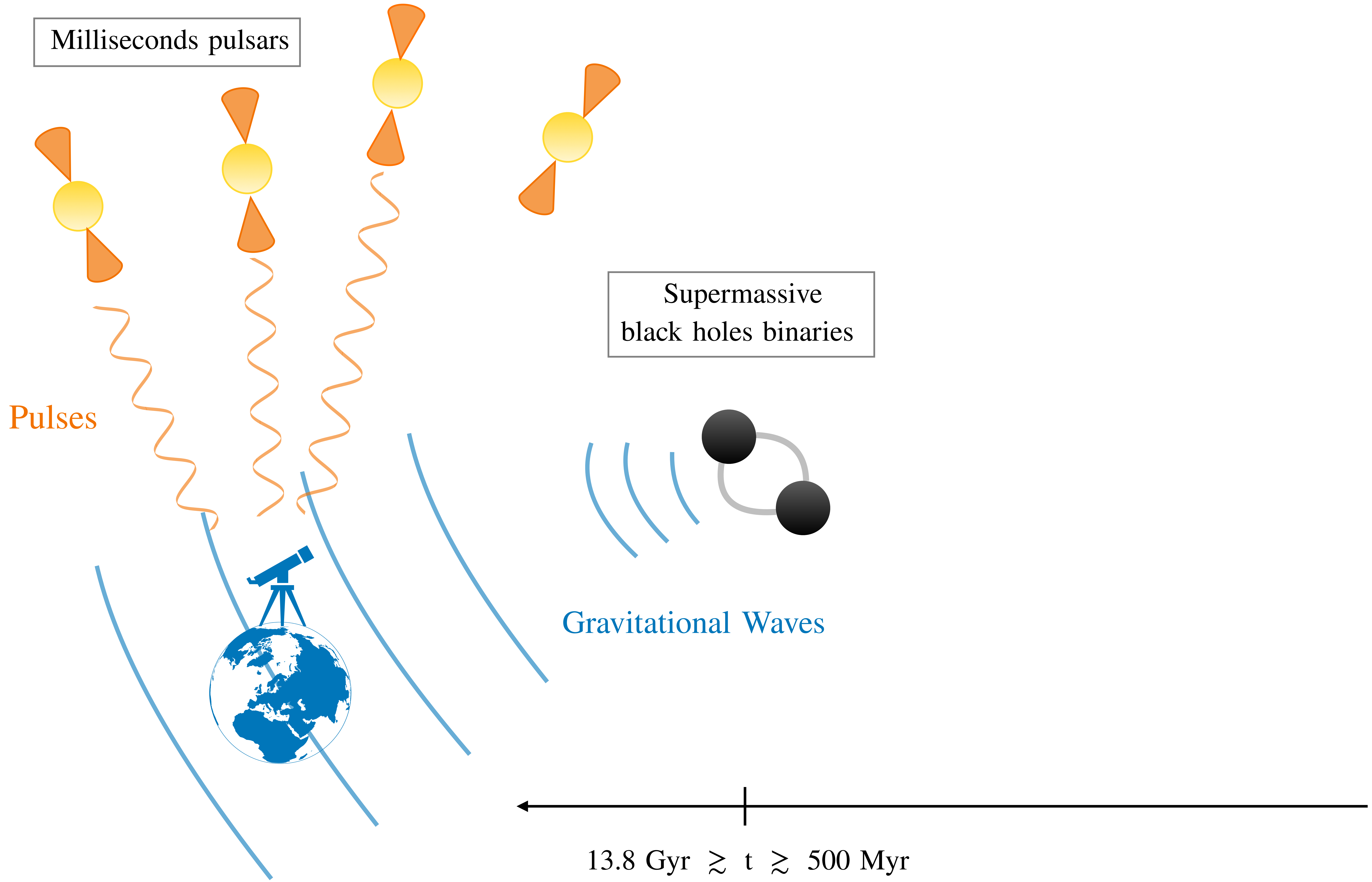
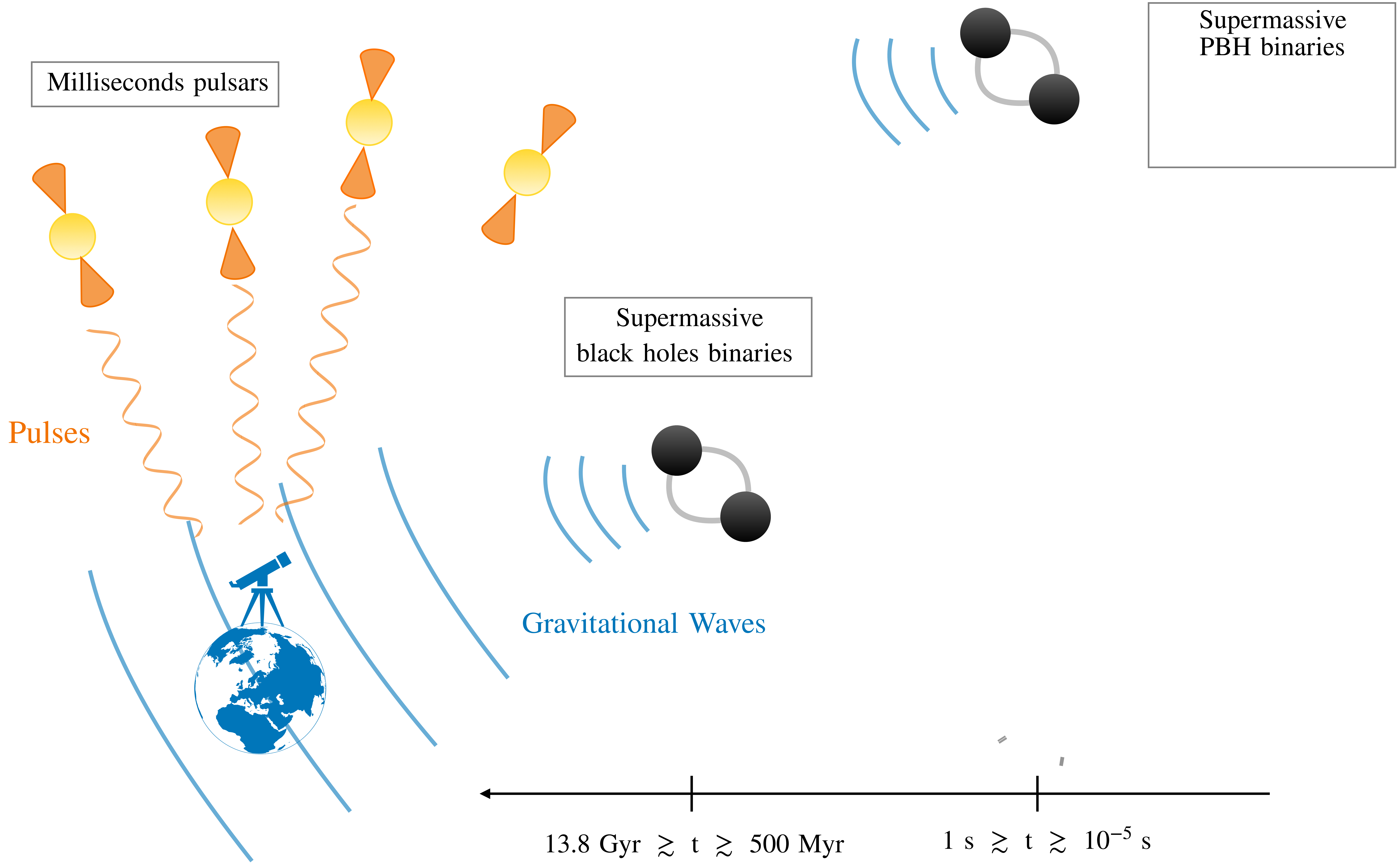


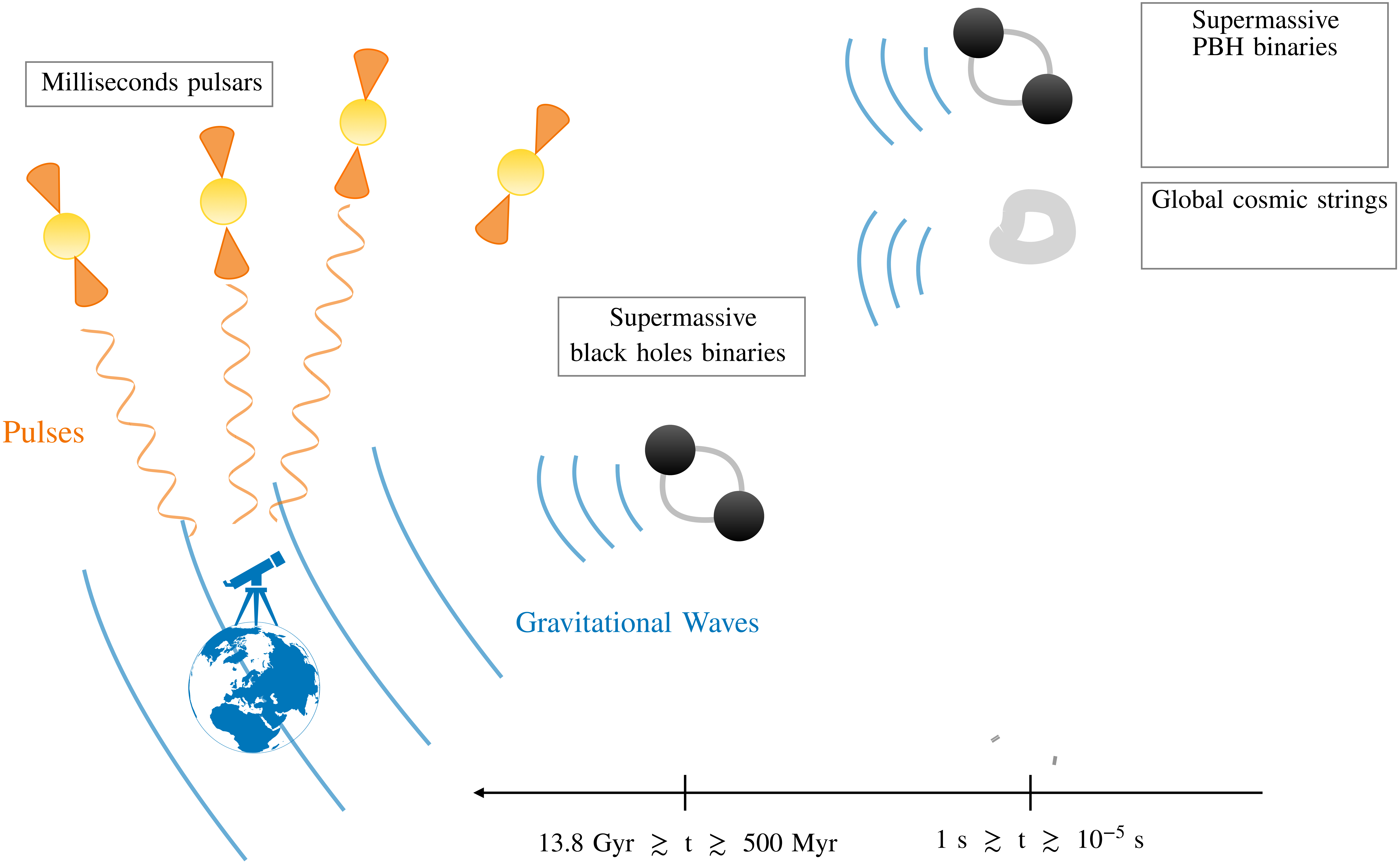
SMBH (mean posterior)
SMBH (astrophysics predictions)
GW-driven SMBH
GW-driven SMBH
Rosado, Sesana, Gair 1503.04803
NG15 (14 bins)
IPTA2 (13 bins)
$\leftarrow f < 1\ \mathrm{yr}^{-1} \rightarrow$
$\Omega_{\rm GW} h^2$
f [Hz]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-10}
10^{-9}
10^{-8}



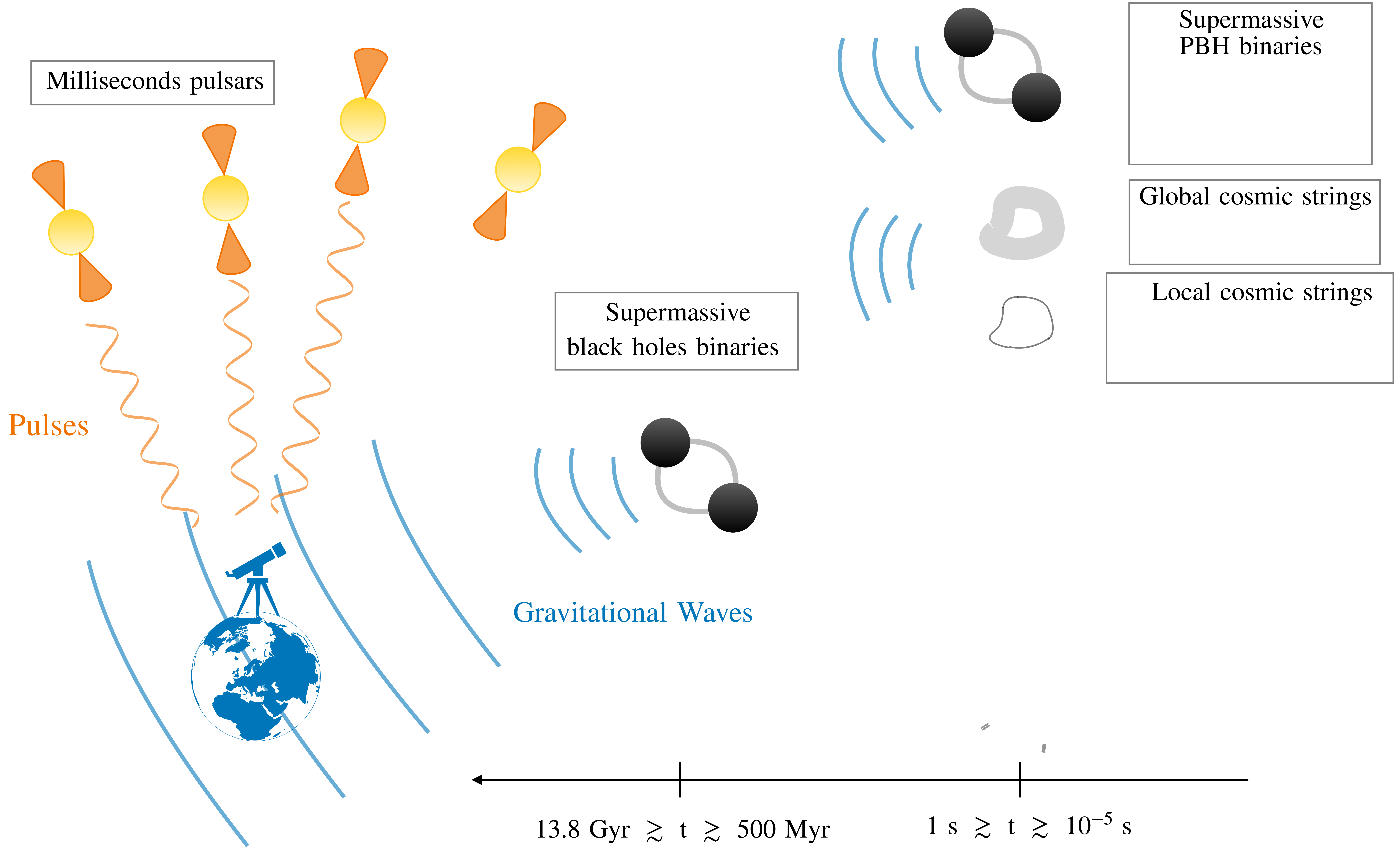
Milliseconds pulsars
Supermassive
black holes binaries
Pulses
Gravitational Waves
13.8 Gyr $\gtrsim$ t $\gtrsim$ 500 Myr

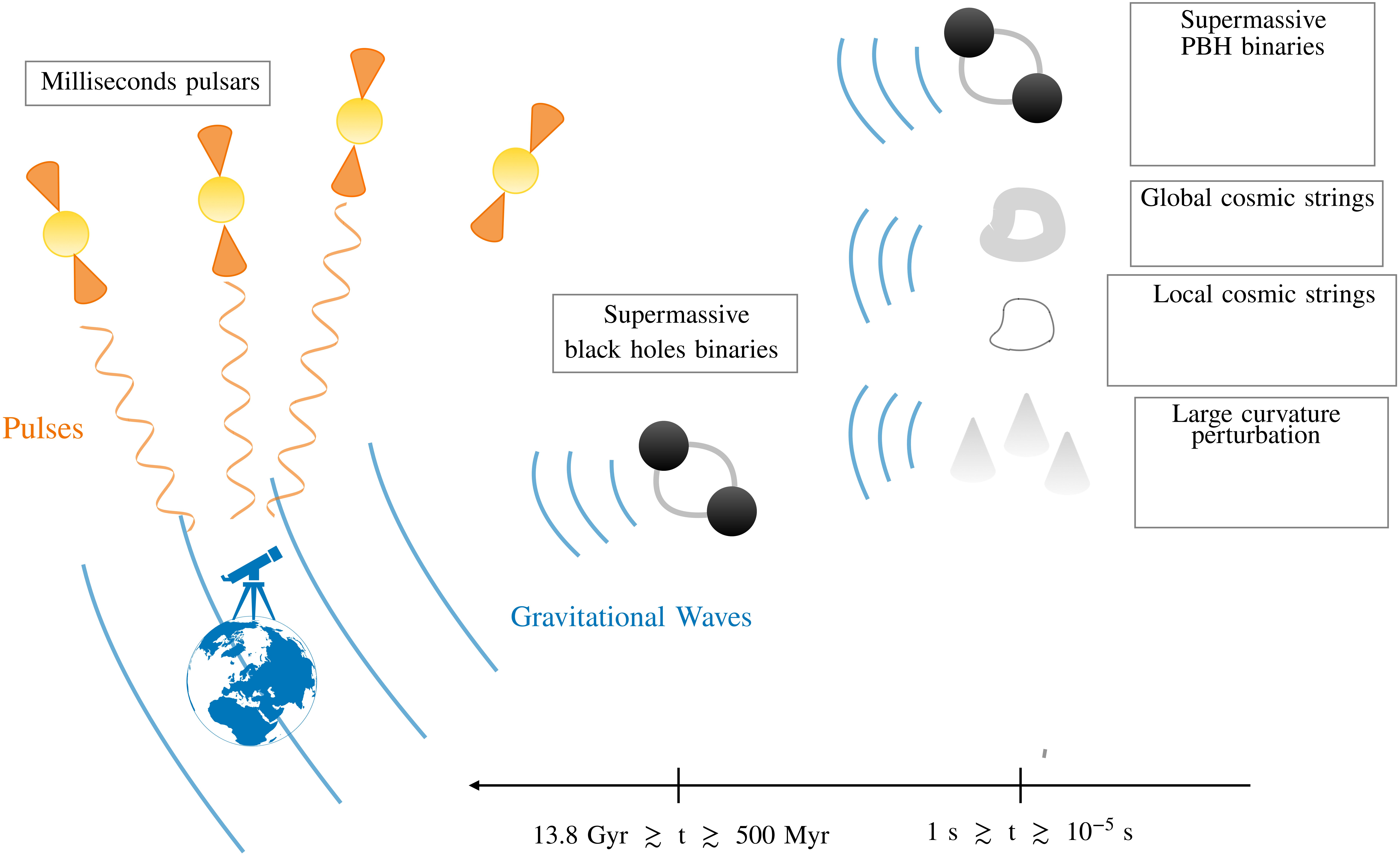


Milliseconds pulsars
Supermassive PBH binaries
Supermassive black holes binaries
Pulses
Gravitational Waves
13.8 Gyr $\gtrsim$ t $\gtrsim$ 500 Myr
1 s $\gtrsim$ t $\gtrsim$ 10^{-5} s

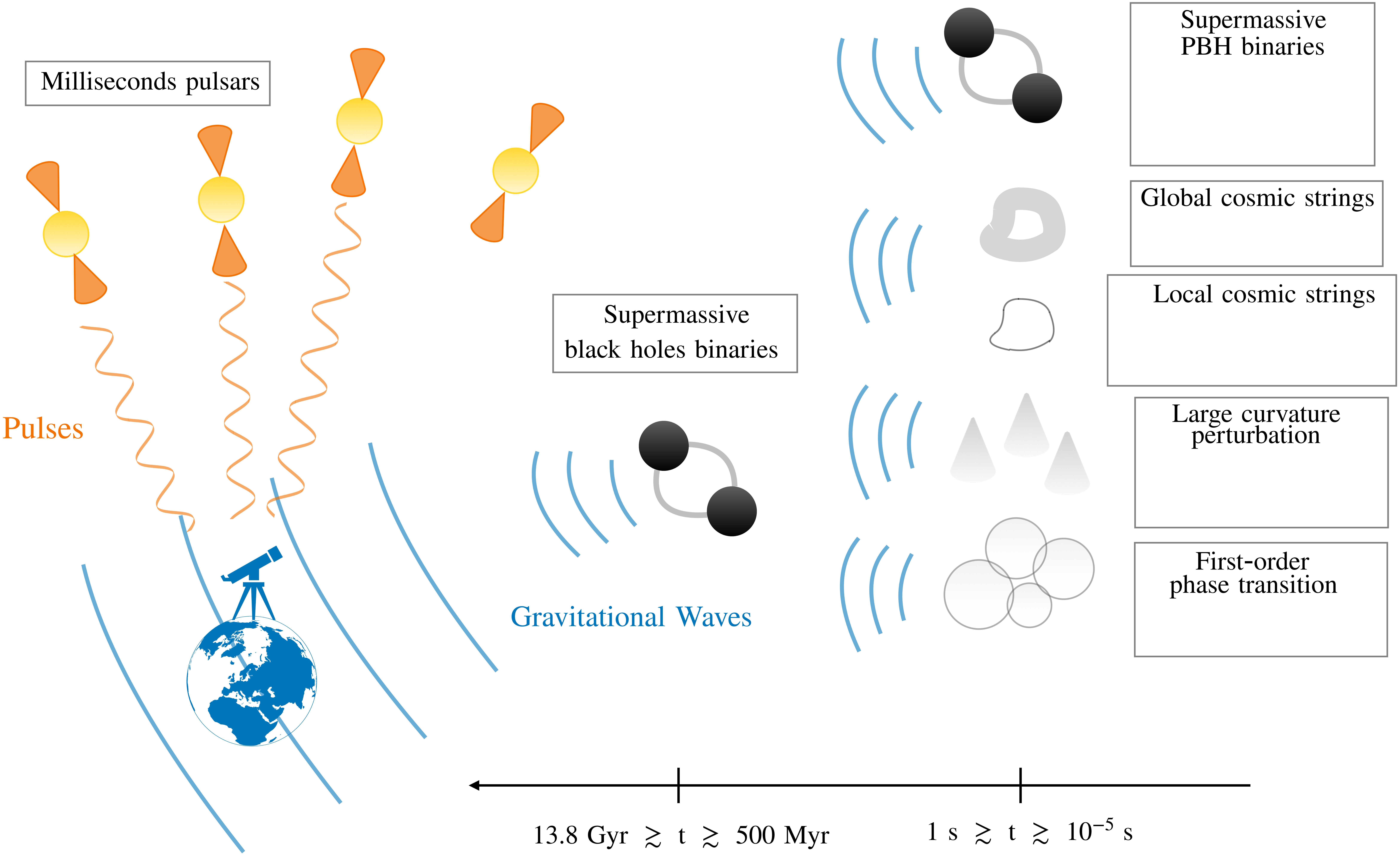


Milliseconds pulsars
Supermassive PBH binaries
Global cosmic strings
Supermassive black holes binaries
Pulses
Gravitational Waves
13.8 Gyr ≳ t ≳ 500 Myr
1 s ≳ t ≳ 10^{-5} s

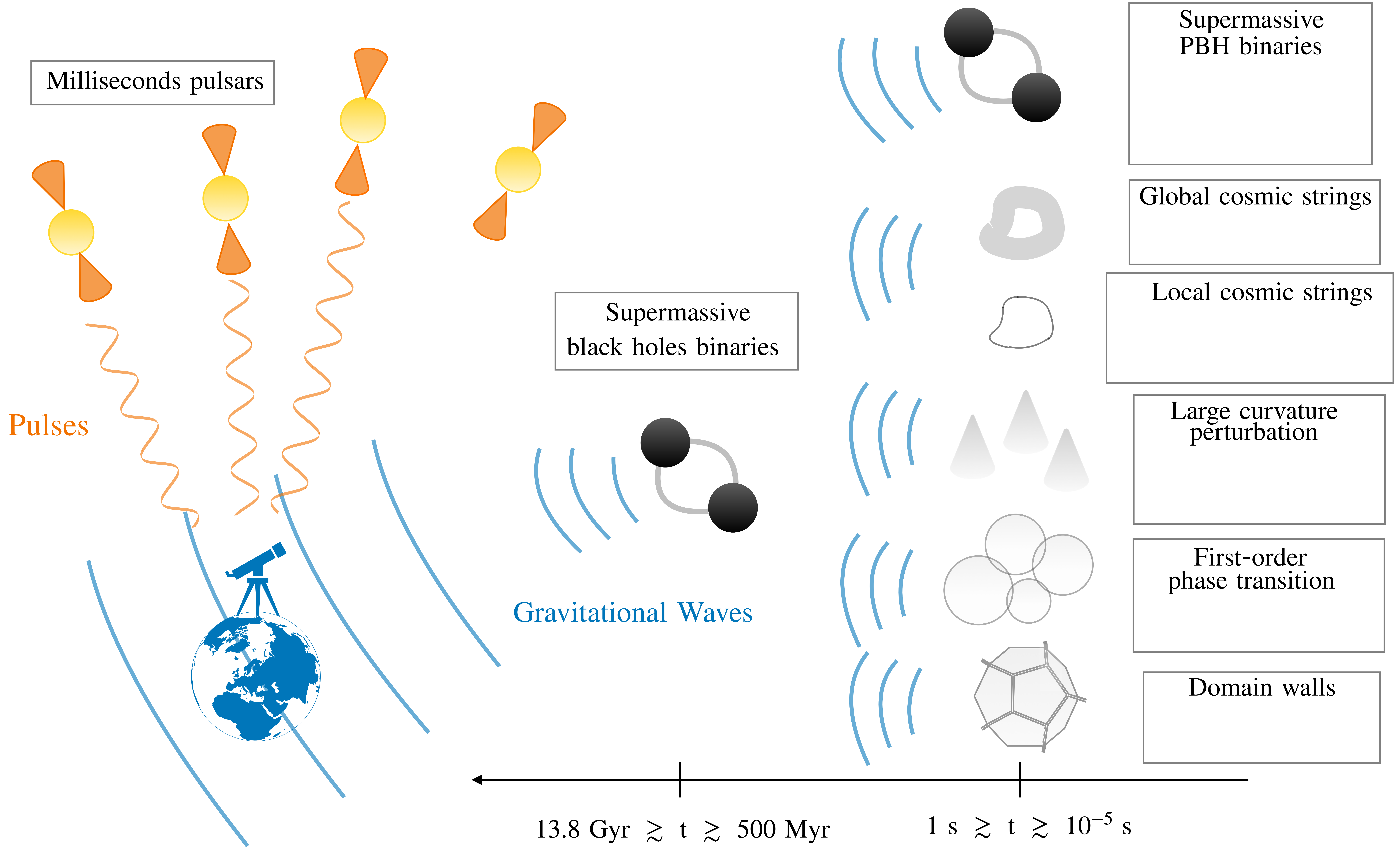

Milliseconds pulsars
Supermassive PBH binaries
Global cosmic strings
Local cosmic strings
Supermassive black holes binaries
Pulses
Gravitational Waves
13.8 Gyr ≳ t ≳ 500 Myr
1 s ≳ t ≳ 10^−5 s



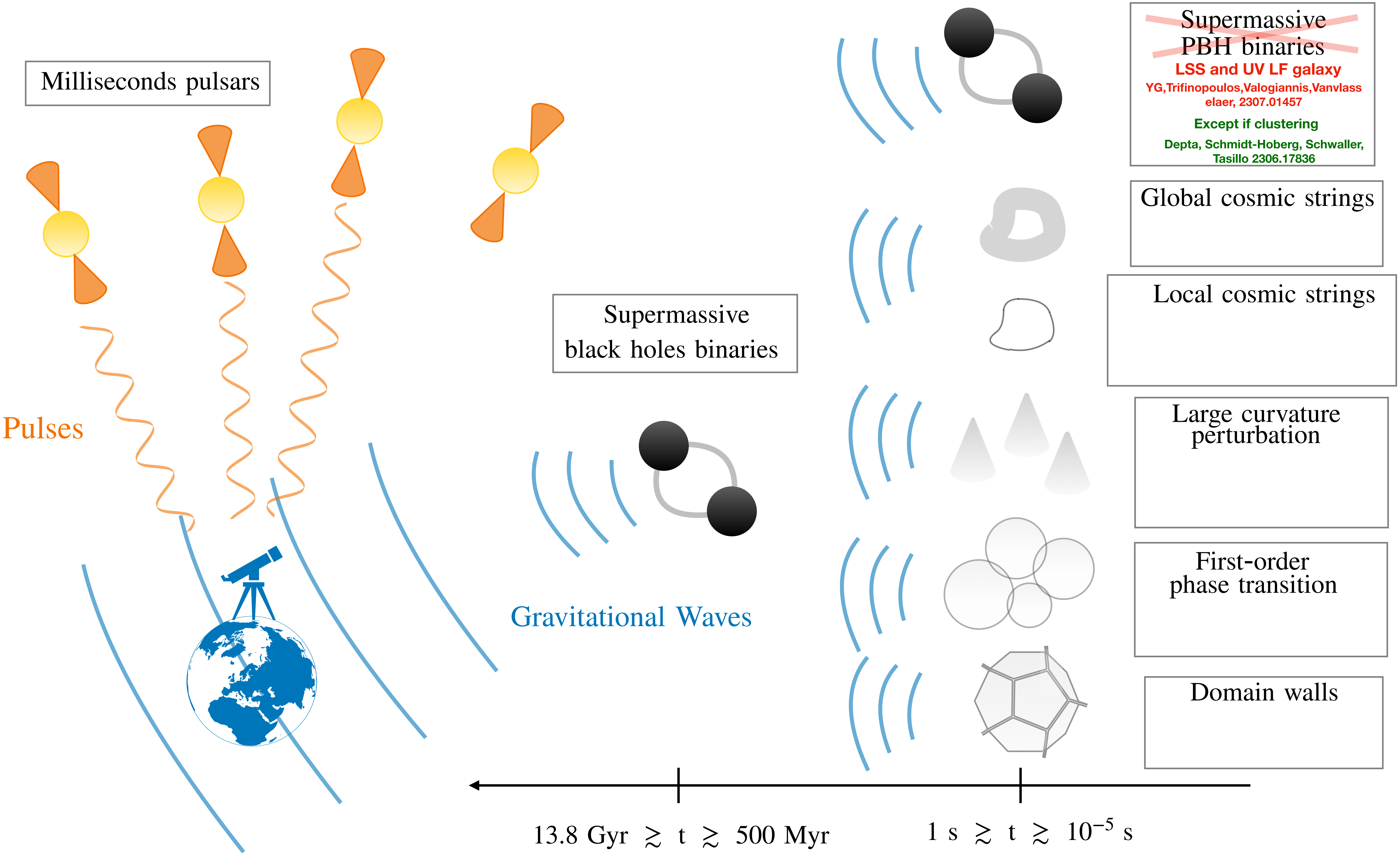
Milliseconds pulsars
Pulses
Supermassive black holes binaries
Gravitational Waves
Supermassive PBH binaries
Global cosmic strings
Local cosmic strings
Large curvature perturbation
13.8 Gyr $\gtrsim$ t $\gtrsim$ 500 Myr
1 s $\gtrsim$ t $\gtrsim$ 10^{-5} s



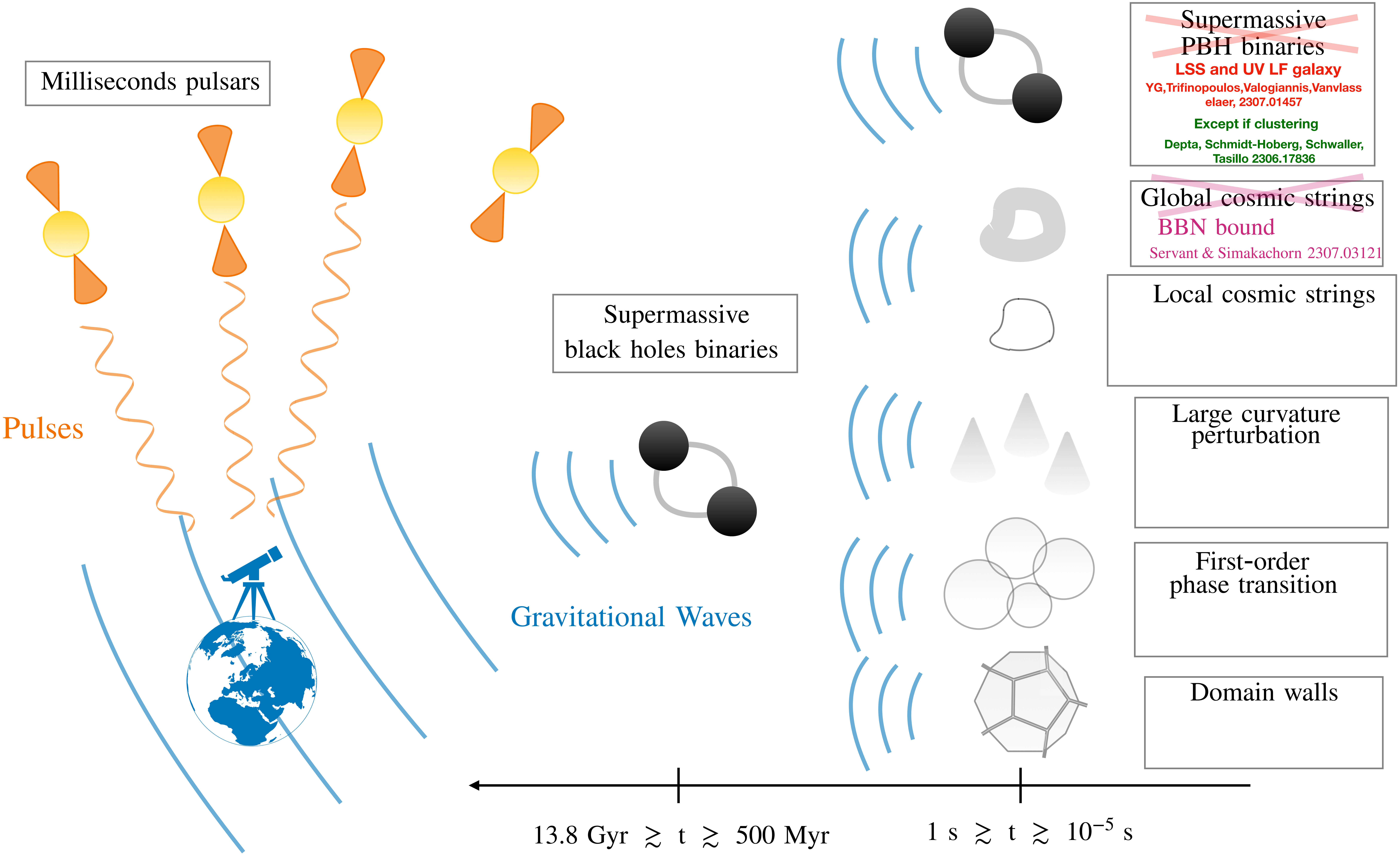
Milliseconds pulsars
Supermassive PBH binaries
Global cosmic strings
Local cosmic strings
Supermassive black holes binaries
Large curvature perturbation
First-order phase transition
Pulses
Gravitational Waves
13.8 Gyr $\gtrsim$ t $\gtrsim$ 500 Myr
1 s $\gtrsim$ t $\gtrsim$ 10^{-5} s



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



Milliseconds pulsars
Pulses
Supermassive black holes binaries
Gravitational Waves
Supermassive PBH binaries
LSS and UV LF galaxy
YG,Trifinopoulos,Valogiannis,Vanvlasselaer, 2307.01457
Except if clustering
Depta, Schmidt-Hoberg, Schwaller, Tasillo 2306.17836
Global cosmic strings
Local cosmic strings
Large curvature perturbation
First-order phase transition
Domain walls
13.8 Gyr ≳ t ≳ 500 Myr
1 s ≳ t ≳ 10^{-5} s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Global cosmic strings
BBN bound
Servant & Simakachorn 2307.03121
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Domain walls
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Local cosmic strings
Not a good fit of NG15
NG15 collab. "New physics"
Except if superstrings
Ellis, Lewicki, Lin, Vaskonen 2306.17147
Large curvature perturbation
First-order phase transition
Domain walls
13.8 Gyr ≳ t ≳ 500 Myr
1 s ≳ t ≳ 10⁻⁵ s

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Large curvature perturbation
Overproduce PBH
Chen, Yuan, Huang PRL 2019
Except if large negative f_{NL}
Vaskonen+ 2306.17149
First-order phase transition
Domain walls
13.8 Gyr $\gtrsim$ t $\gtrsim$ 500 Myr
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Vaskonen+ 2306.17149
First-order phase transition
Produce ten-solar-mass PBH
YG, 2307.04239, Phys.Rev.Lett.
Domain walls
13.8 Gyr ≳ t ≳ 500 Myr
1 s ≳ t ≳ 10^-5 s

Milliseconds pulsars
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Domain walls
Produce ten-solar-mass PBH
YG, Vitagliano 2306.17841
13.8 Gyr $\gtrsim$ t $\gtrsim$ 500 Myr
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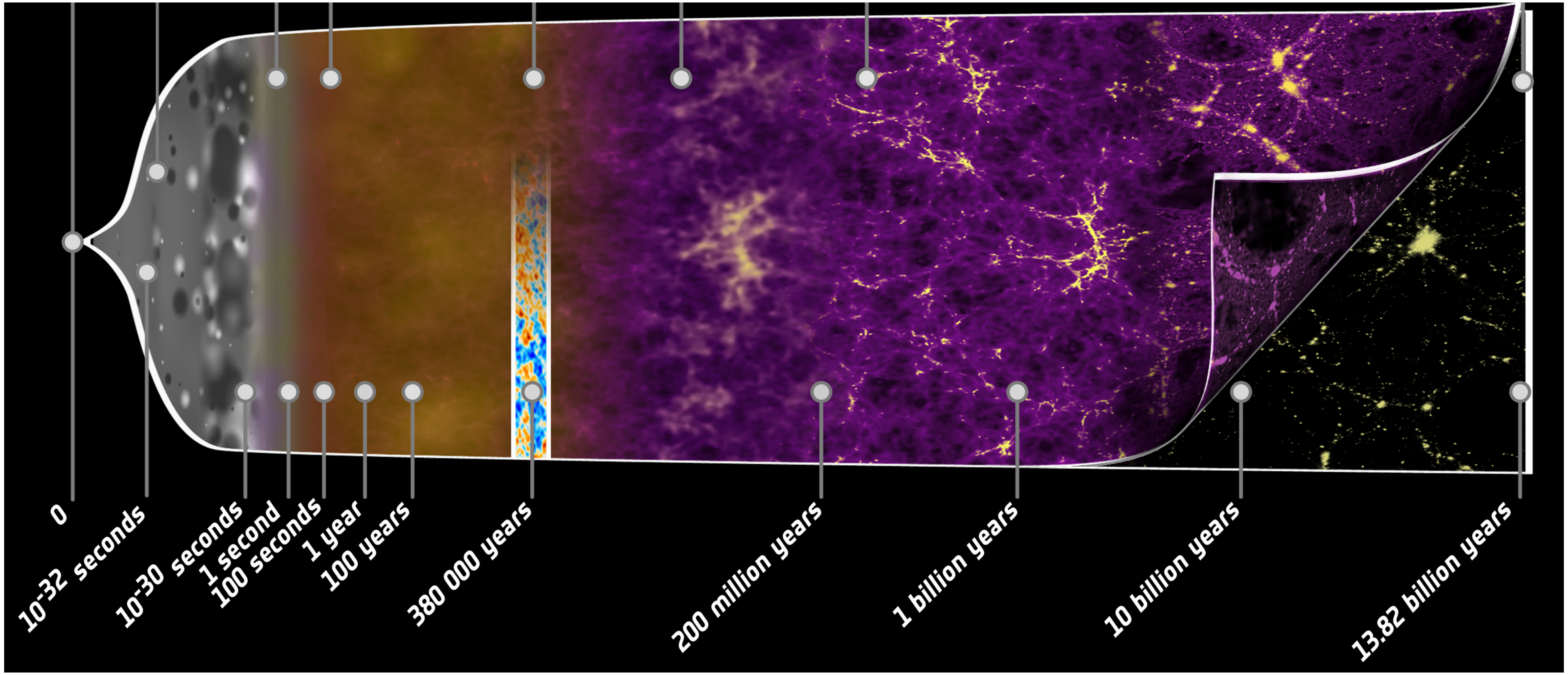
What is Primordial Black Holes ?

→ **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 :

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

$\equiv R_{\mathrm{H}}$

$\equiv M_{\mathrm{H}}$

How do they form ?

Friedmann's equation :

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

How do they form ?

Friedmann's equation :

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

$\Updownarrow$

Schwarschild's equation

How do they form ?

Friedmann's equation :

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

$\Updownarrow$

Schwarschild's equation

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

How do they form ?

Friedmann's equation :

$\Updownarrow$

Schwarschild's equation

$$\frac{R_{\rm H} - 2GM_{\rm H}}{R_H} \gtrsim 0.45$$

↑ Radiation pressure

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

How do they form ?

Friedmann's equation :

$\Updownarrow$

Schwarzschild's equation

$$\frac{\langle \delta\rho \rangle_H}{\rho} \gtrsim 0.45$$

Radiation pressure

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

What can generate large $\langle \delta\rho \rangle / \rho$?

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1) PBHs from primordial scalar fluctuation

B. Carr and J. E. Lidsey, Phys. Rev. D 48, 543 (1993) *P. Ivanov, P. Naselsky, and I. Novikov, Phys. Rev. D 50, 7173 (1994)*

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2) PBHs from cosmic strings

Requires $G\mu \sim 10^{-6}$ for PBH to be observable (cosmic rays)

S. W. Hawking, Phys.Lett.B 231 (1989) 237-239

R. R. Caldwell and P. Casper, Phys.Rev.D 53 (1996), 9509012

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Excluded by PTA $G\mu \lesssim 10^{-10}$
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3) PBHs from Domain Walls Networks

Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019), 1807.01707

G. B. Gelmini, A. Simpson, and E. Vitagliano, 2207.07126, JCAP 02, 031,

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4) PBHs from Supercooled 1st-order Phase Transition

1982: Kodama, Sasaki, Sato, (Prog.Theor.Phys. 68 (1982) 1979)

2021: Liu, Bian, Can, Guo, Wang, 2106.05637, Phys.Rev.D 105 (2022) 2

2022: Kawana, T. Kim, and P. Lu, 2212.14037

2023: Lewicki, Toczek, Vaskonen, JHEP 09 (2023) 092, 2305.04924

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4) PBHs from Supercooled 1st-order Phase Transition

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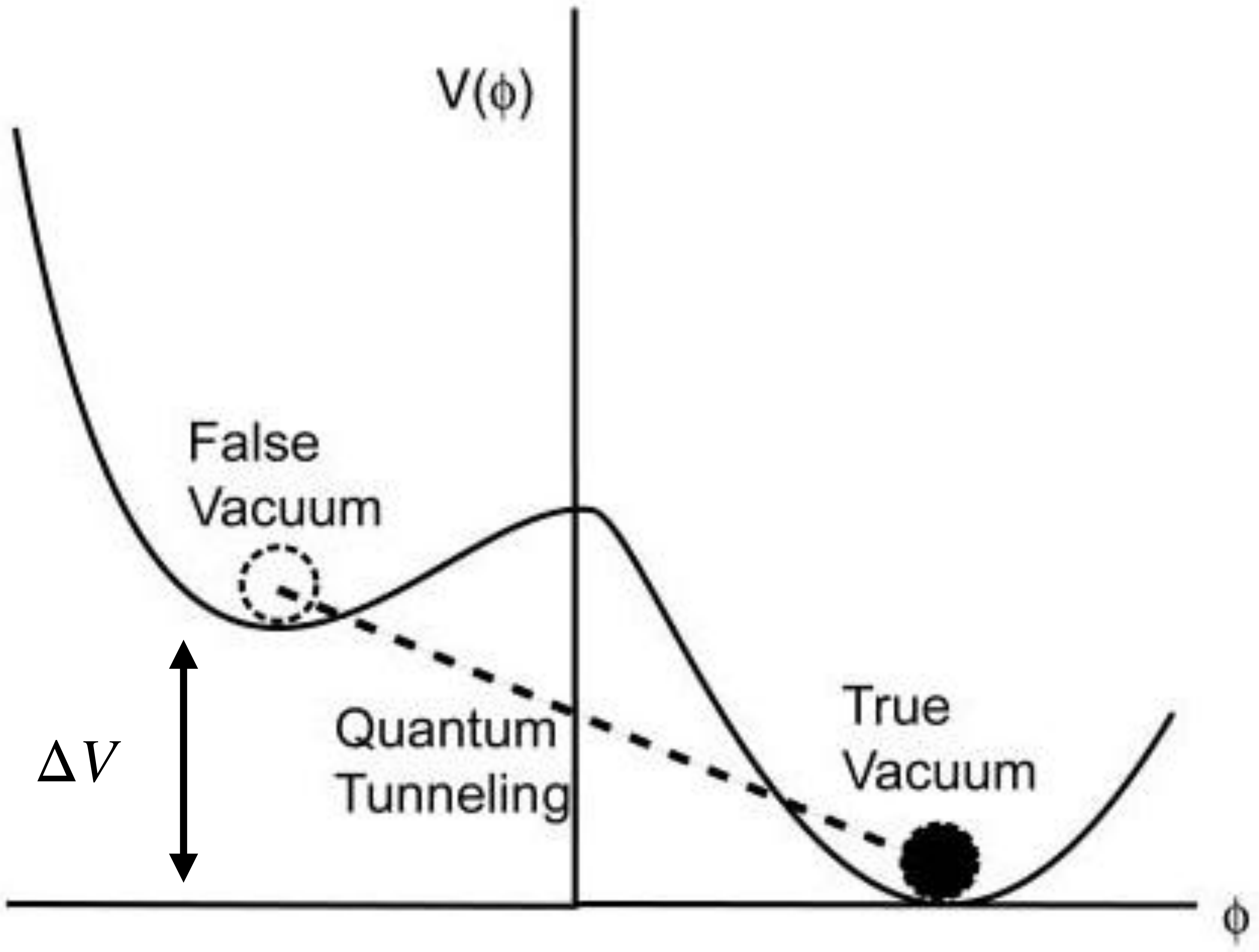
YG, Volansky, 2305.04942

YG, 2307.04239, Phys.Rev.Lett. 131 (2023) 17

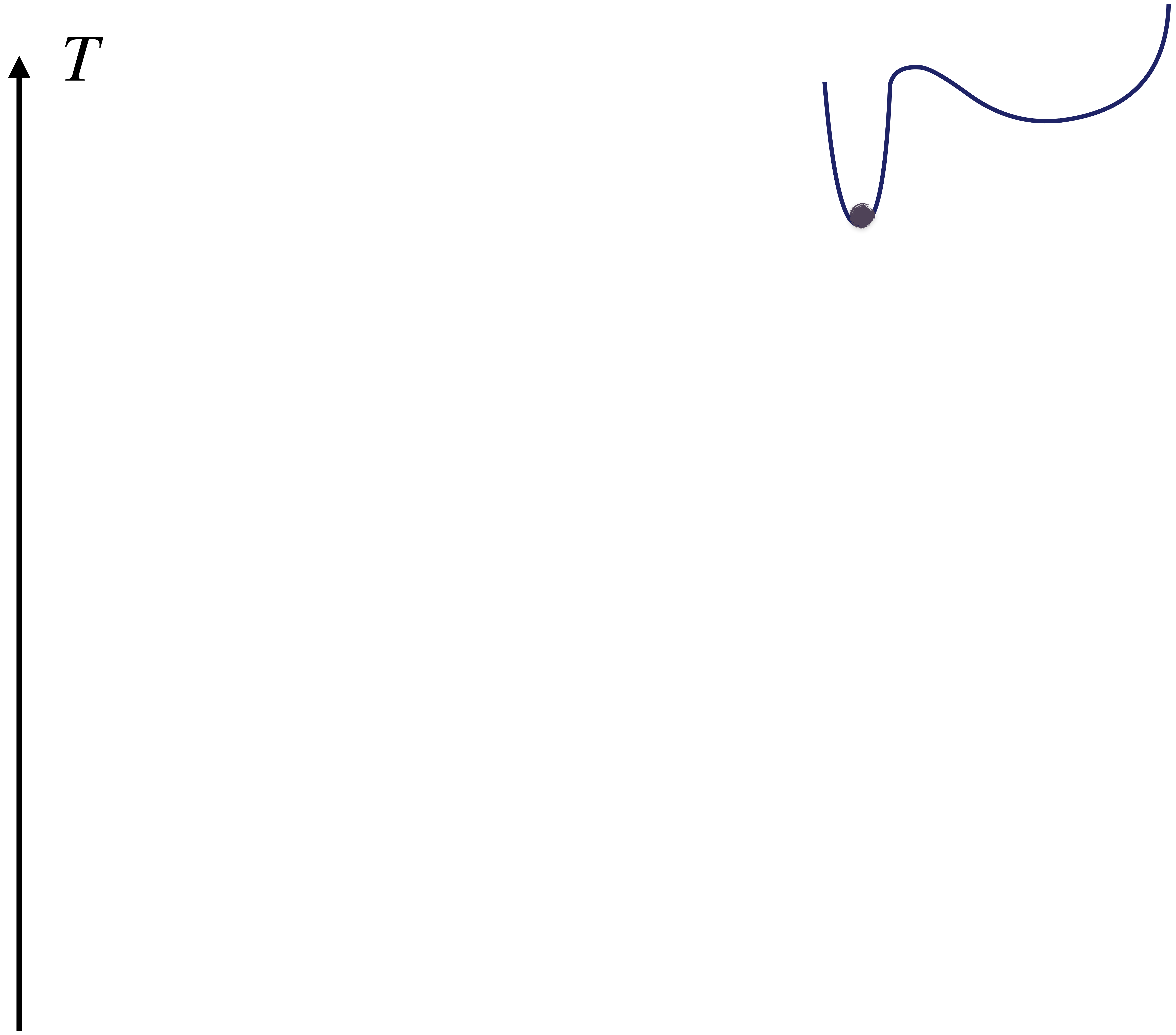
YG, 2311.13640

PBHs formation during supercooled phase transition

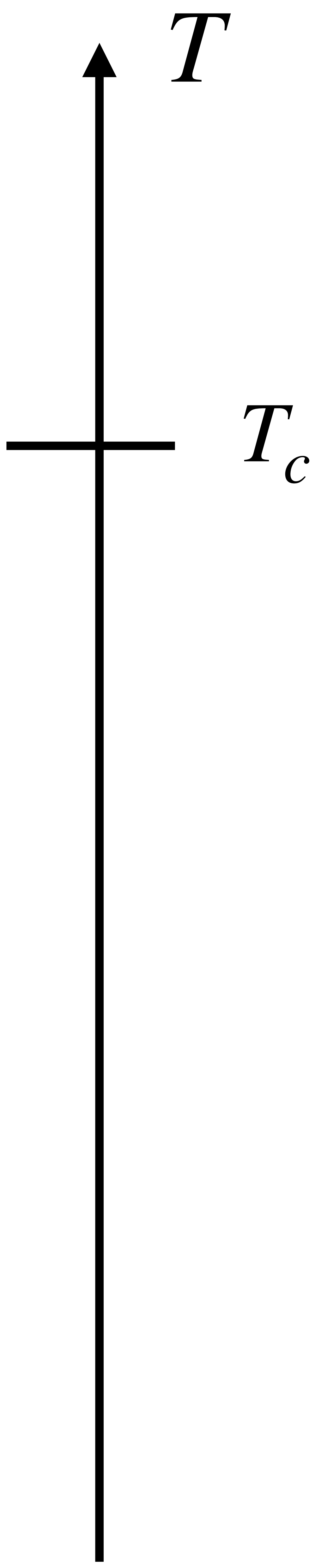
Guth 1980 "Old inflation idea"



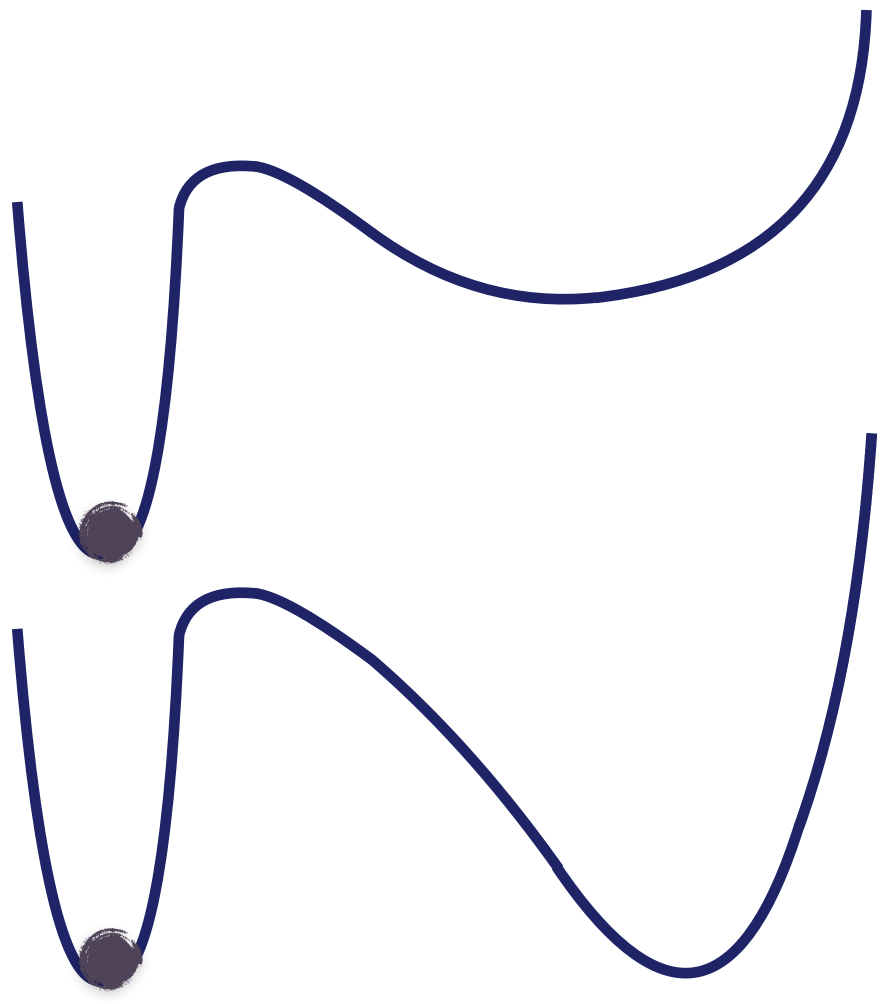
Supercooled 1stOPT = delayed PT



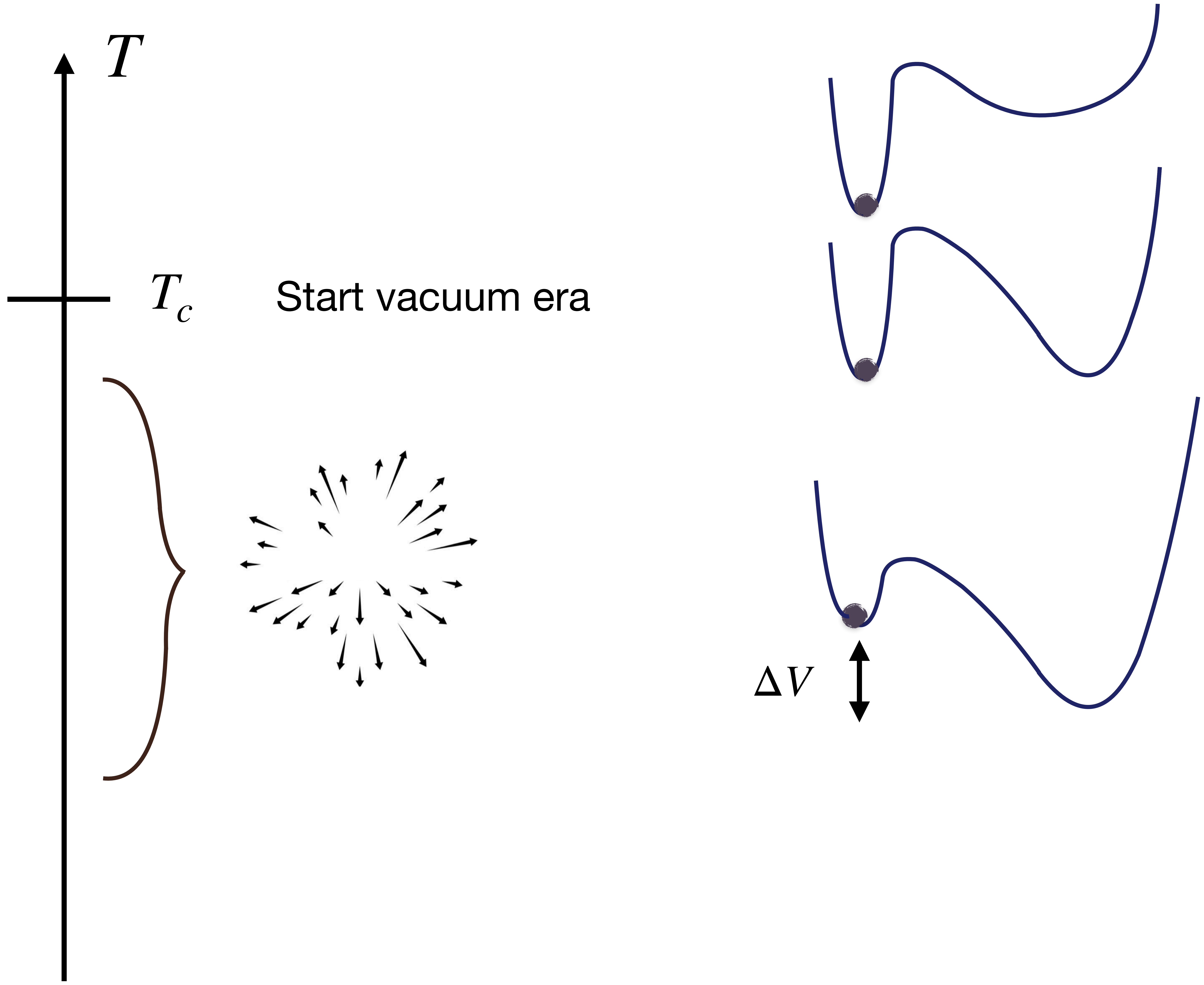
Supercooled 1stOPT = delayed PT



Start vacuum era



Supercooled 1stOPT = delayed PT



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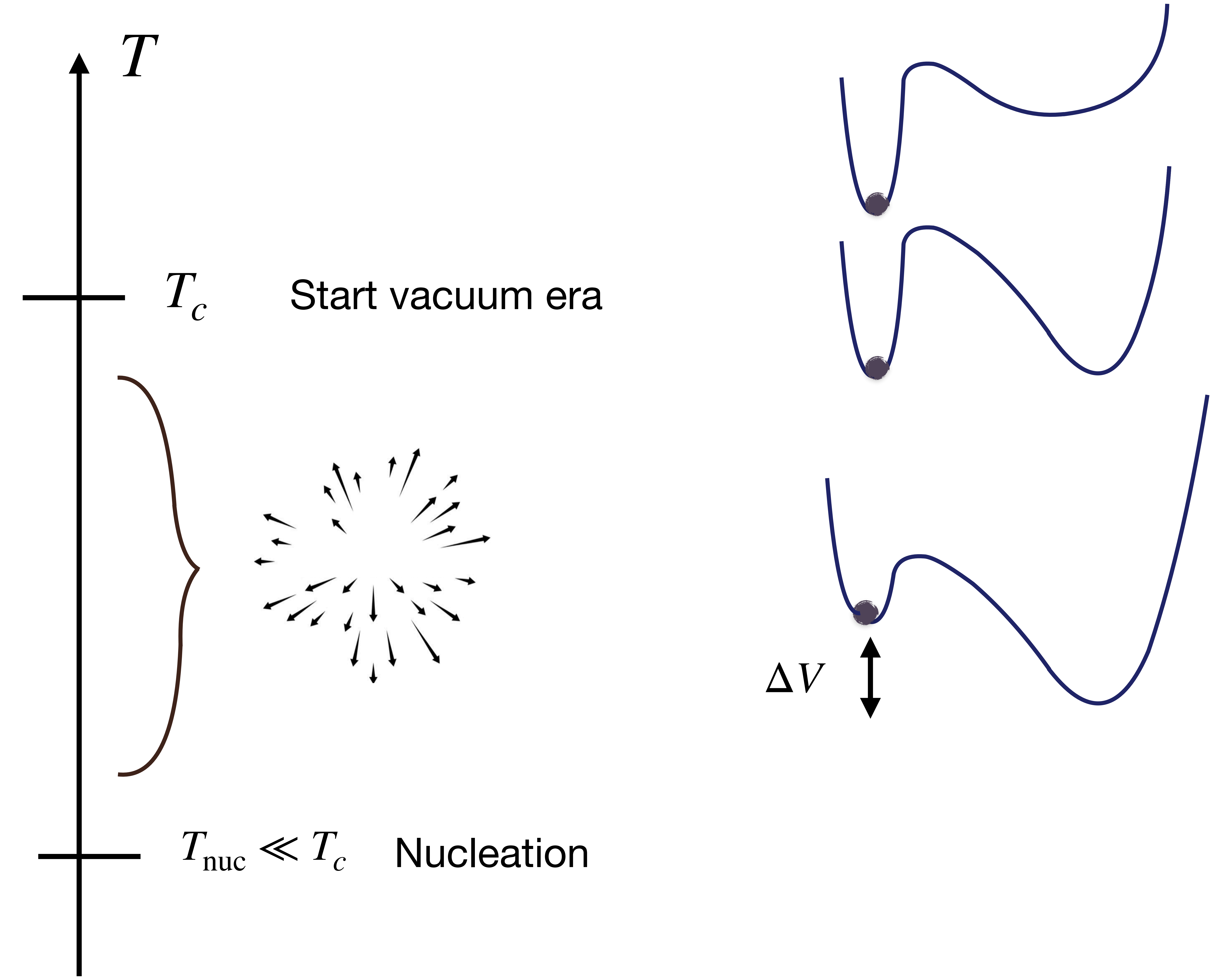

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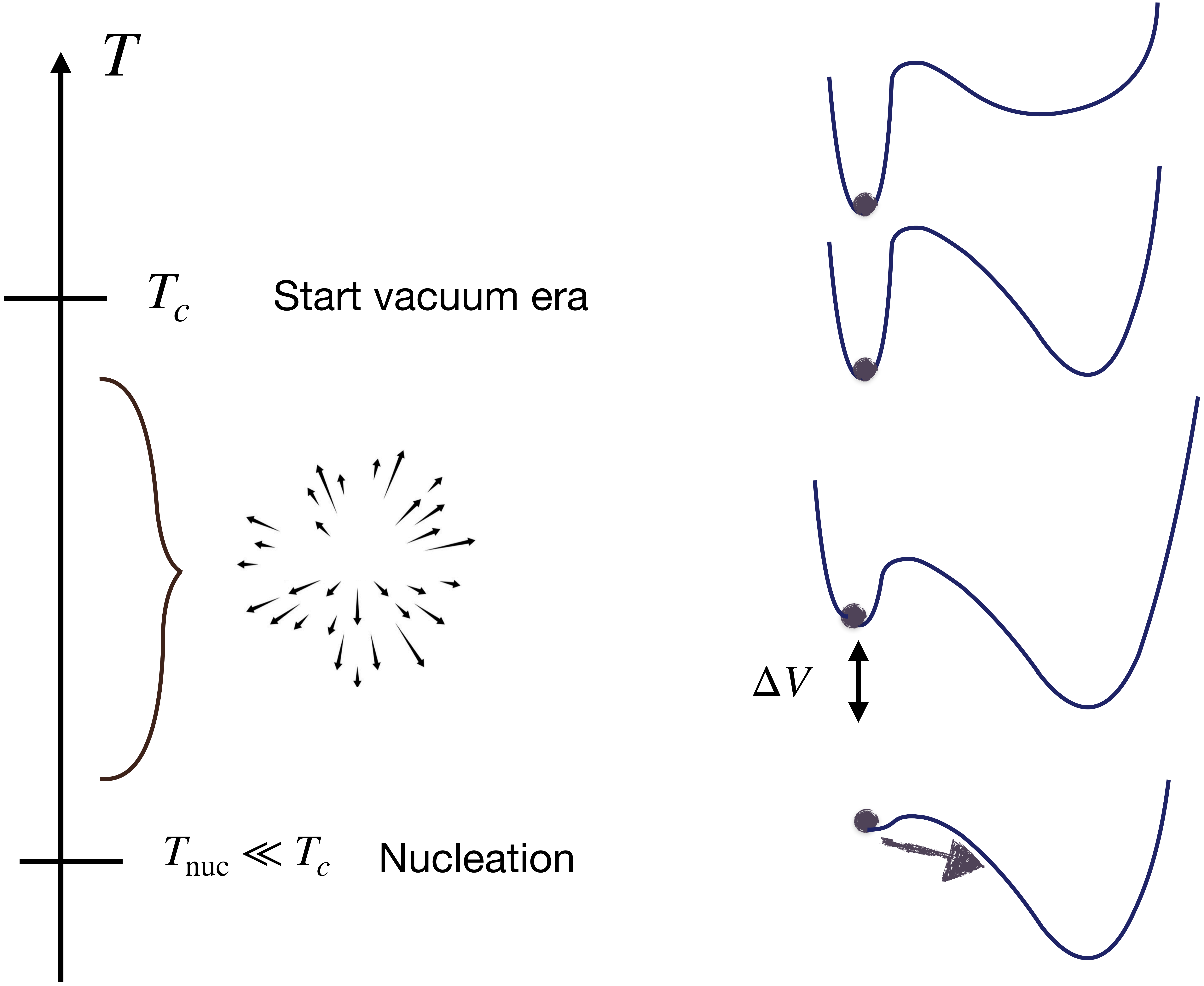
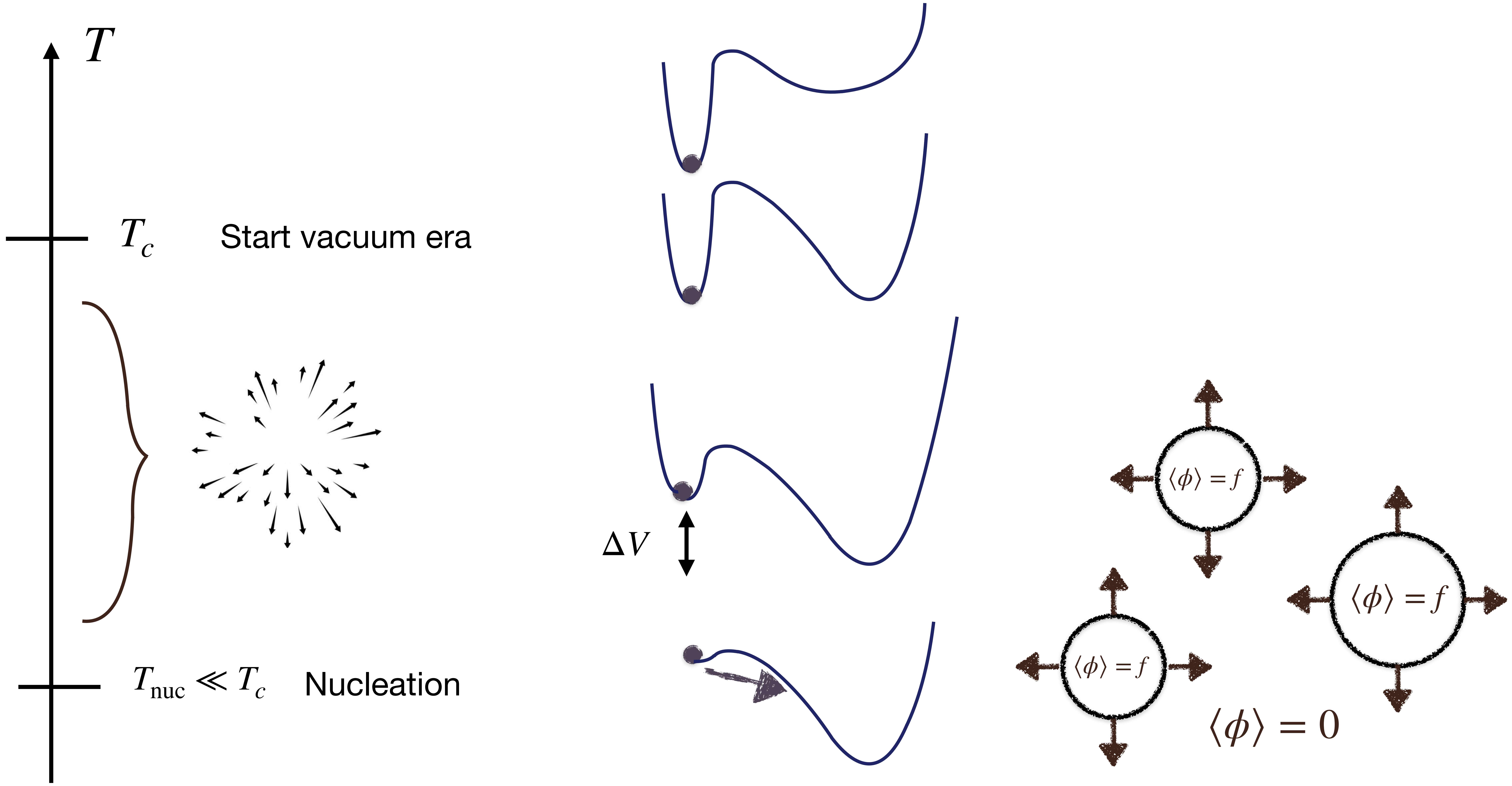


Supercooled 1stOPT = delayed PT



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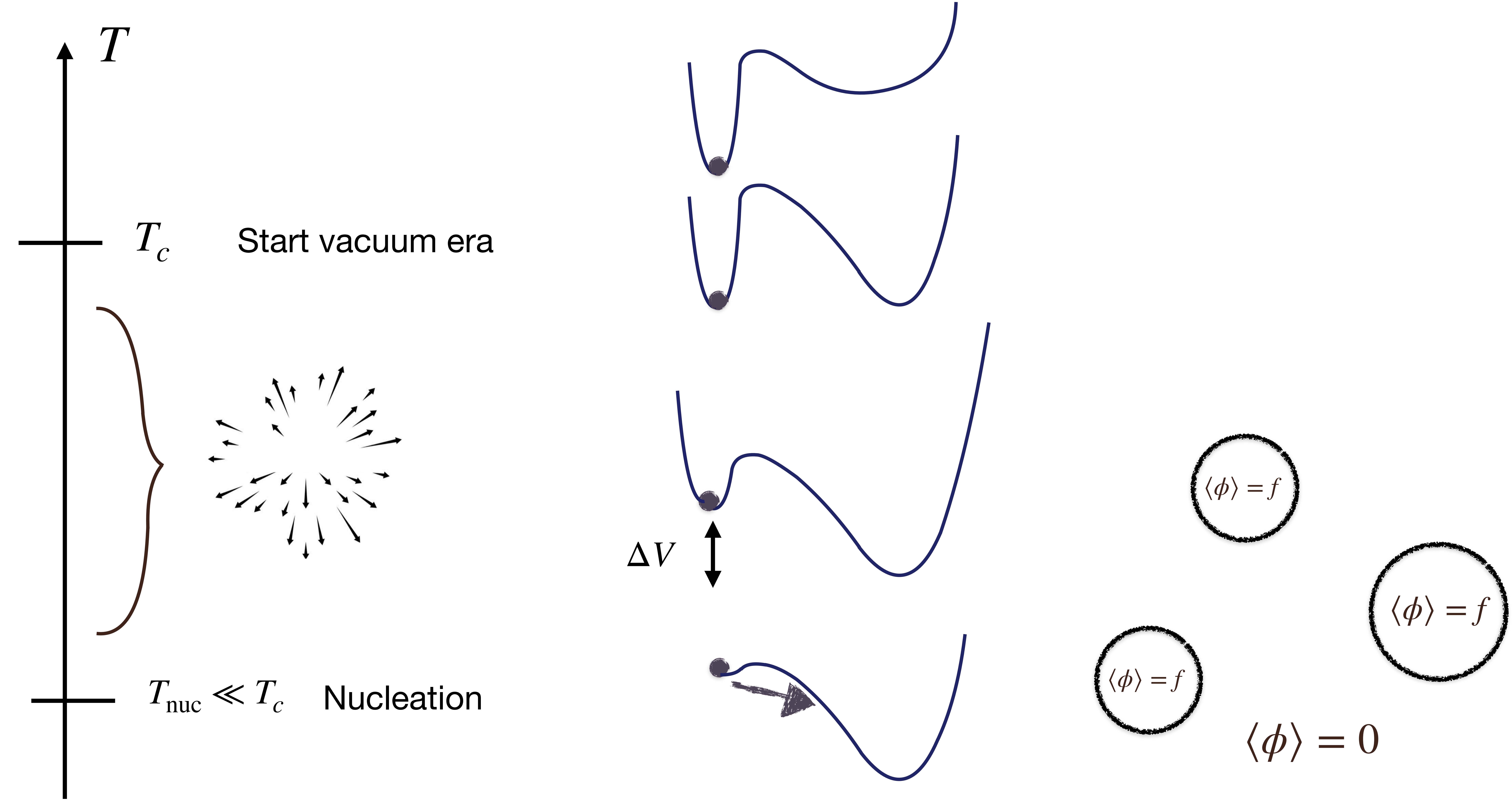

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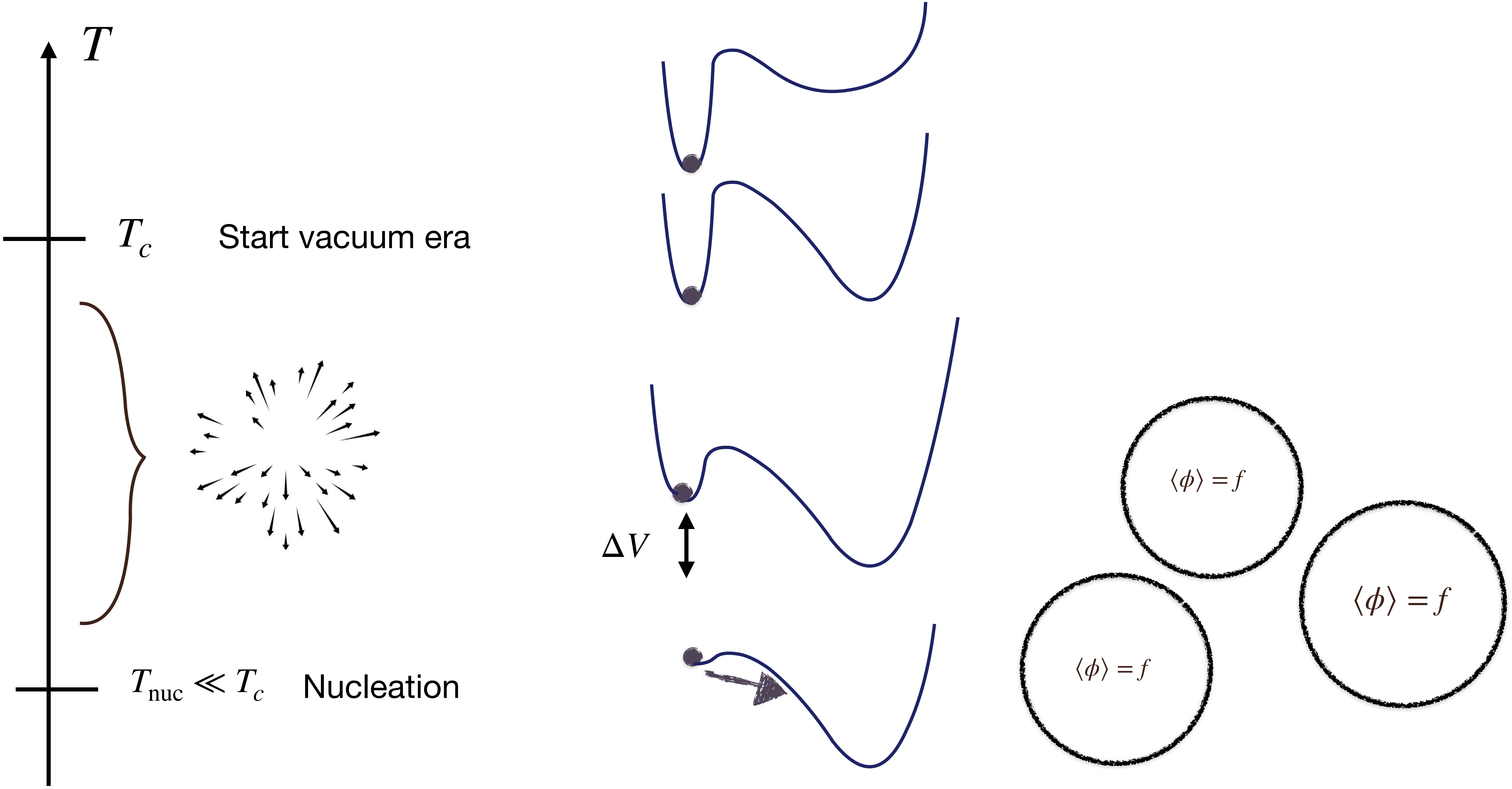

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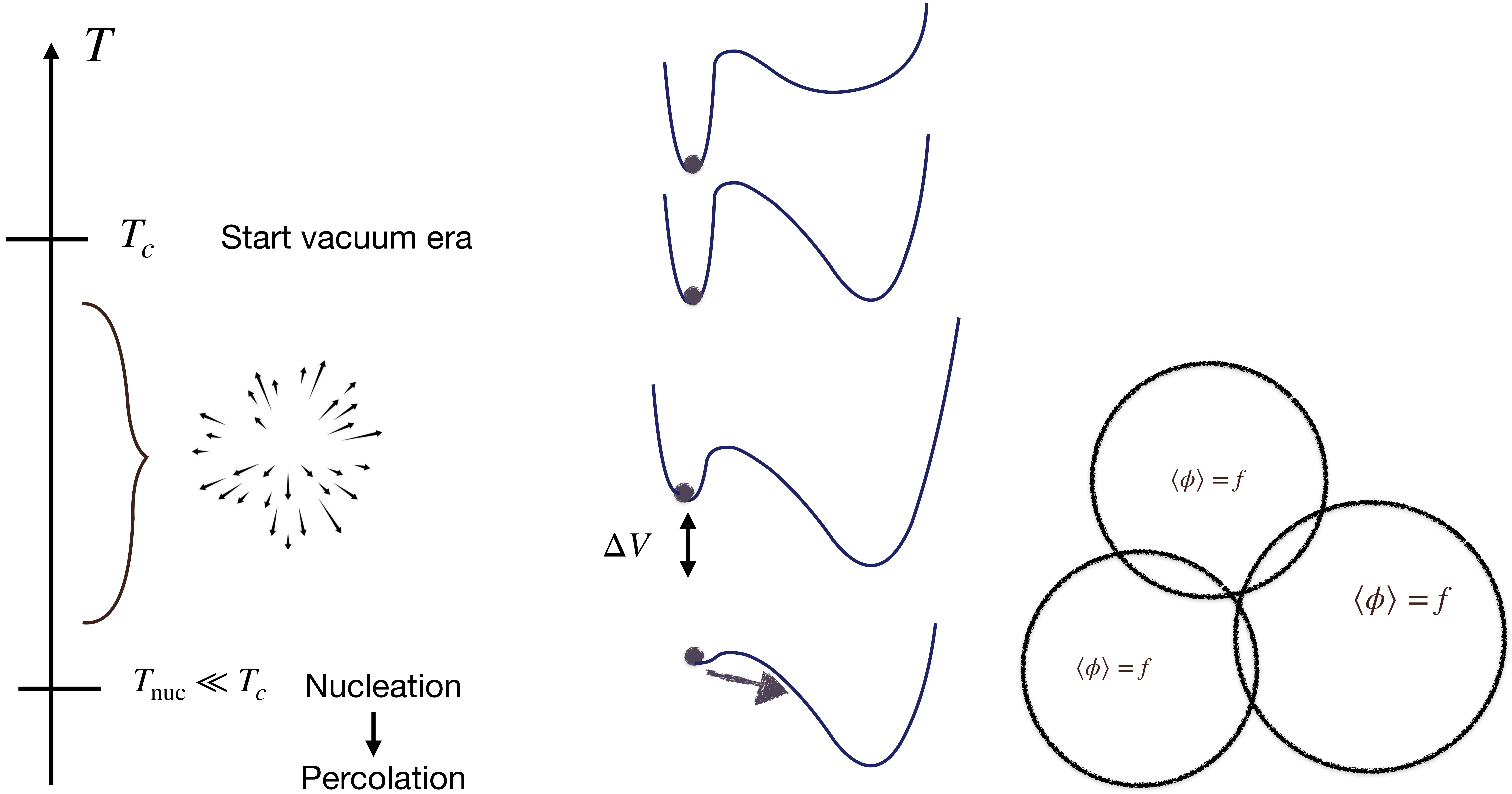
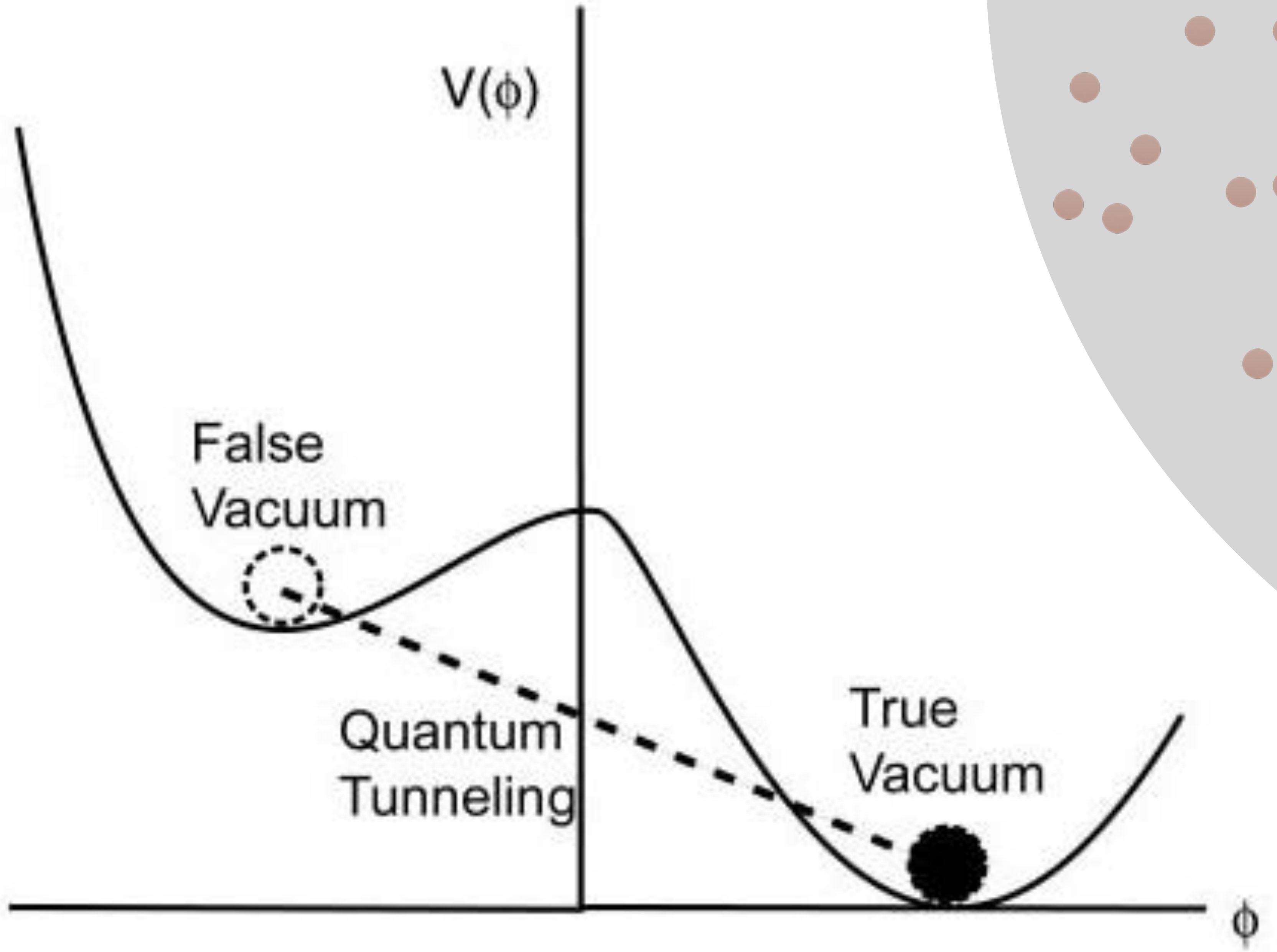
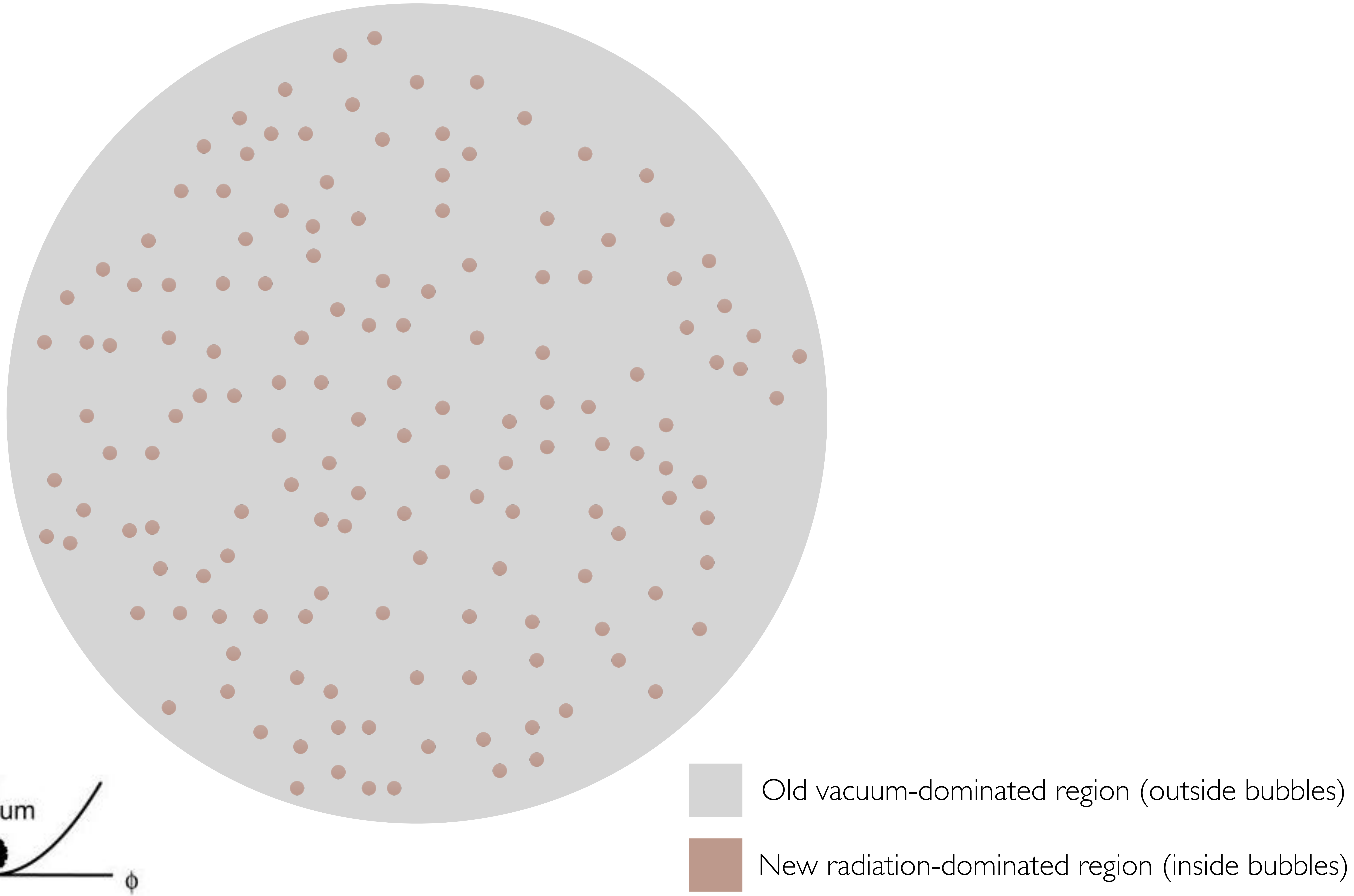


PBHs from 1stOPT

YG, Volansky 2305:04942





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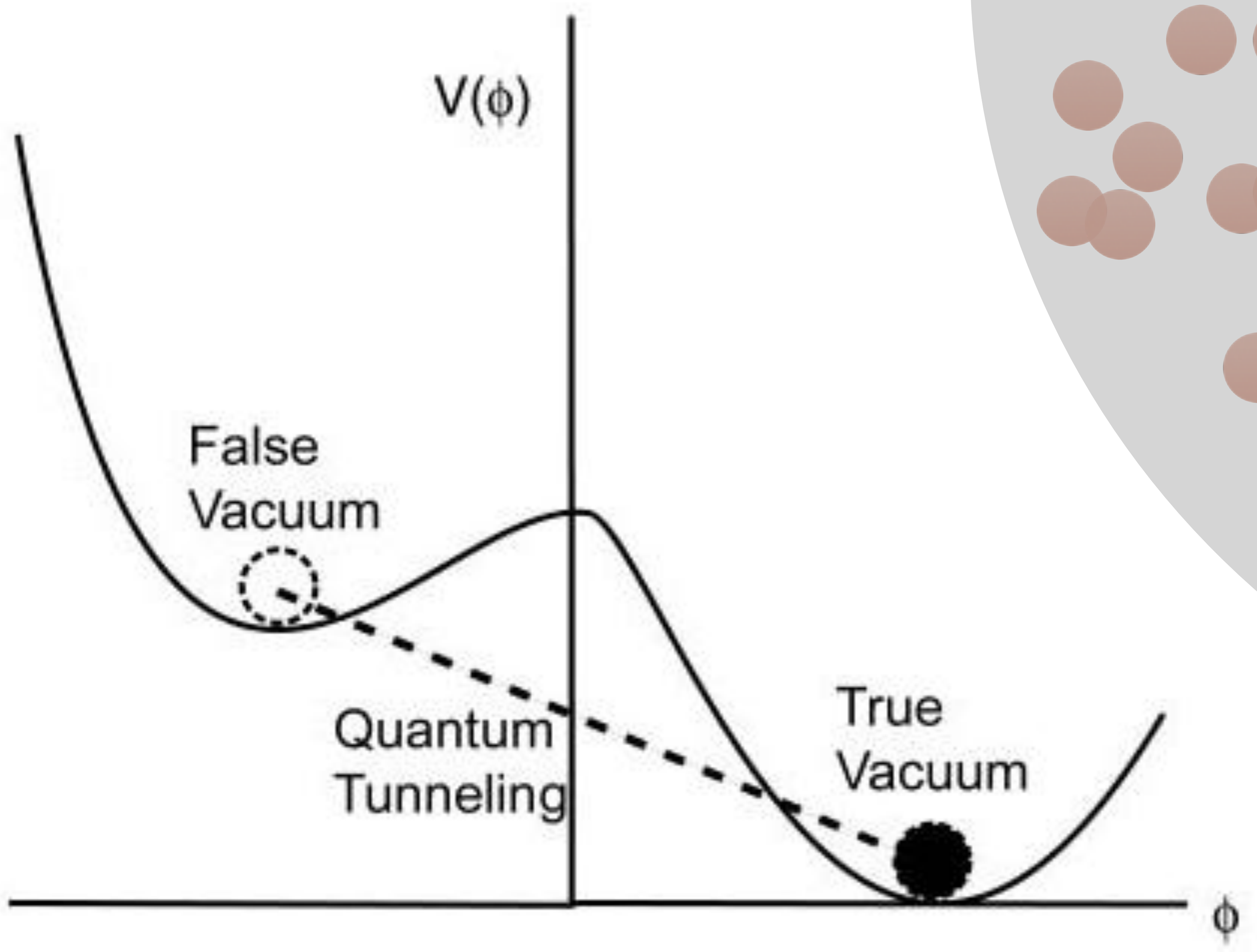

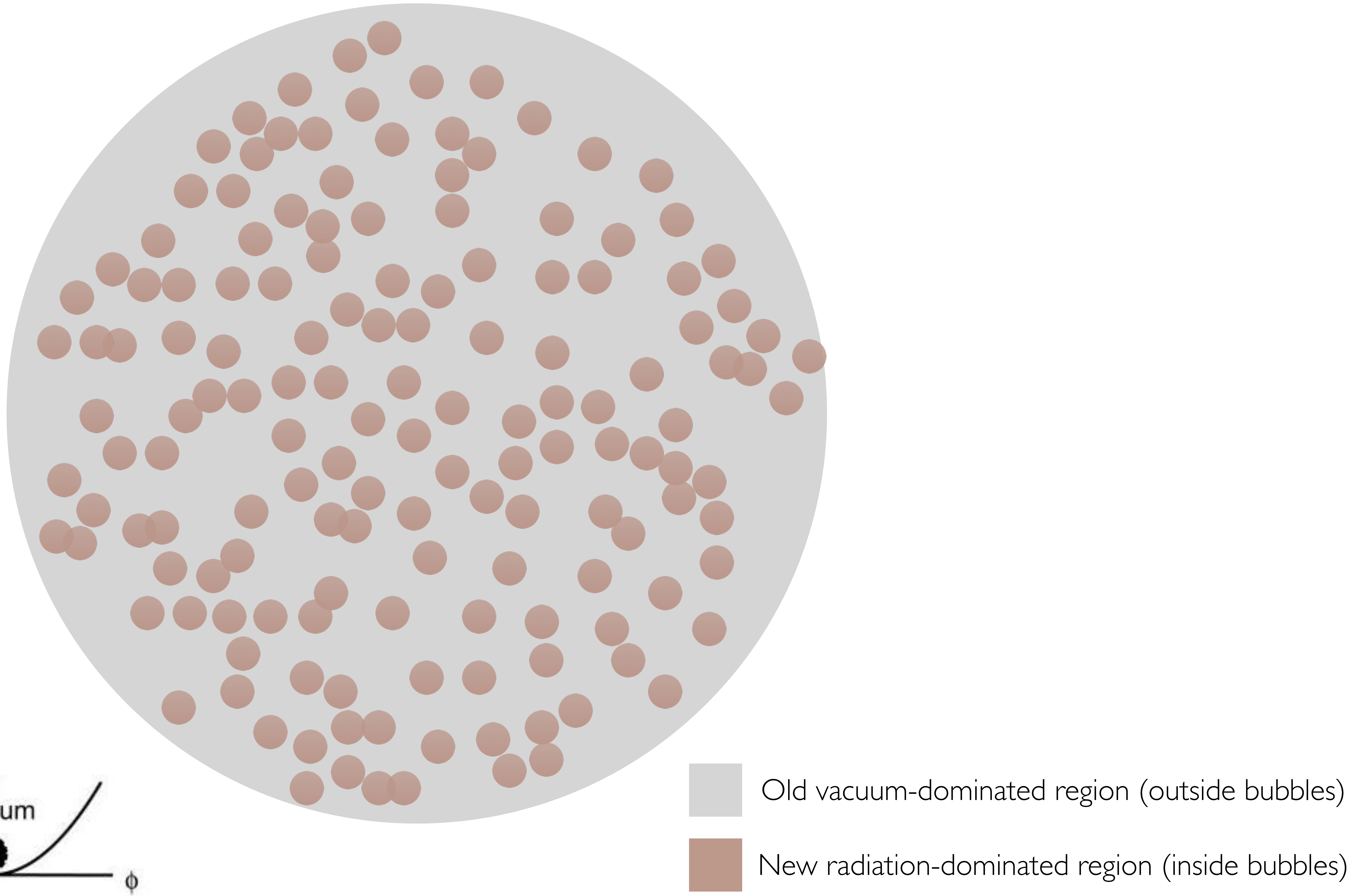

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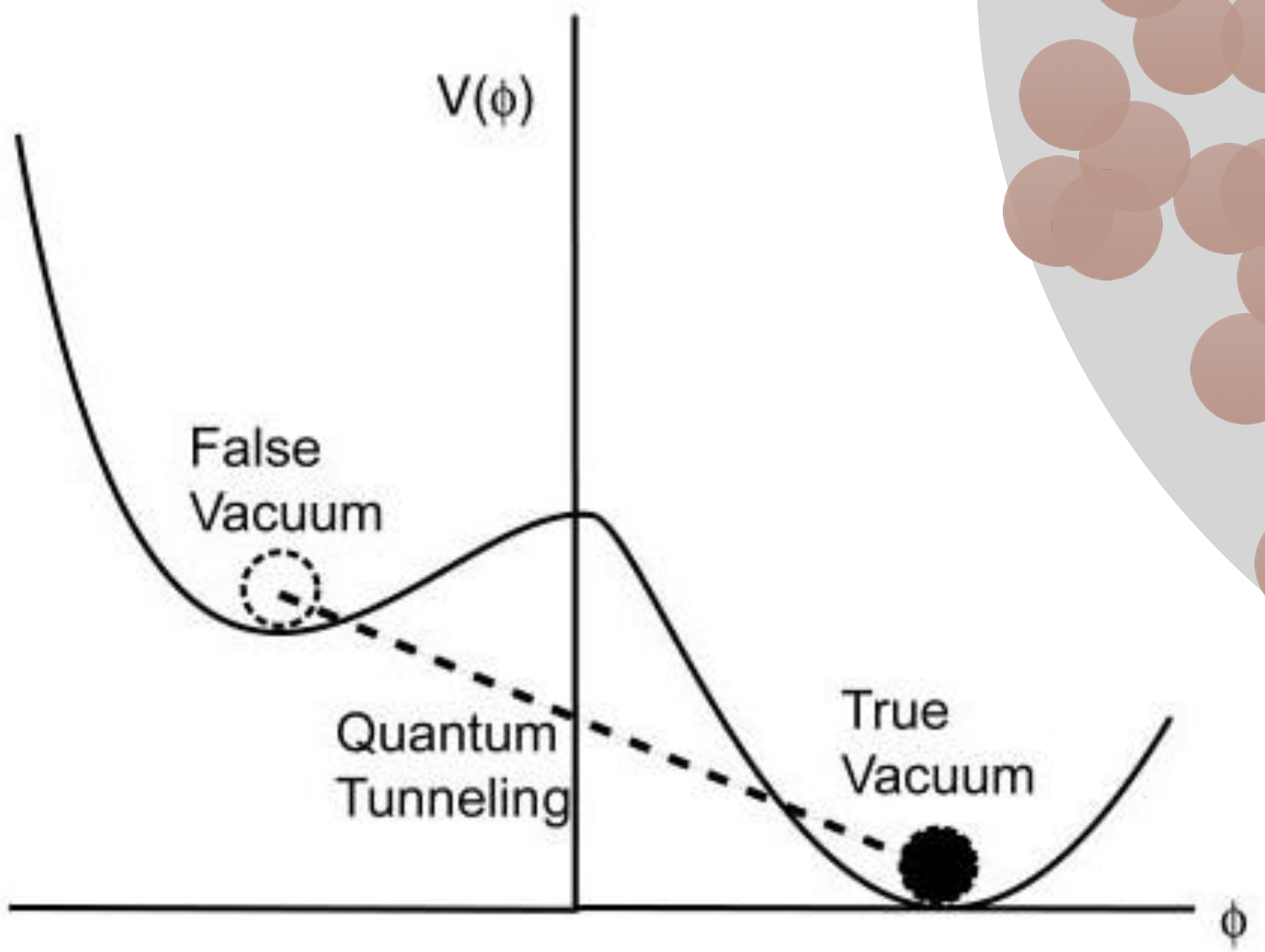

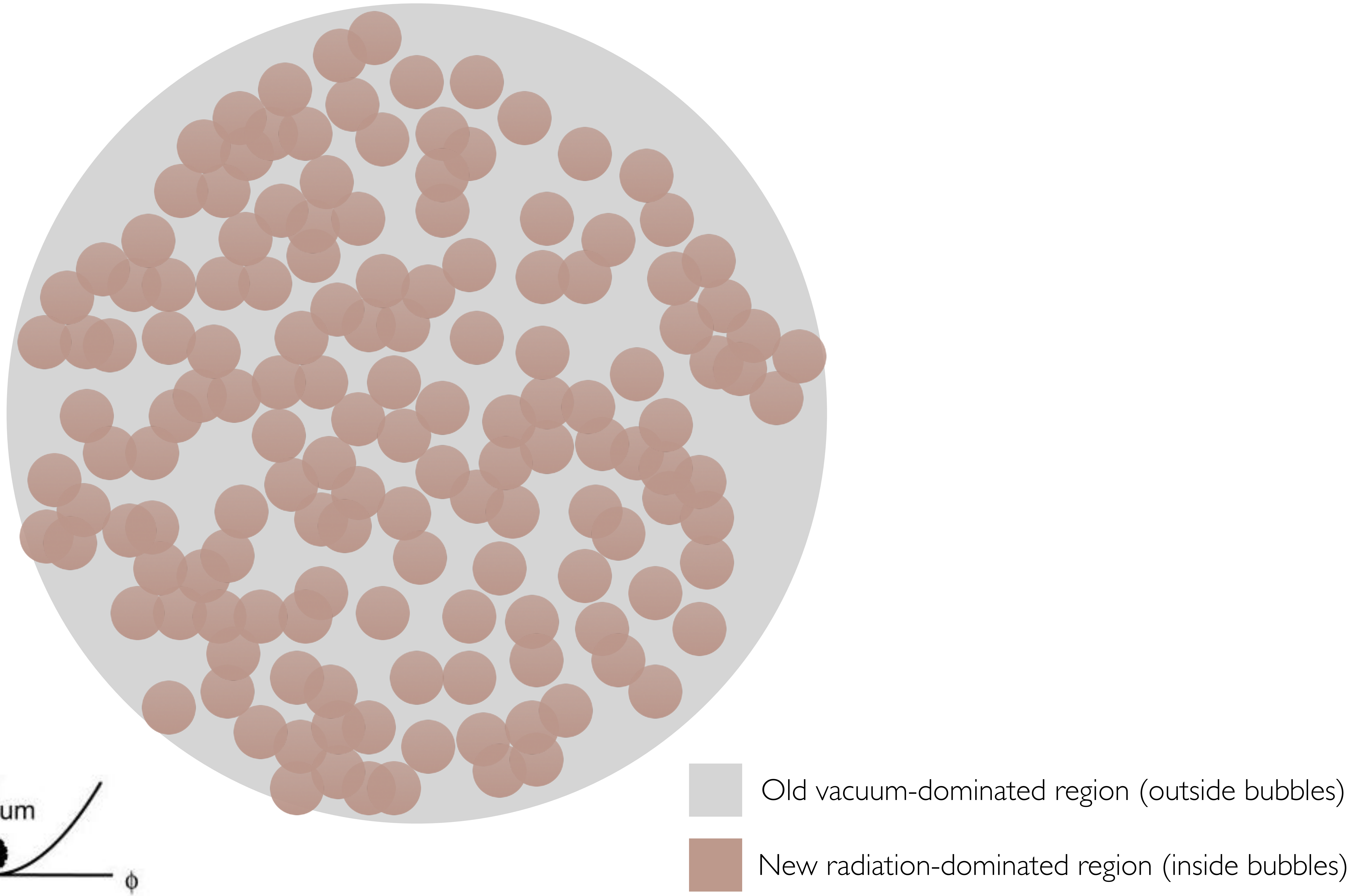

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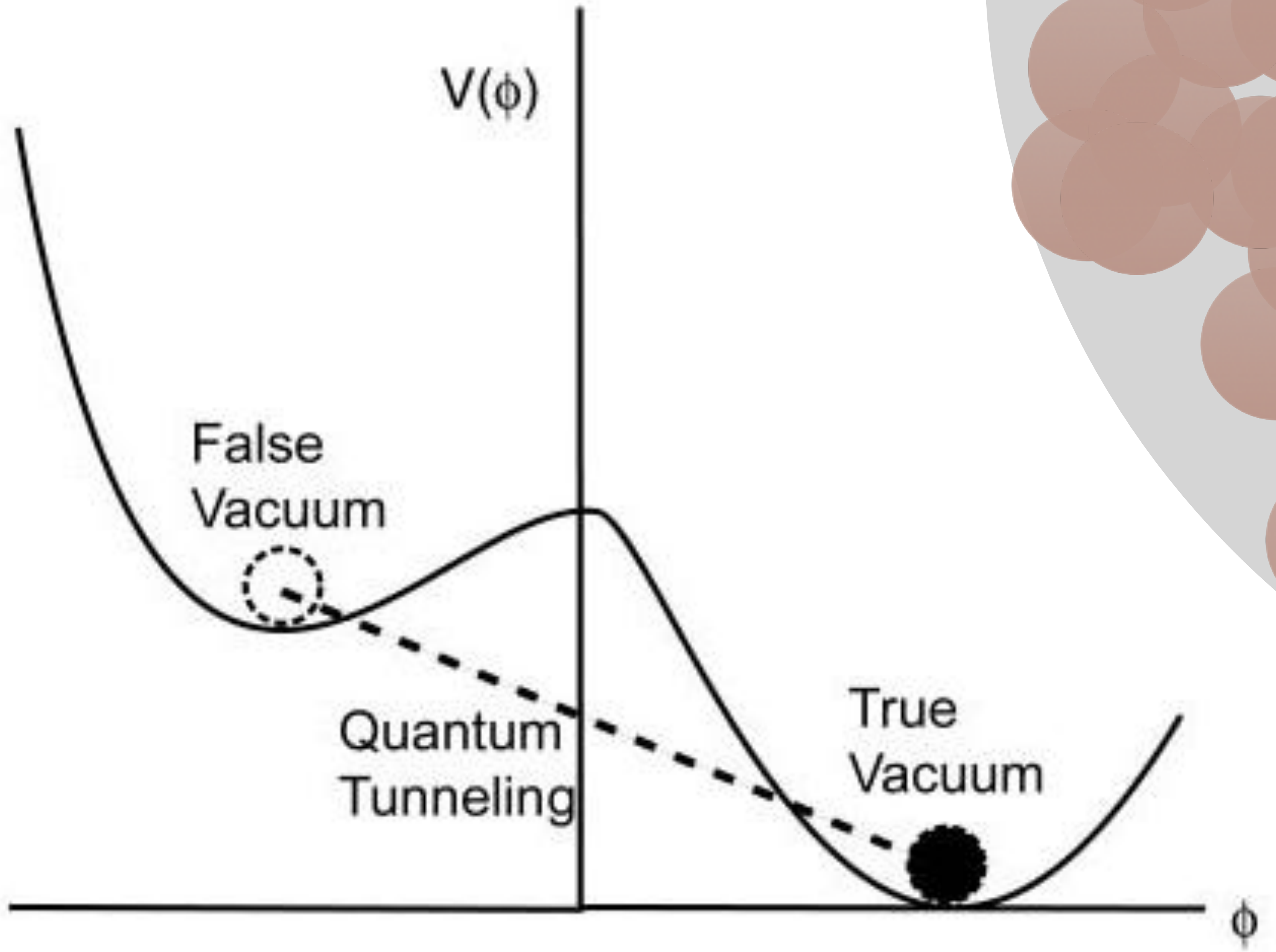

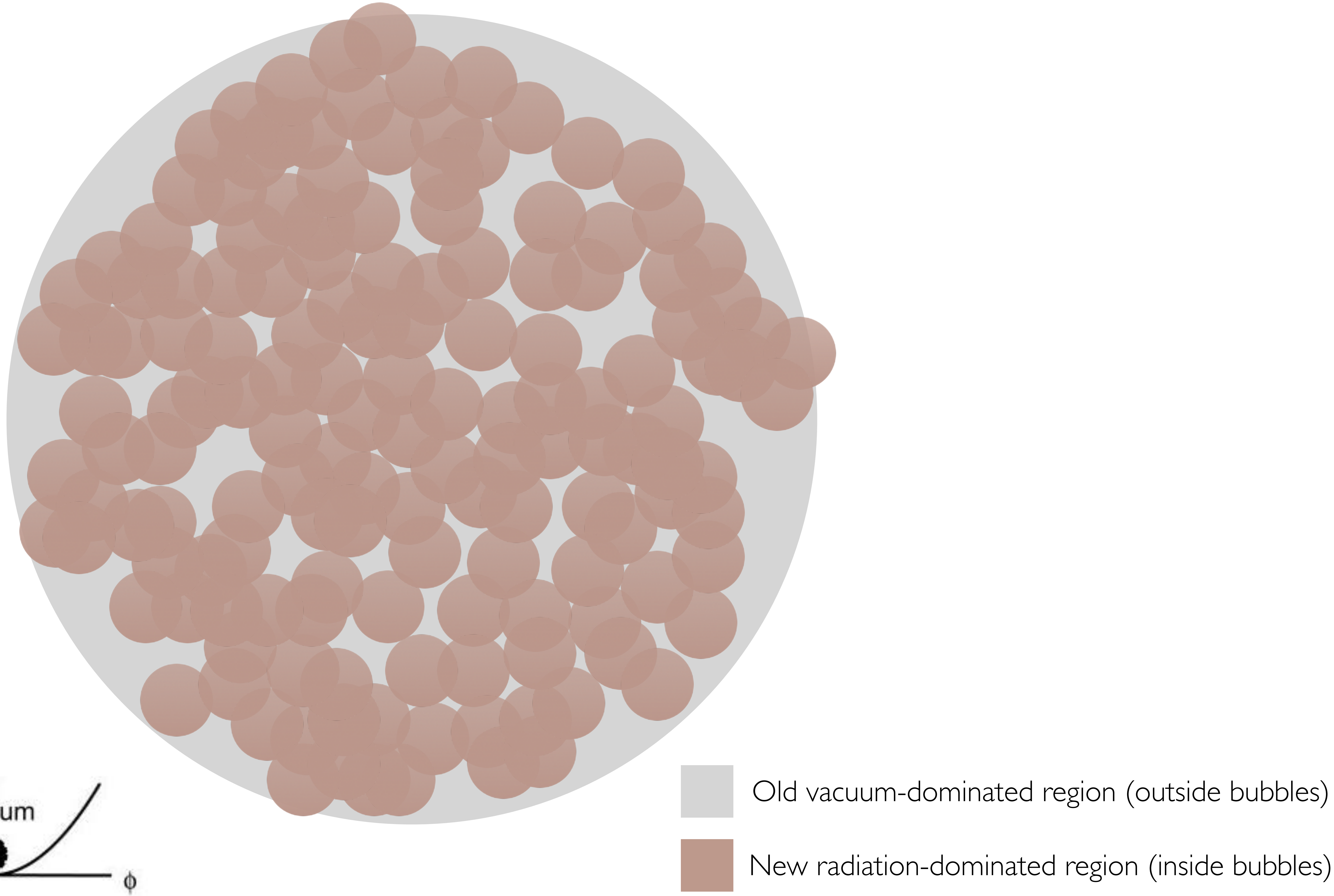

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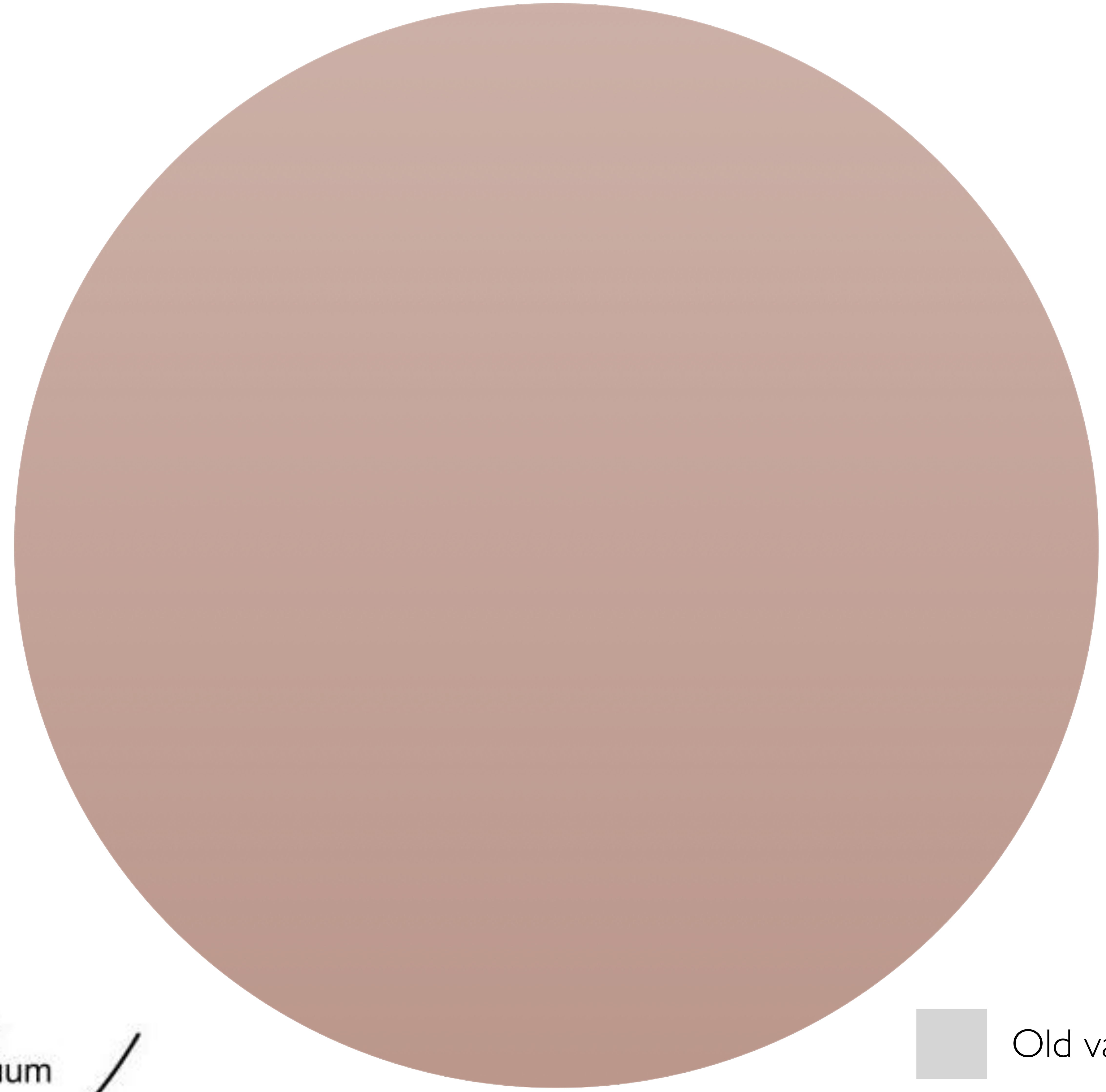
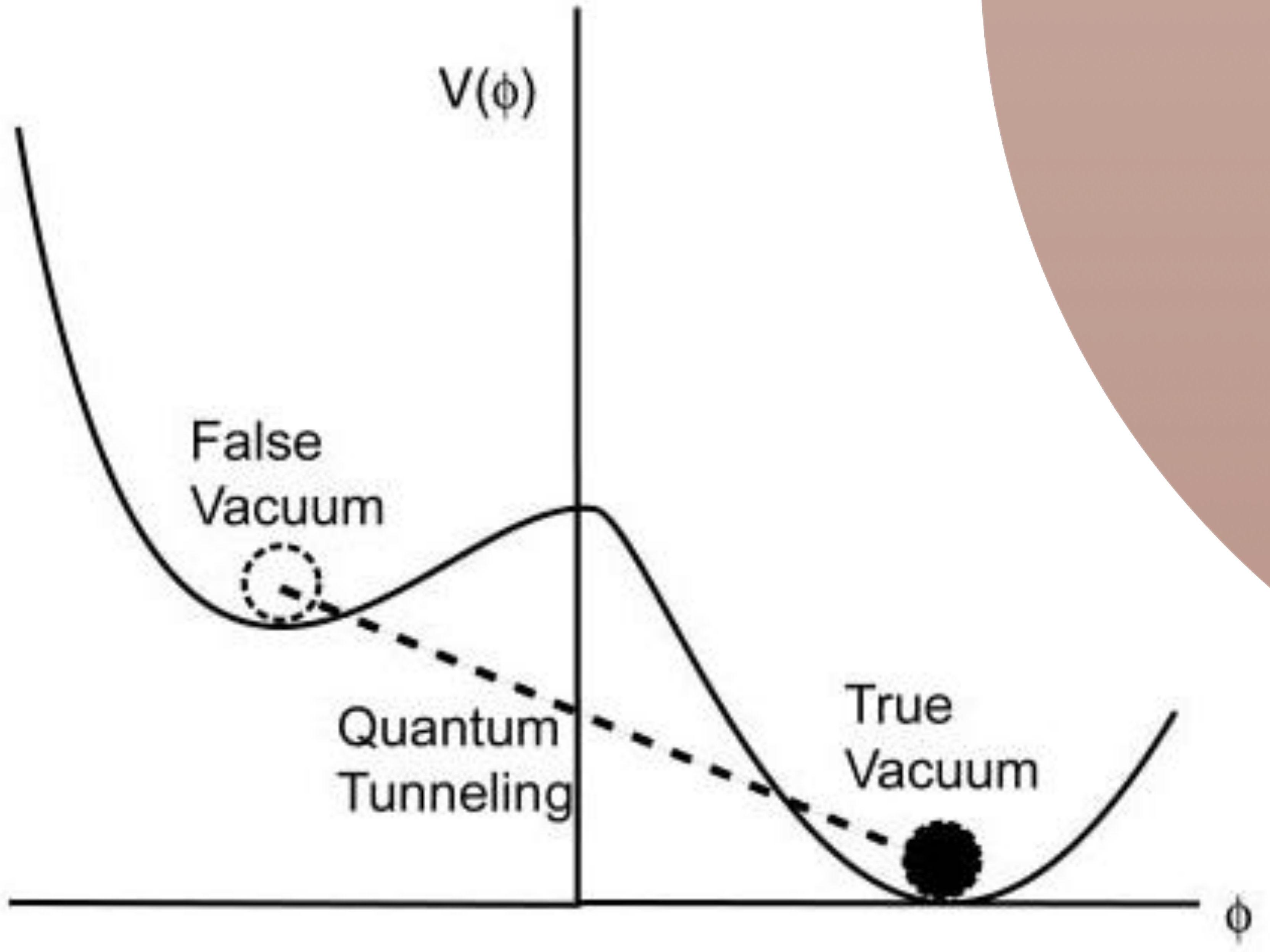


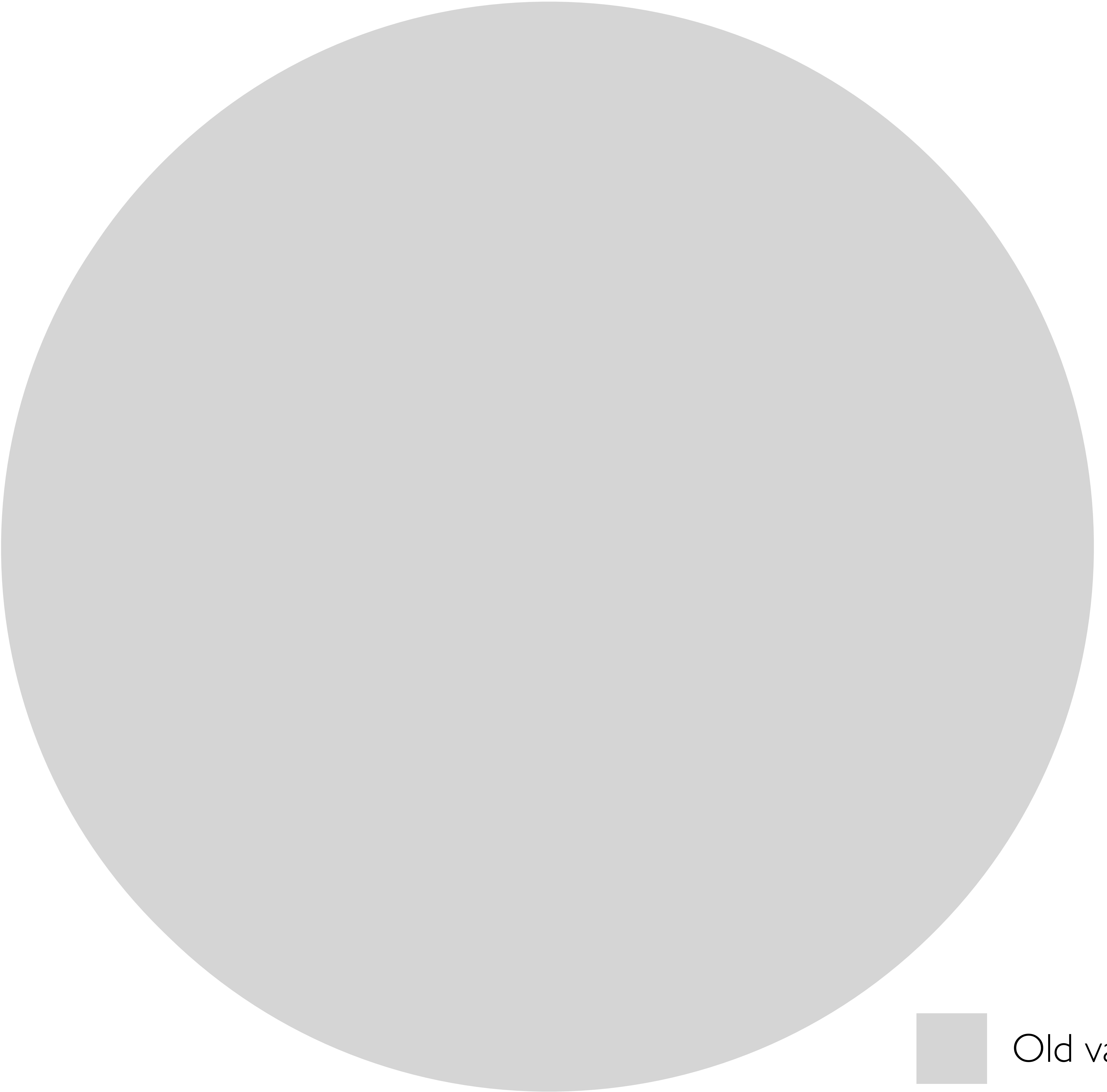


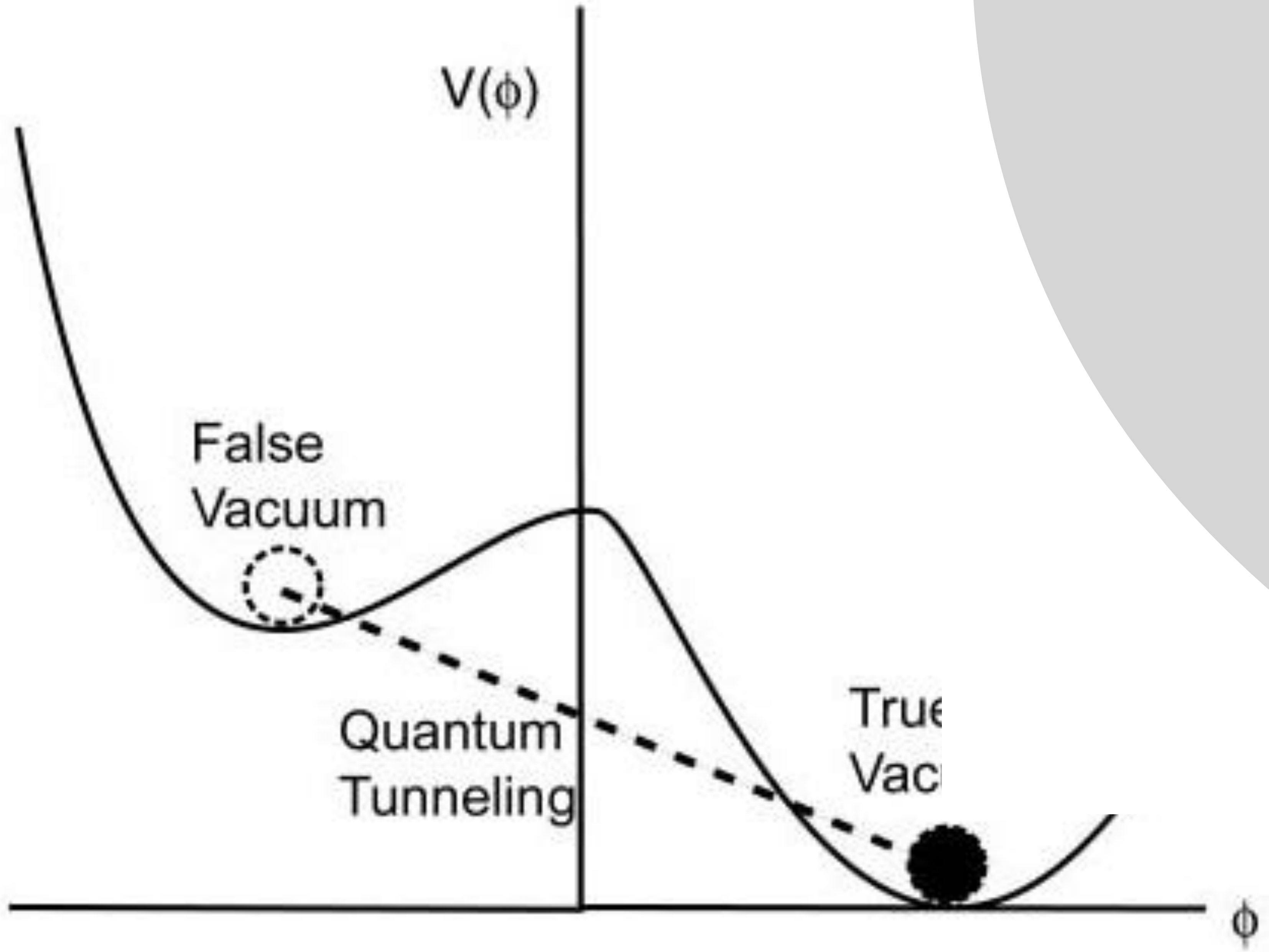
Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

PBHs from 1stOPT

YG, Volansky 2305:04942





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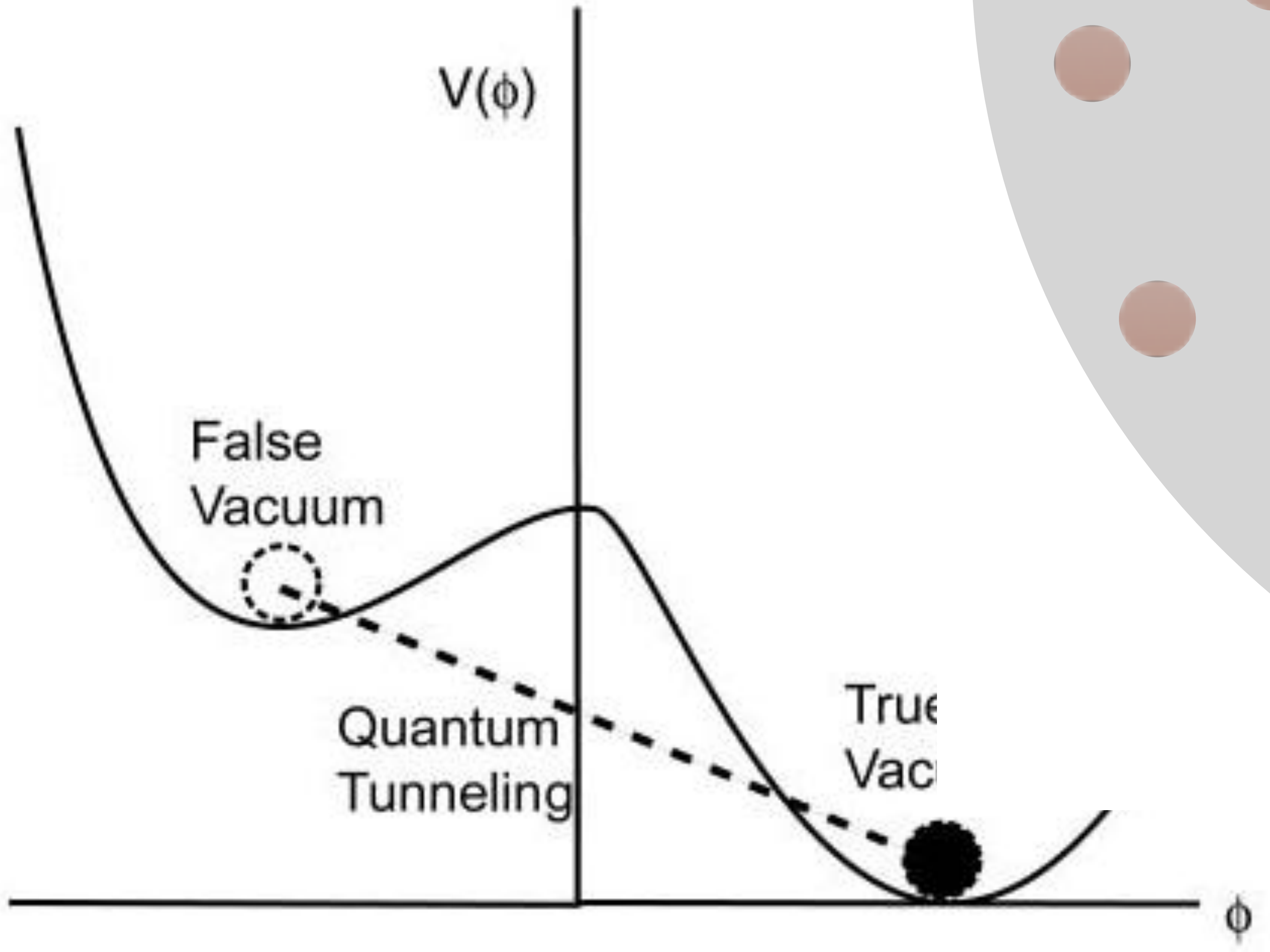
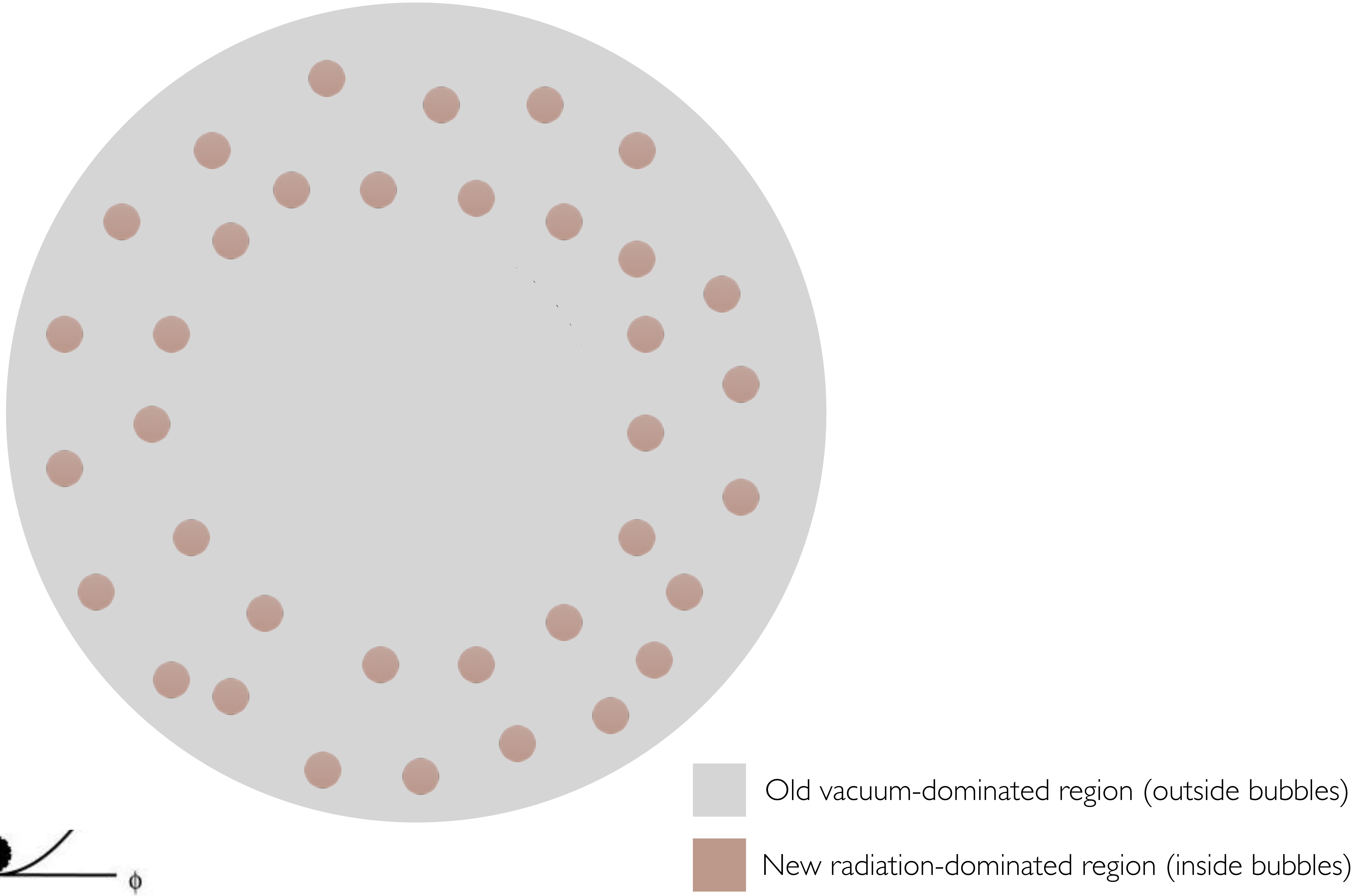
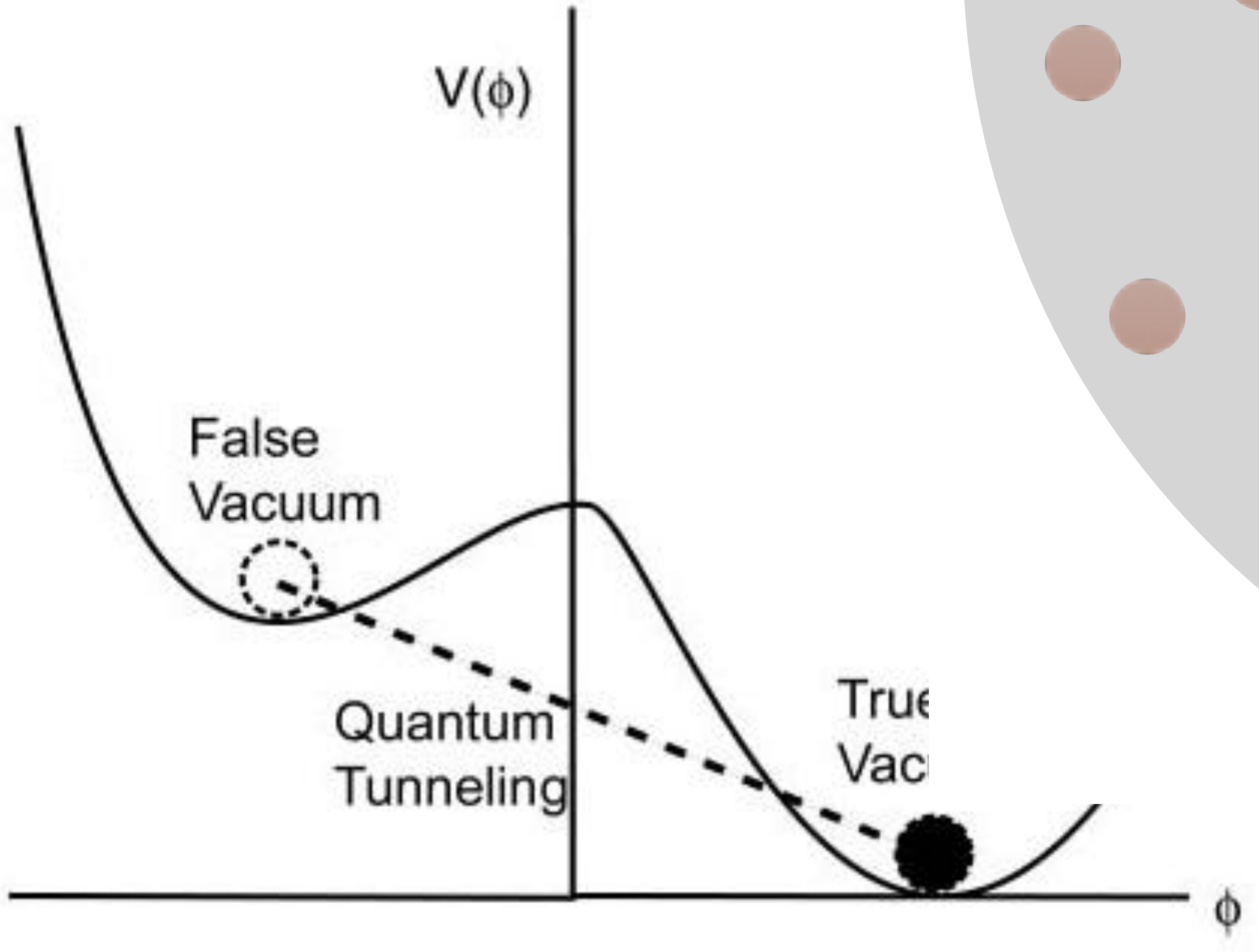
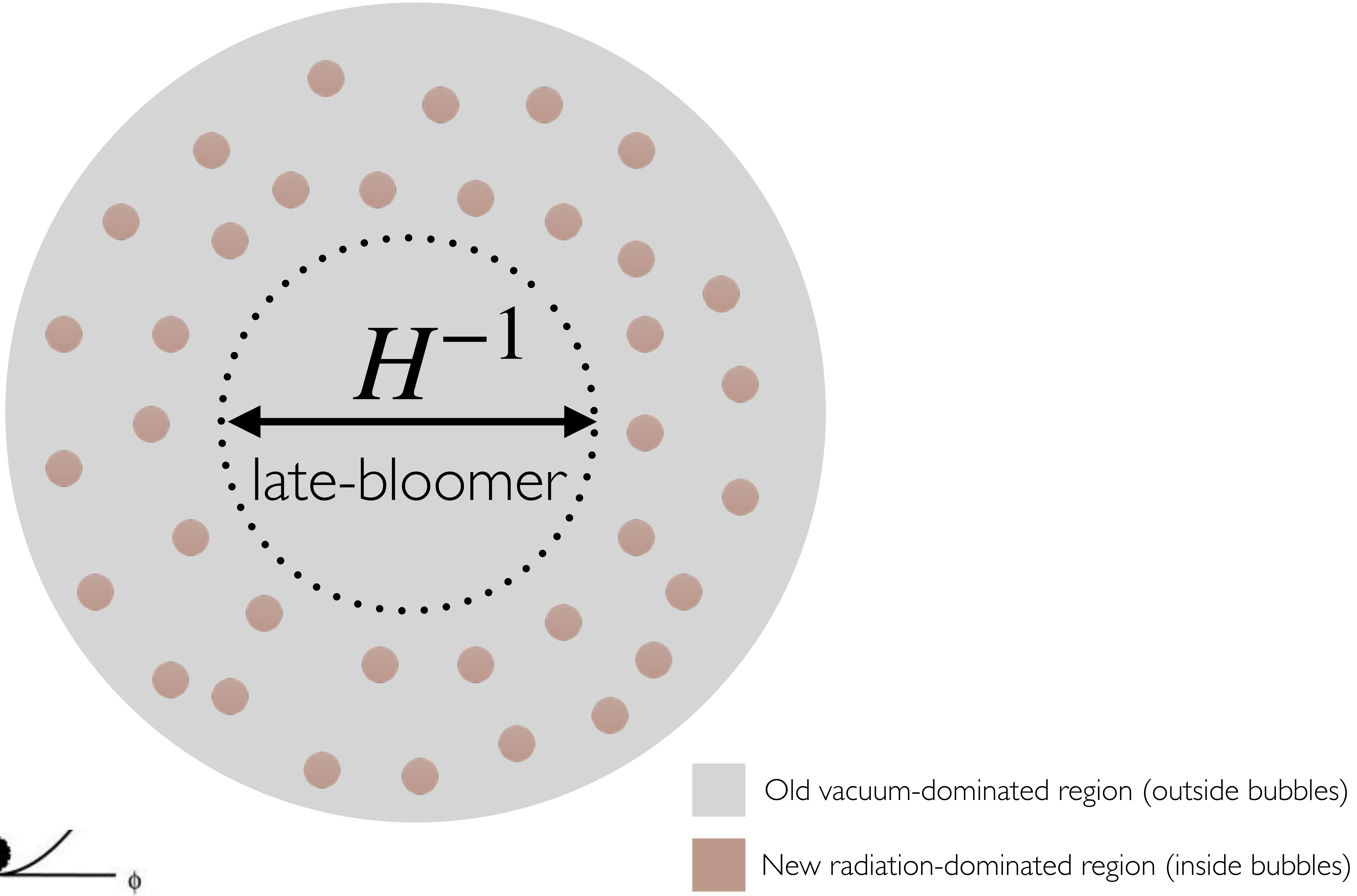




PBHs from 1stOPT

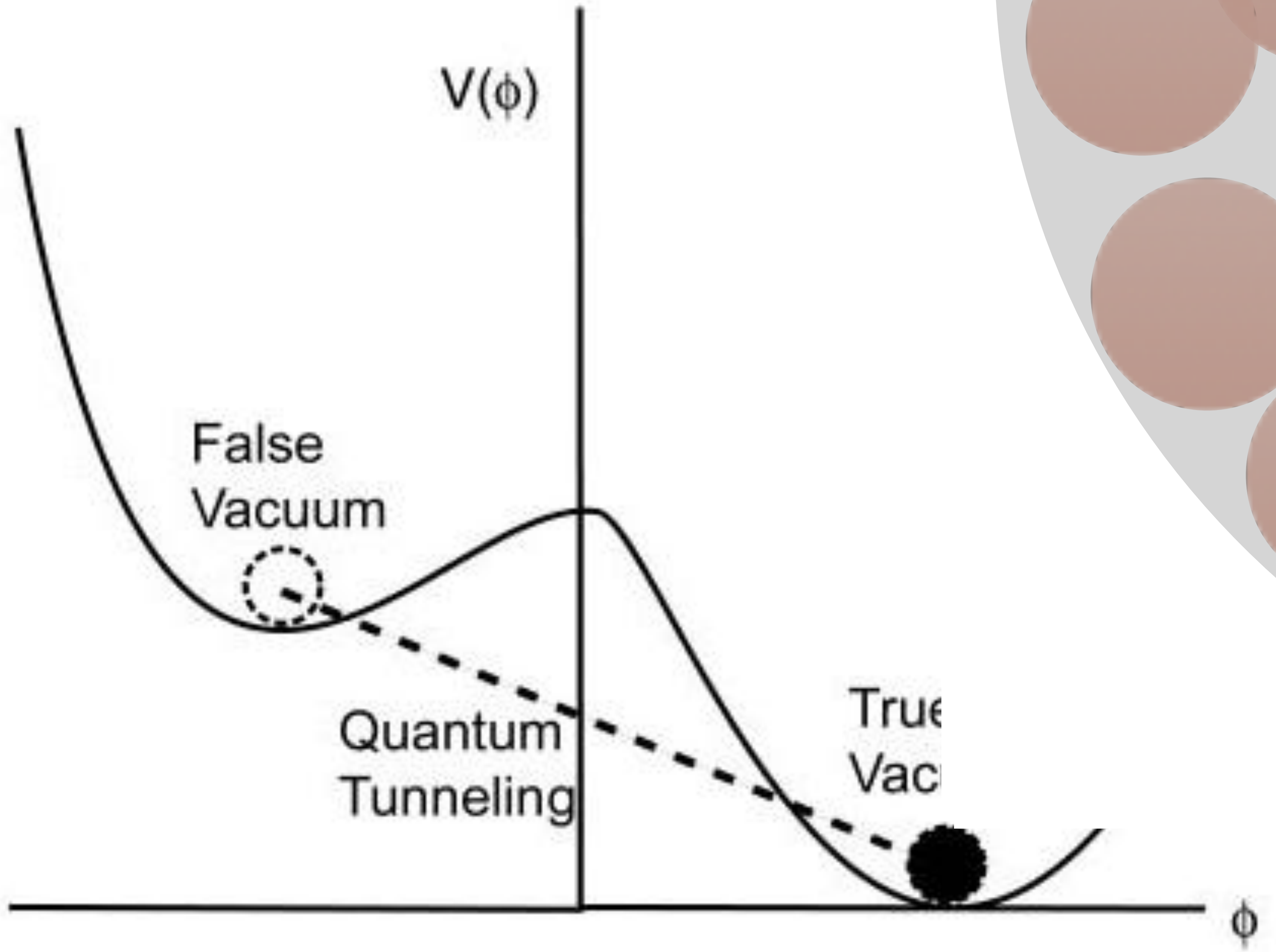
YG, Volansky 2305:04942

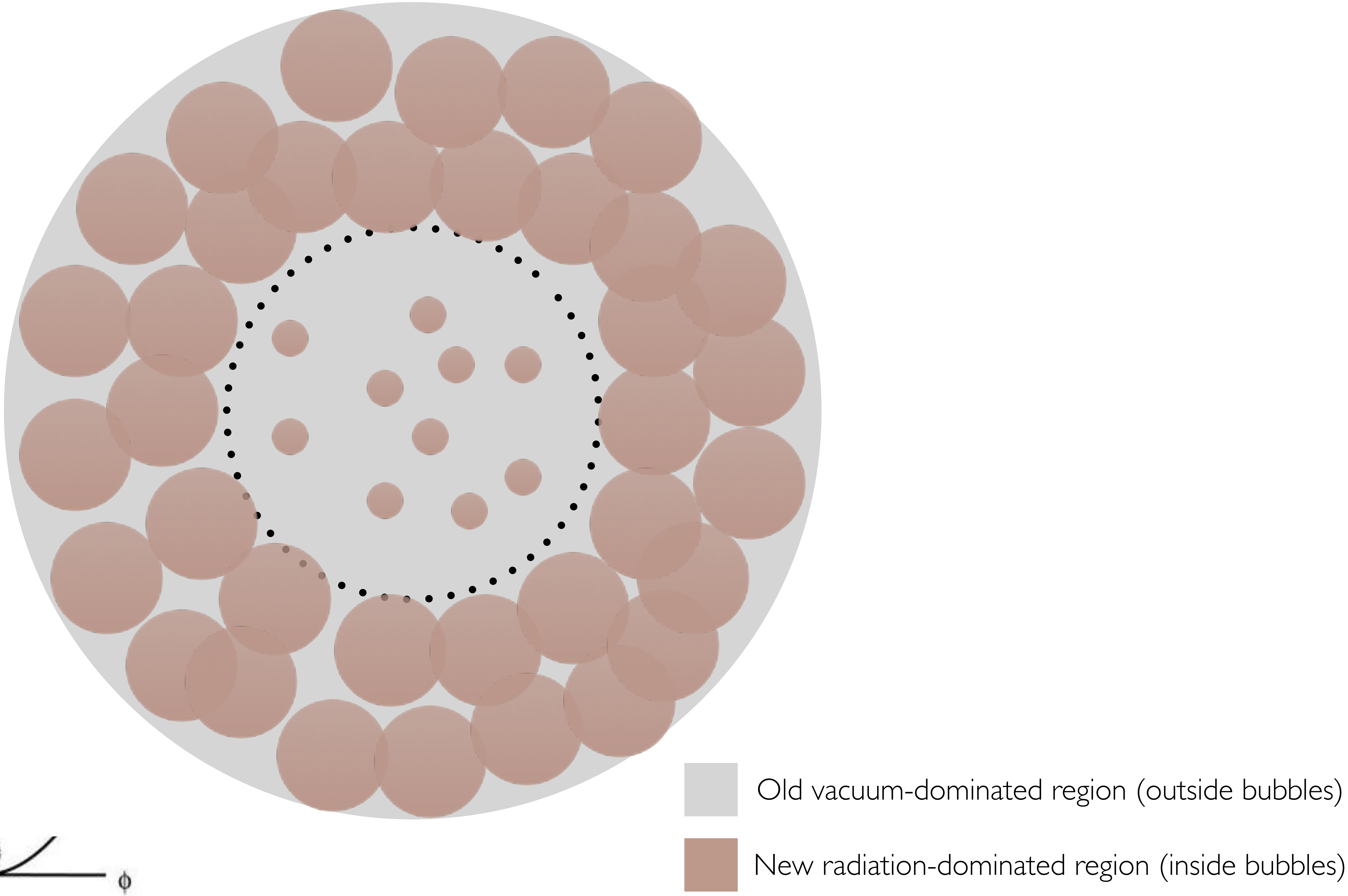




PBHs from 1stOPT

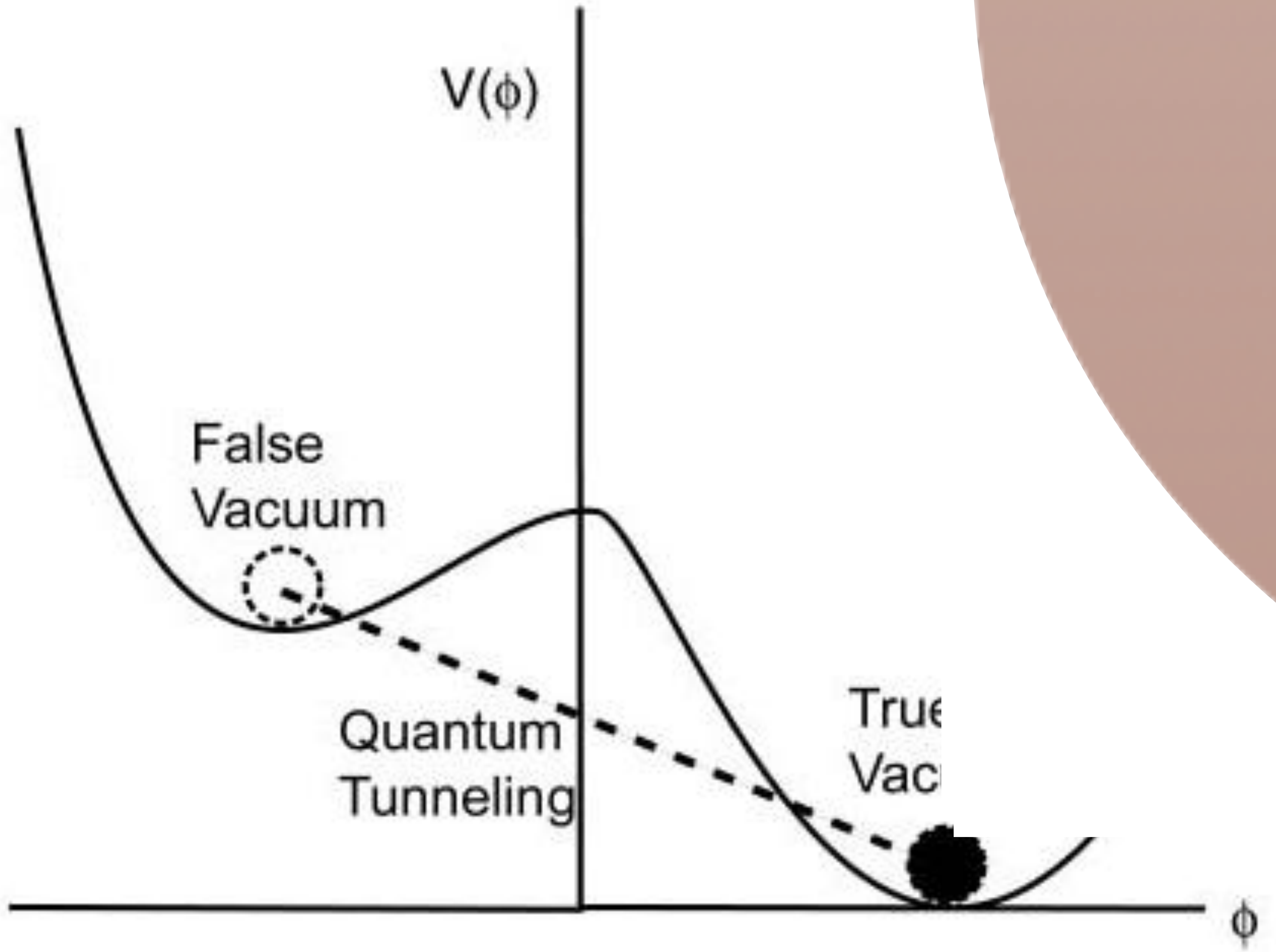
YG, Volansky 2305:04942

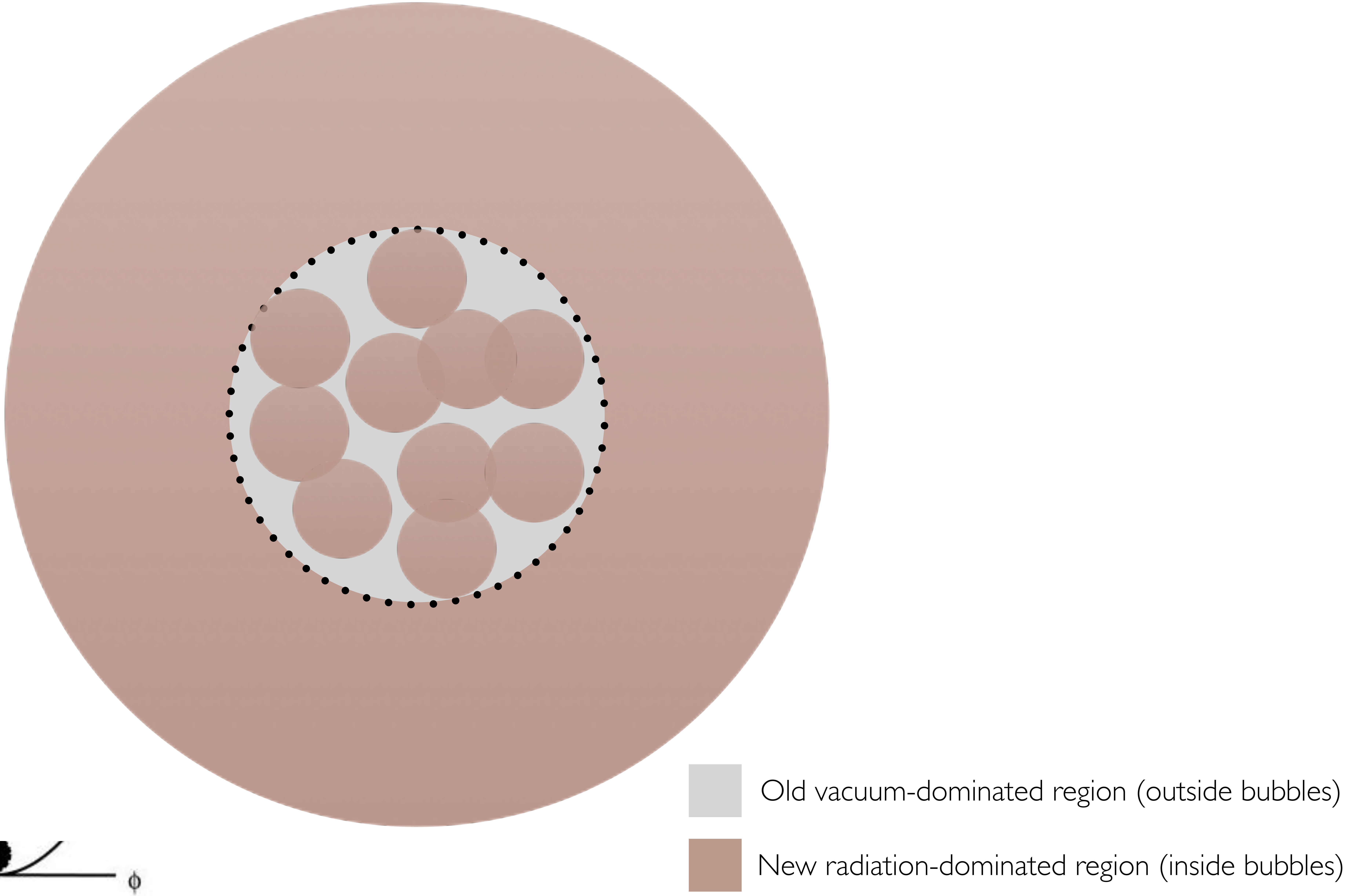




PBHs from 1stOPT

YG, Volansky 2305:04942





PBHs from 1stOPT

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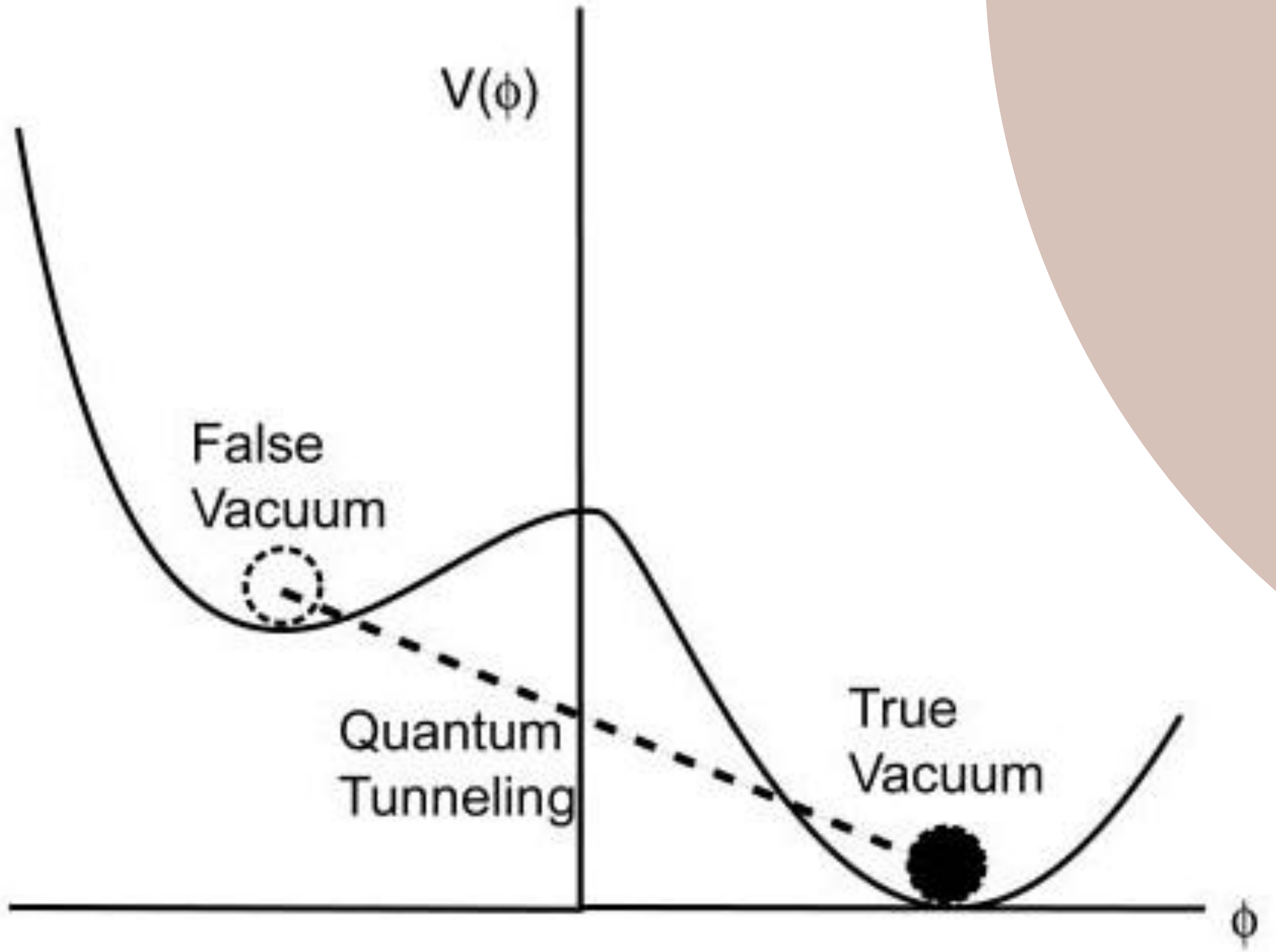
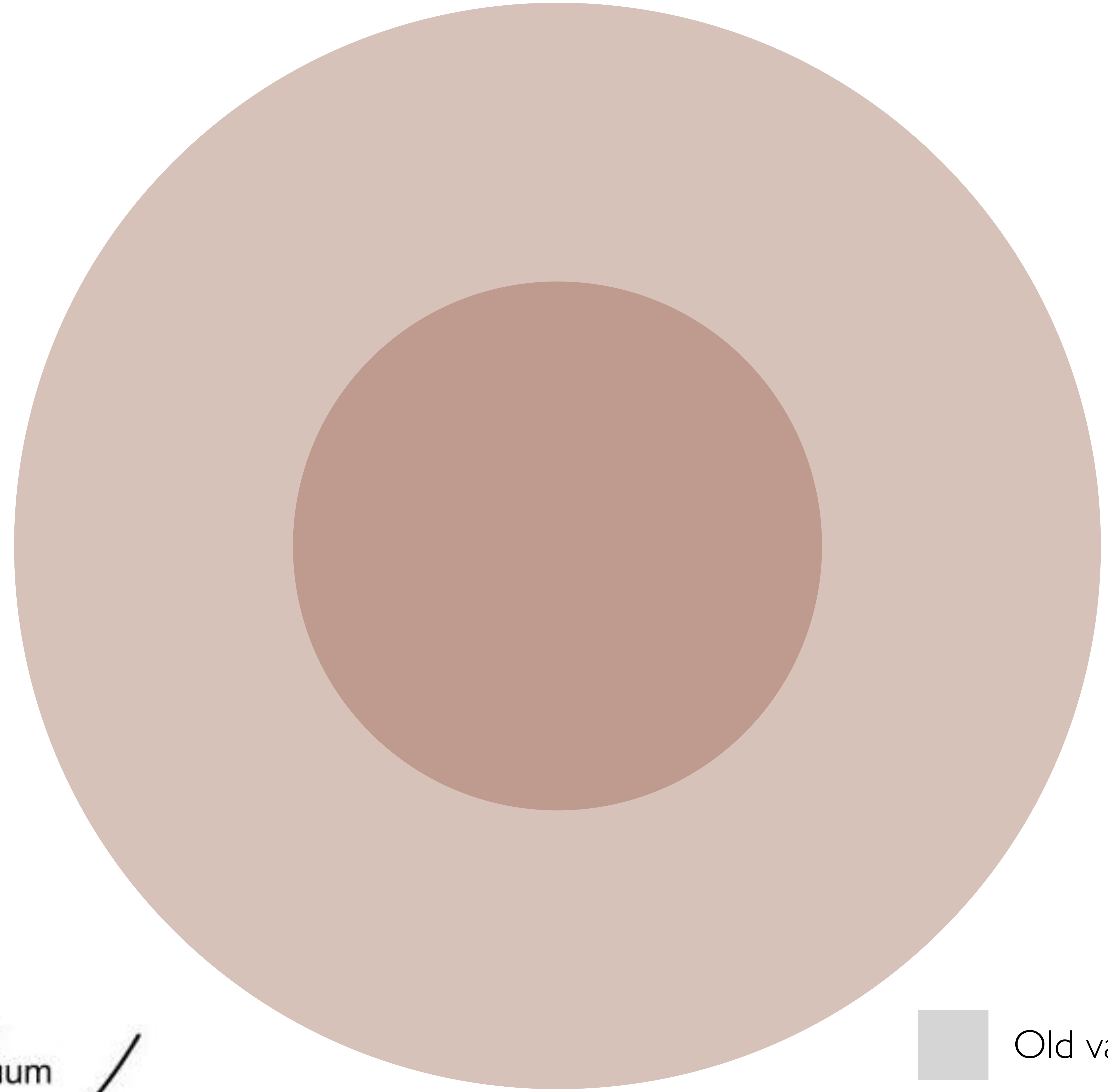


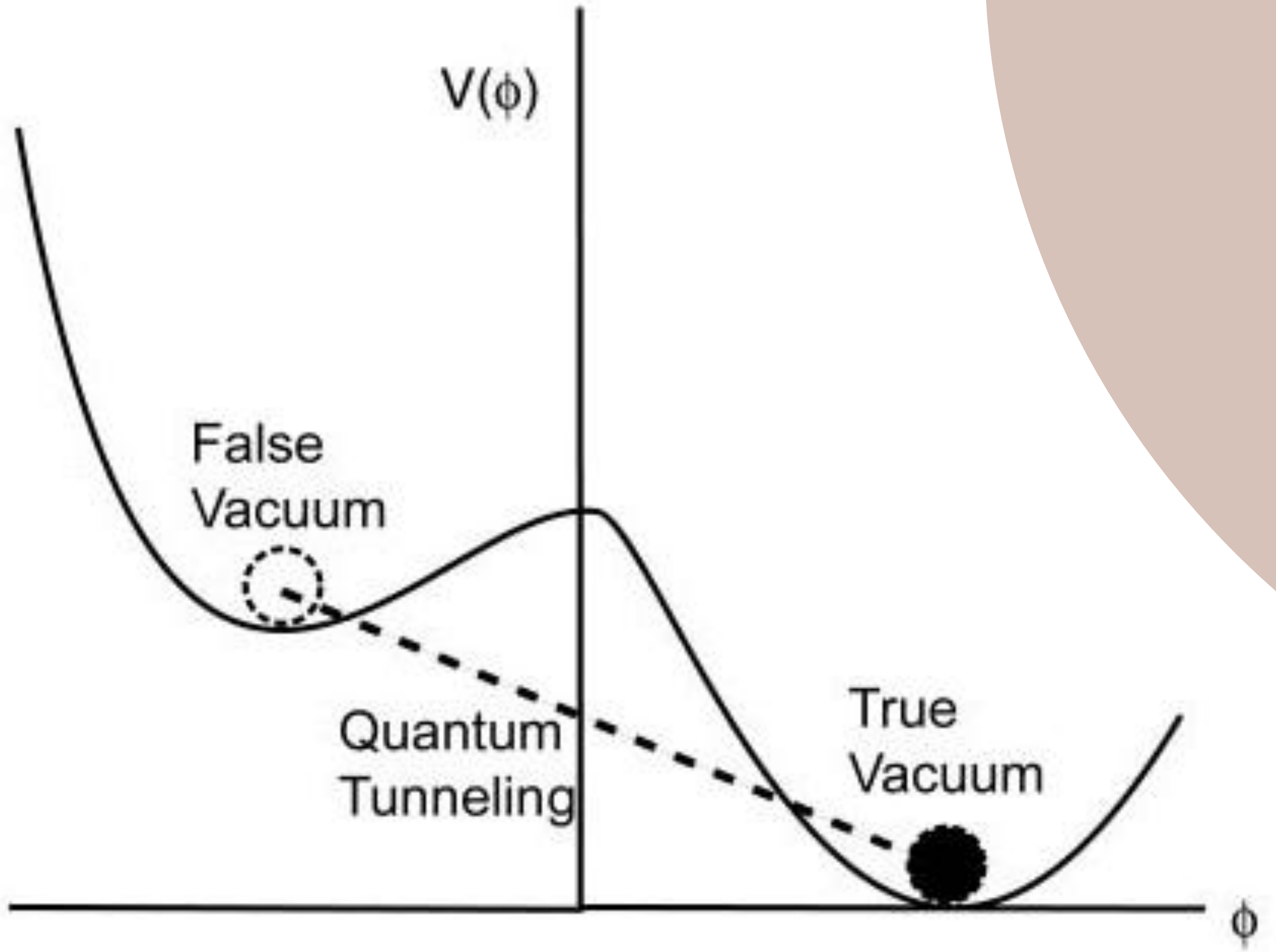


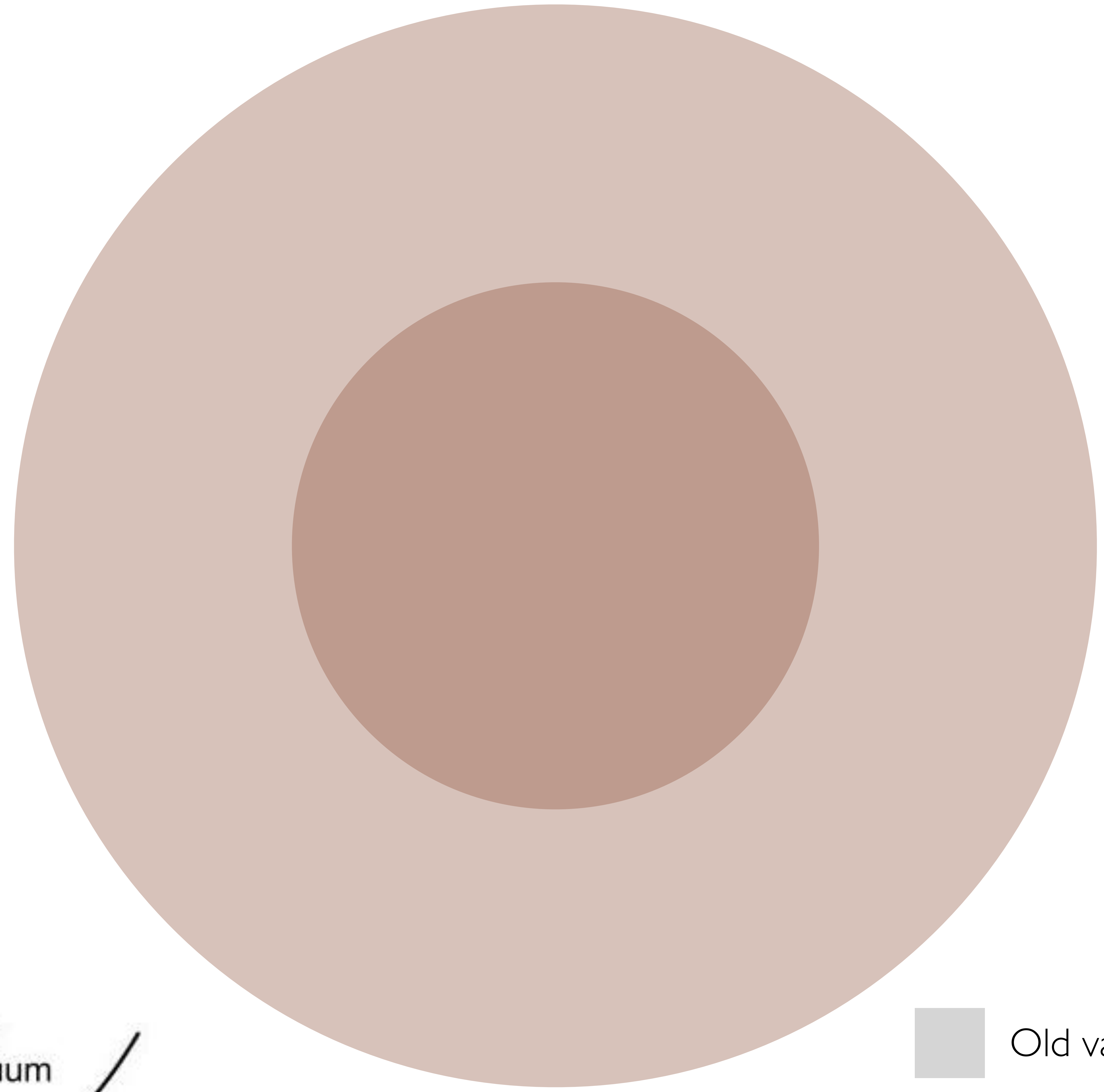
Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

PBHs from 1stOPT

YG, Volansky 2305:04942





if

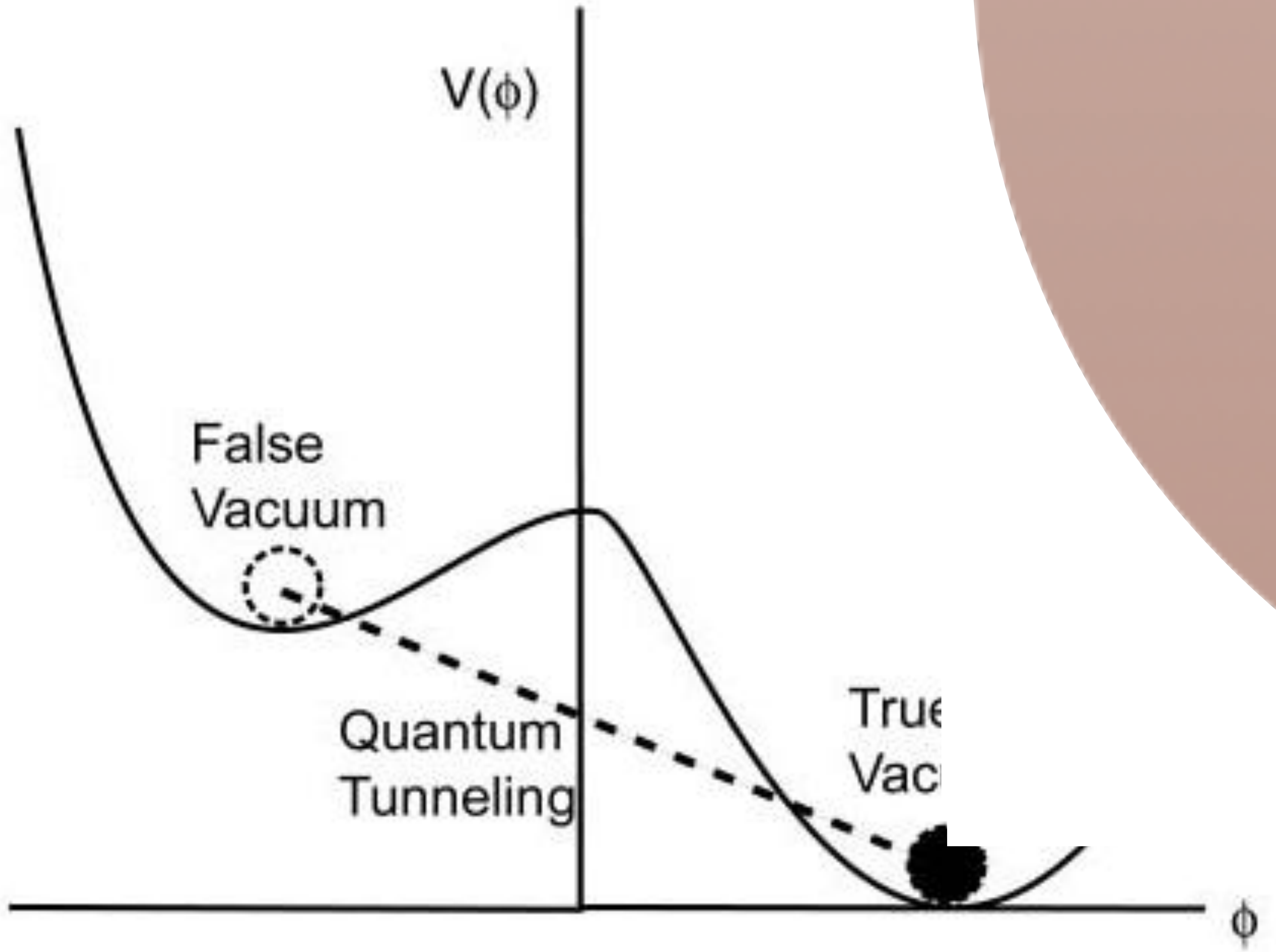
$$\delta\rho/\rho \gtrsim 0.45.$$

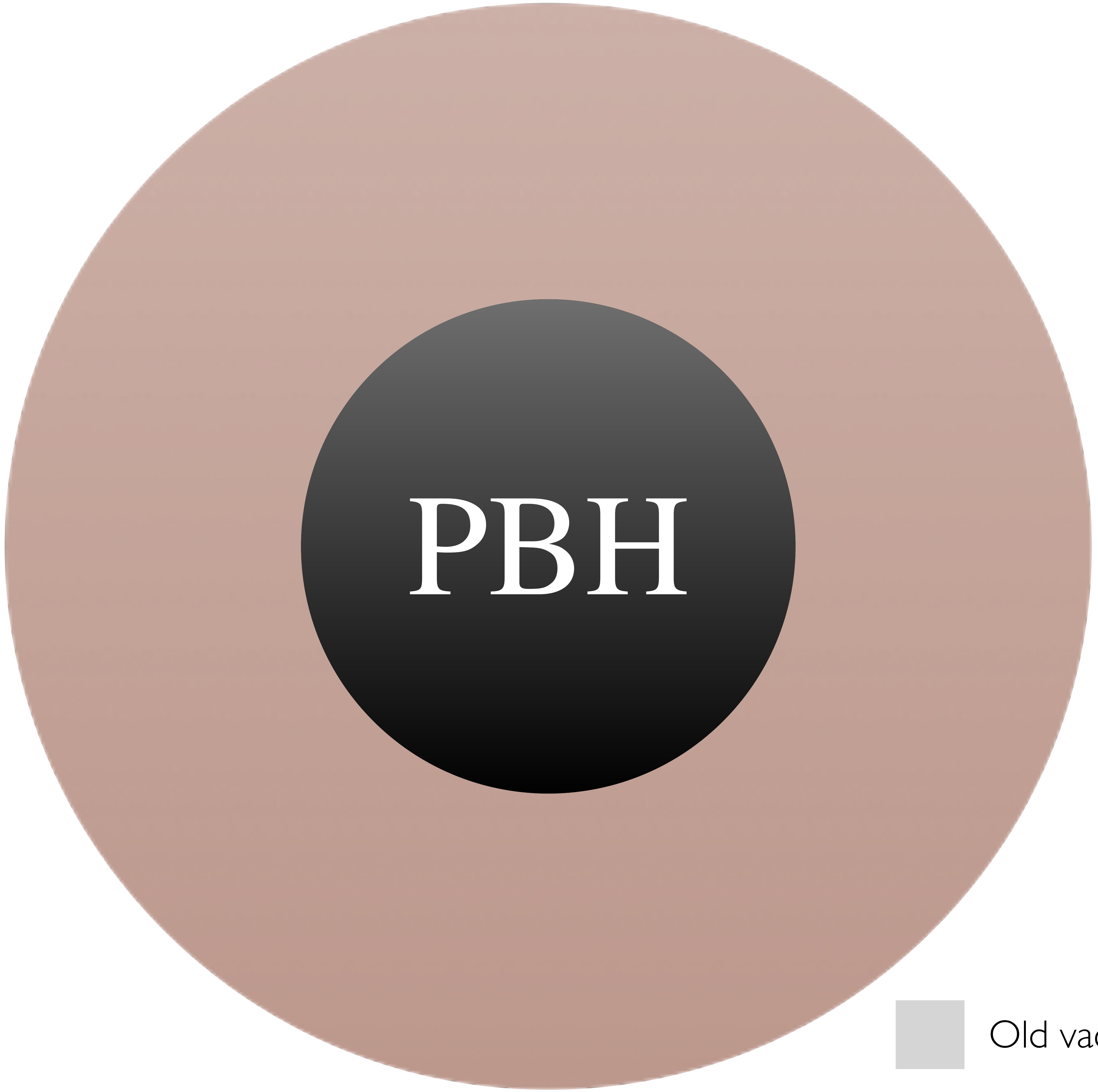
Old vacuum-dominated region (outside bubbles)

New radiation-dominated region (inside bubbles)

PBHs from 1stOPT

YG, Volansky 2305:04942





if

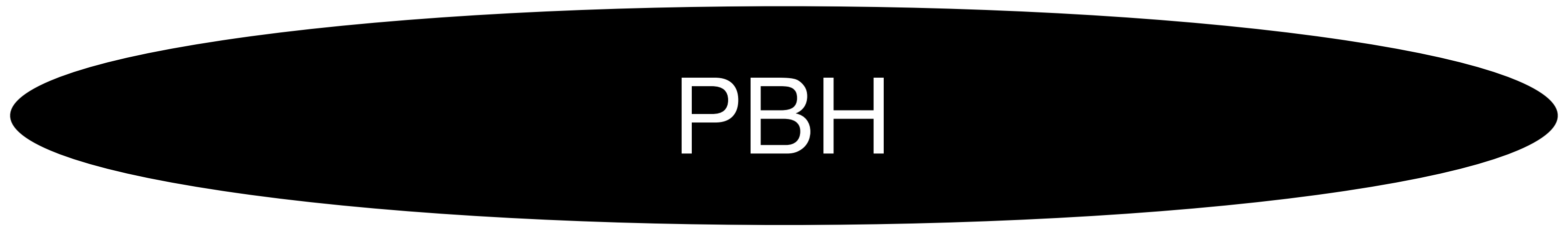
$$\delta\rho/\rho \gtrsim 0.45.$$

then

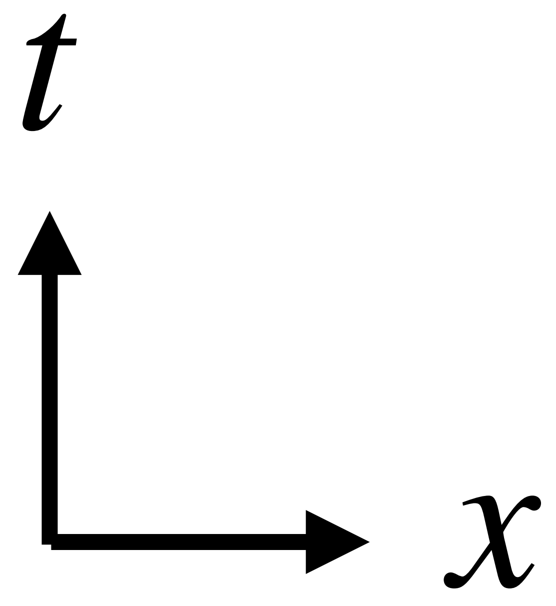
PBH

Old vacuum-dominated region (outside bubbles)

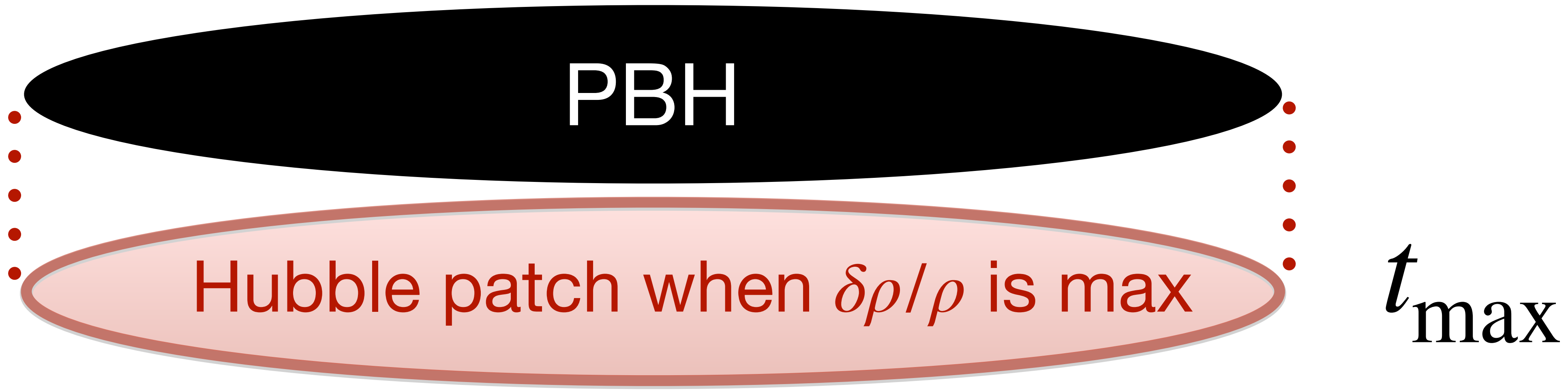
New radiation-dominated region (inside bubbles)

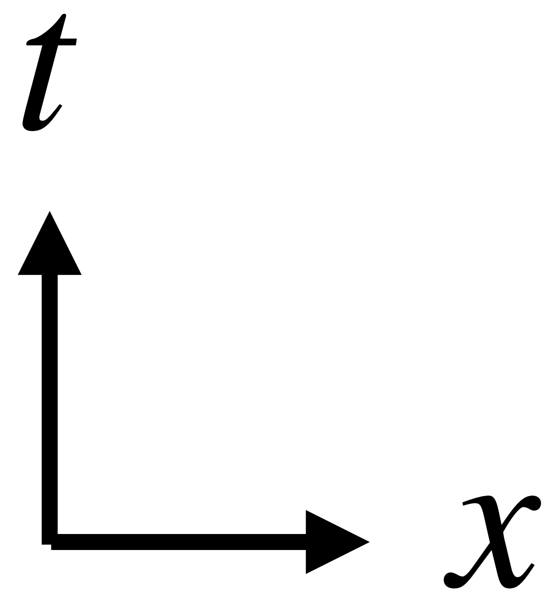


YG, Volansky 2305:04942



YG, Volansky 2305:04942





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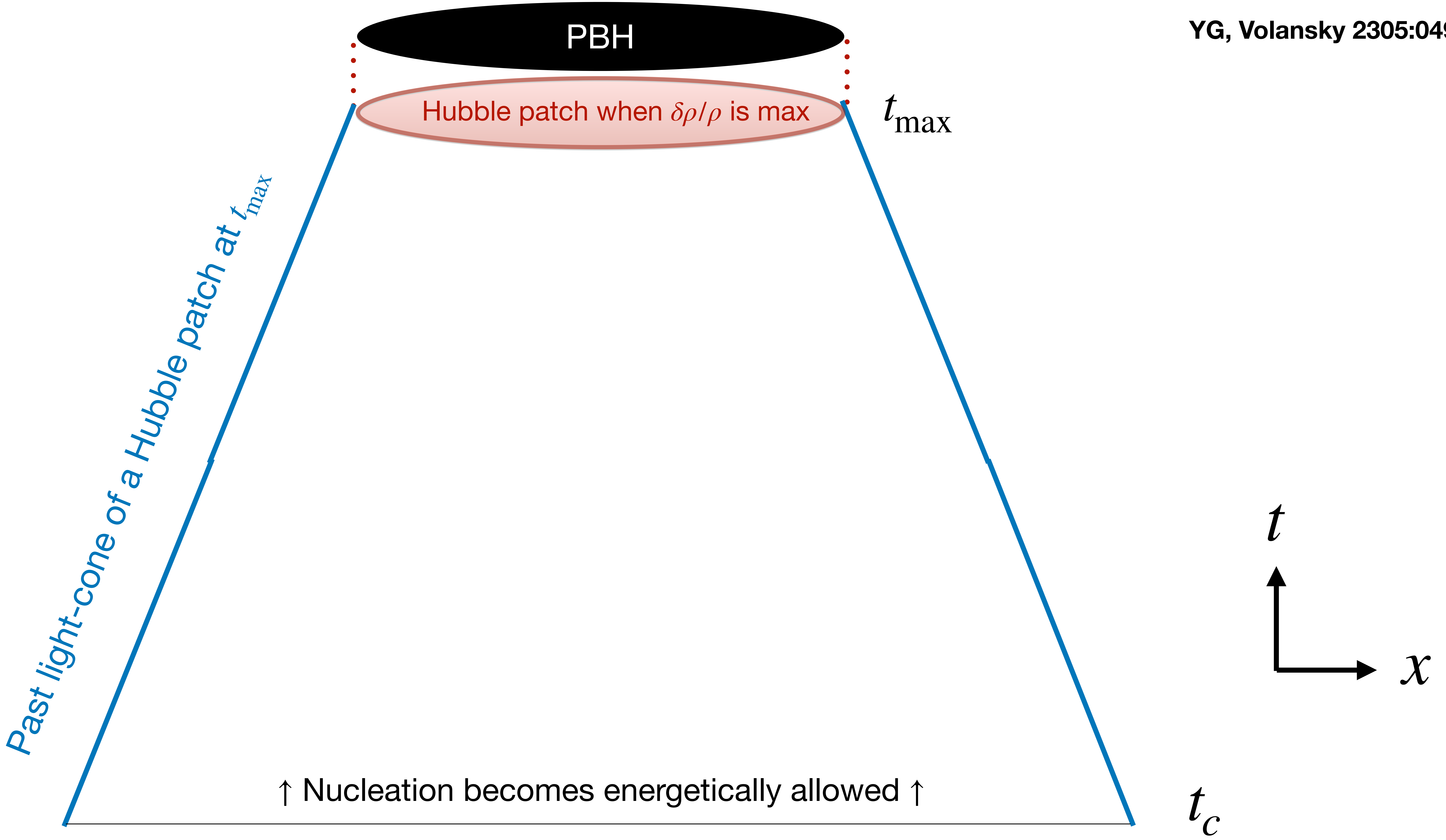
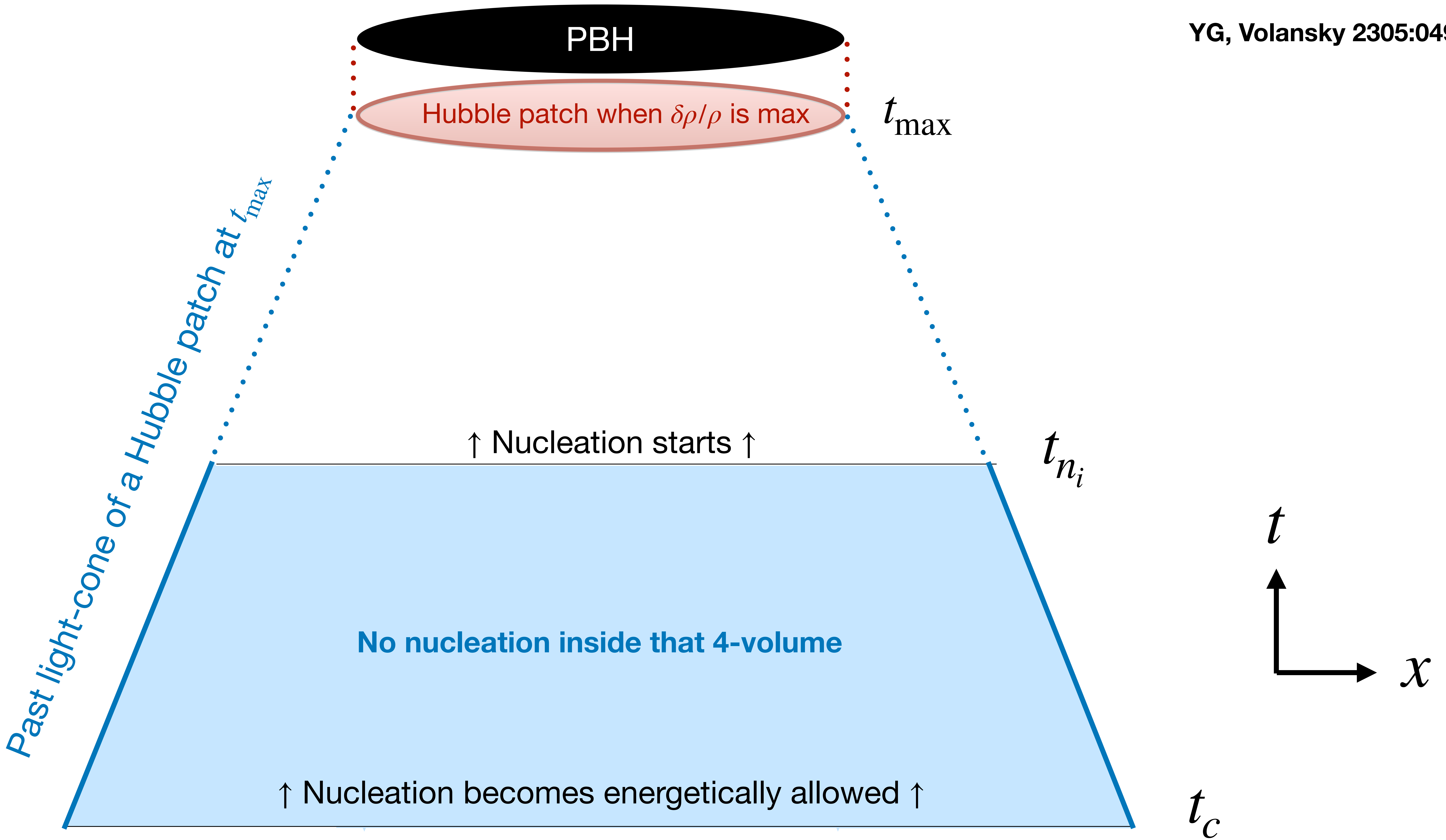
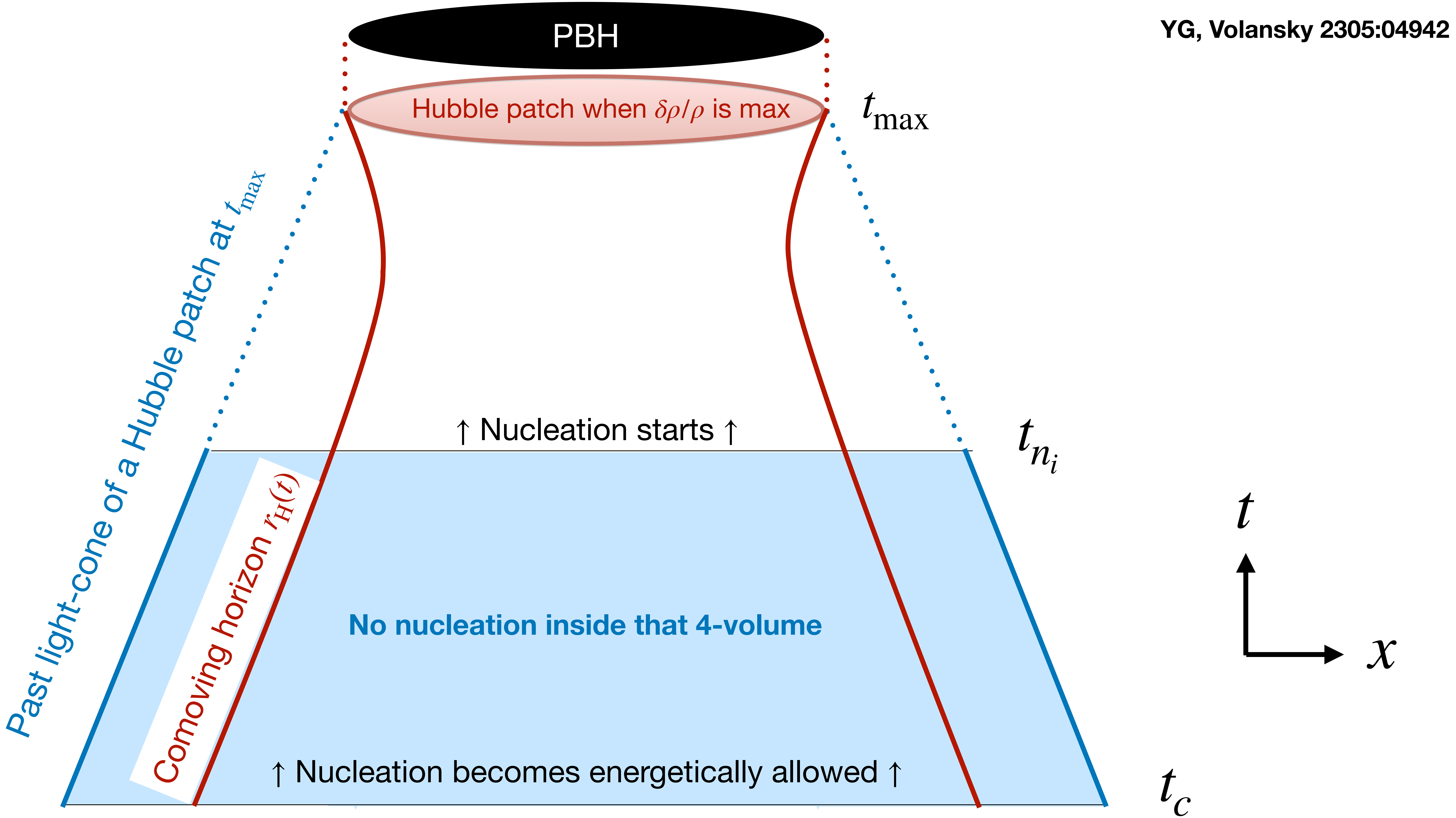
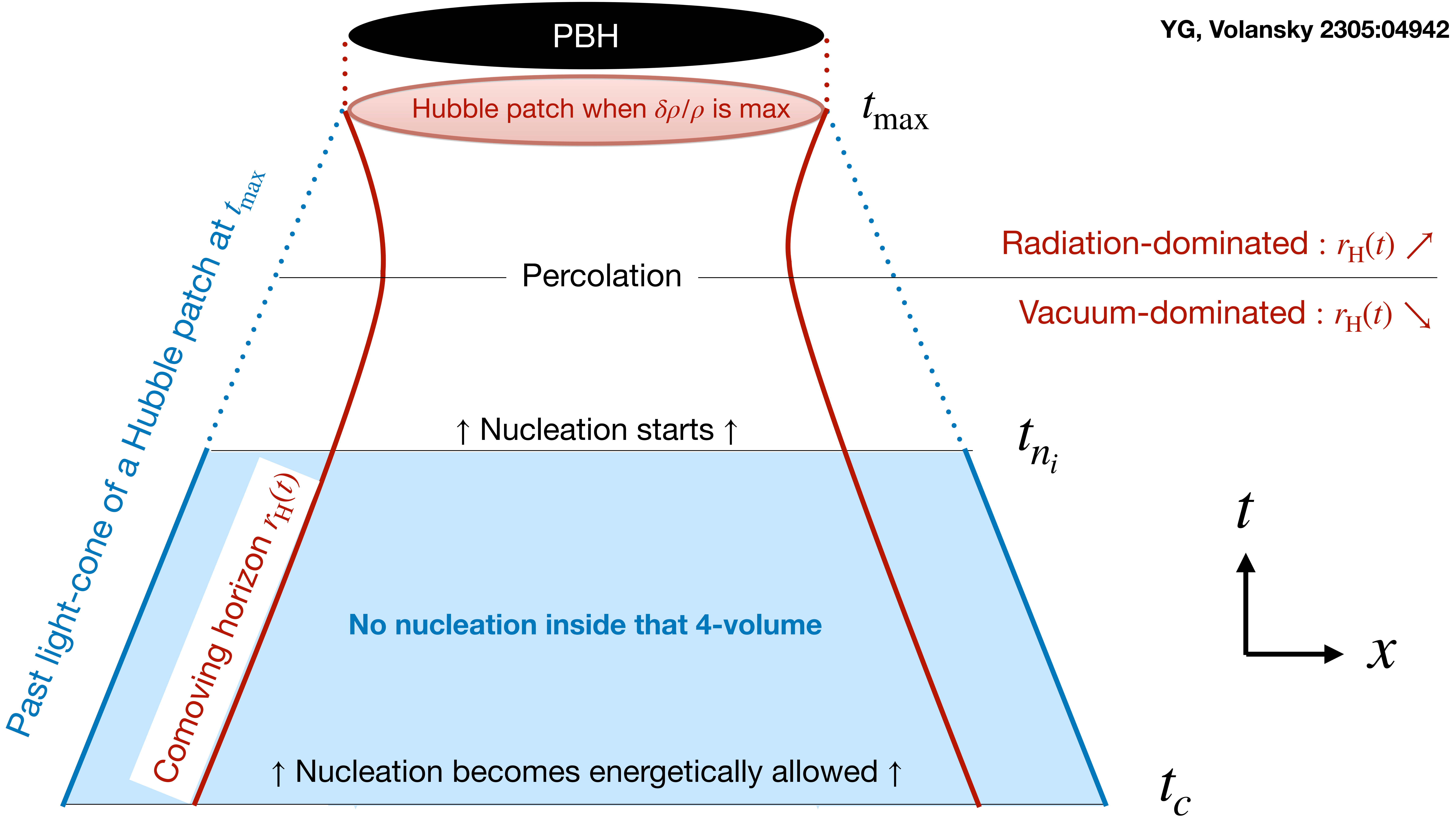




YG, Volansky 2305:04942


YG, Volansky 2305:04942
PBH
Hubble patch when $\delta\rho/\rho$ is max
$t_{\max}$
Past light-cone of a Hubble patch at $t_{\max}$
Comoving horizon $r_{\rm H}(t)$
↑ Nucleation starts ↑
t_{n_i}
No nucleation inside that 4-volume
↑ Nucleation becomes energetically allowed ↑
t_c
t
x



YG, Volansky 2305:04942
PBH
Hubble patch when $\delta\rho/\rho$ is max
$t_{\rm max}$
Past light-cone of a Hubble patch at $t_{\rm max}$
Radiation-dominated : $r_{\rm H}(t)$ ↗
Percolation
Vacuum-dominated : $r_{\rm H}(t)$ ↘
↑ Nucleation starts ↑
t_{n_i}
Comoving horizon $r_{\rm H}(t)$
No nucleation inside that 4-volume
t
x
↑ Nucleation becomes energetically allowed ↑
t_c

Collapse probability : $$\boxed{\mathscr{P}_{\rm coll} = \exp\left[-\int_{t_c}^{t_{n_i}} dt'\,\Gamma(t')a(t')^3\frac{4\pi}{3}\left(\frac{1}{a(t_{\max})H(t_{\max})}+\int_{t'}^{t_{\max}}\frac{d\tilde{t}}{a(\tilde{t})}\right)^3\right]}$$

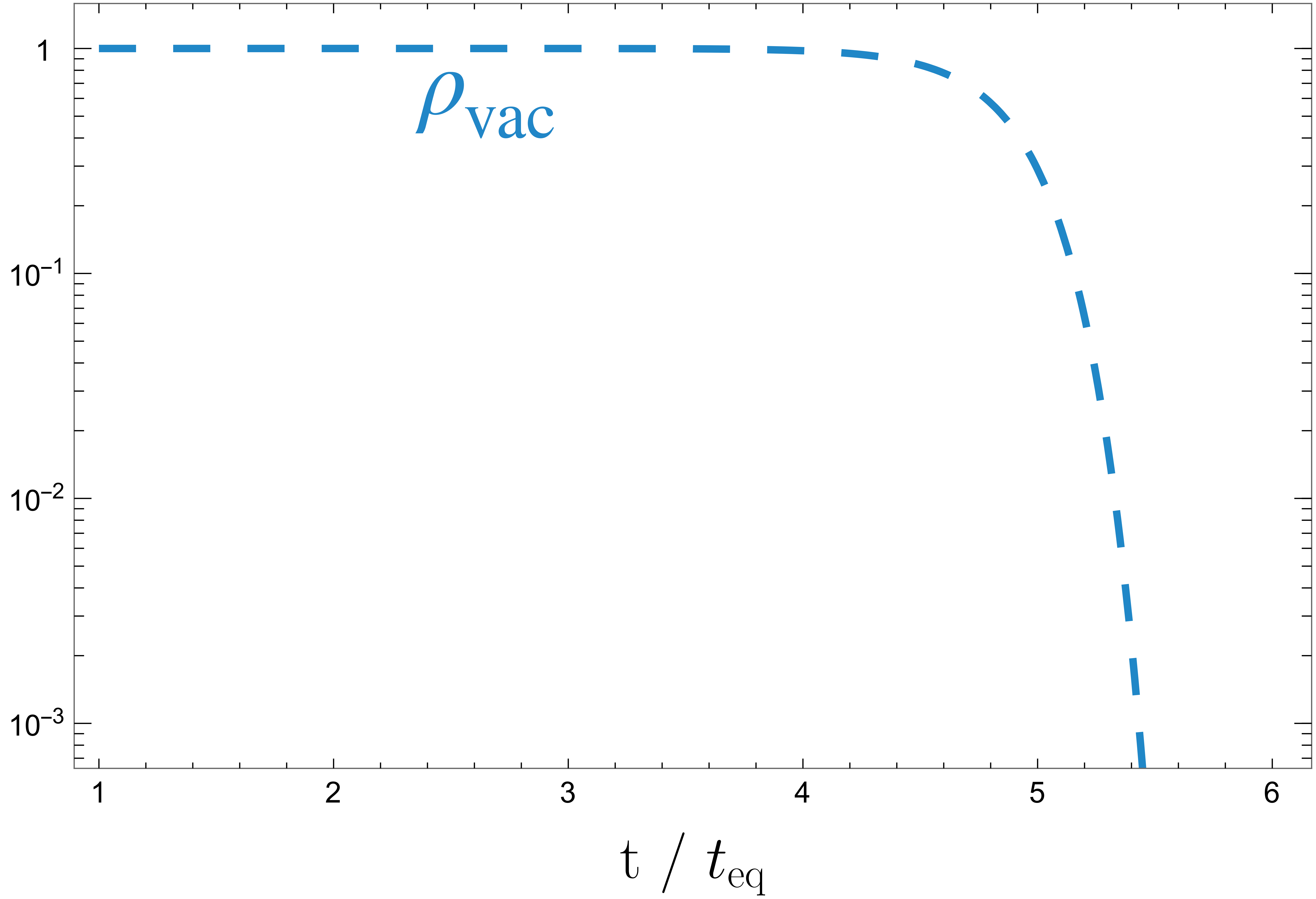
Friedmann equation : $$\frac{\dot{a}(t)}{a(t)} = \sqrt{\frac{\rho_{\rm V}(t;t_{n_i})+\rho_{\rm R}(t;t_{n_i})}{3M_{\rm pl}^2}}$$

Vacuum energy : $$\rho_V(t;t_{n_i}) = \Delta V \exp\left[-\int_{t_{n_i}}^{t} dt'\,\Gamma(t')a(t')^3\frac{4}{3}\pi\left(\int_{t'}^{t}\frac{d\tilde{t}}{a(\tilde{t})}\right)^3\right]$$

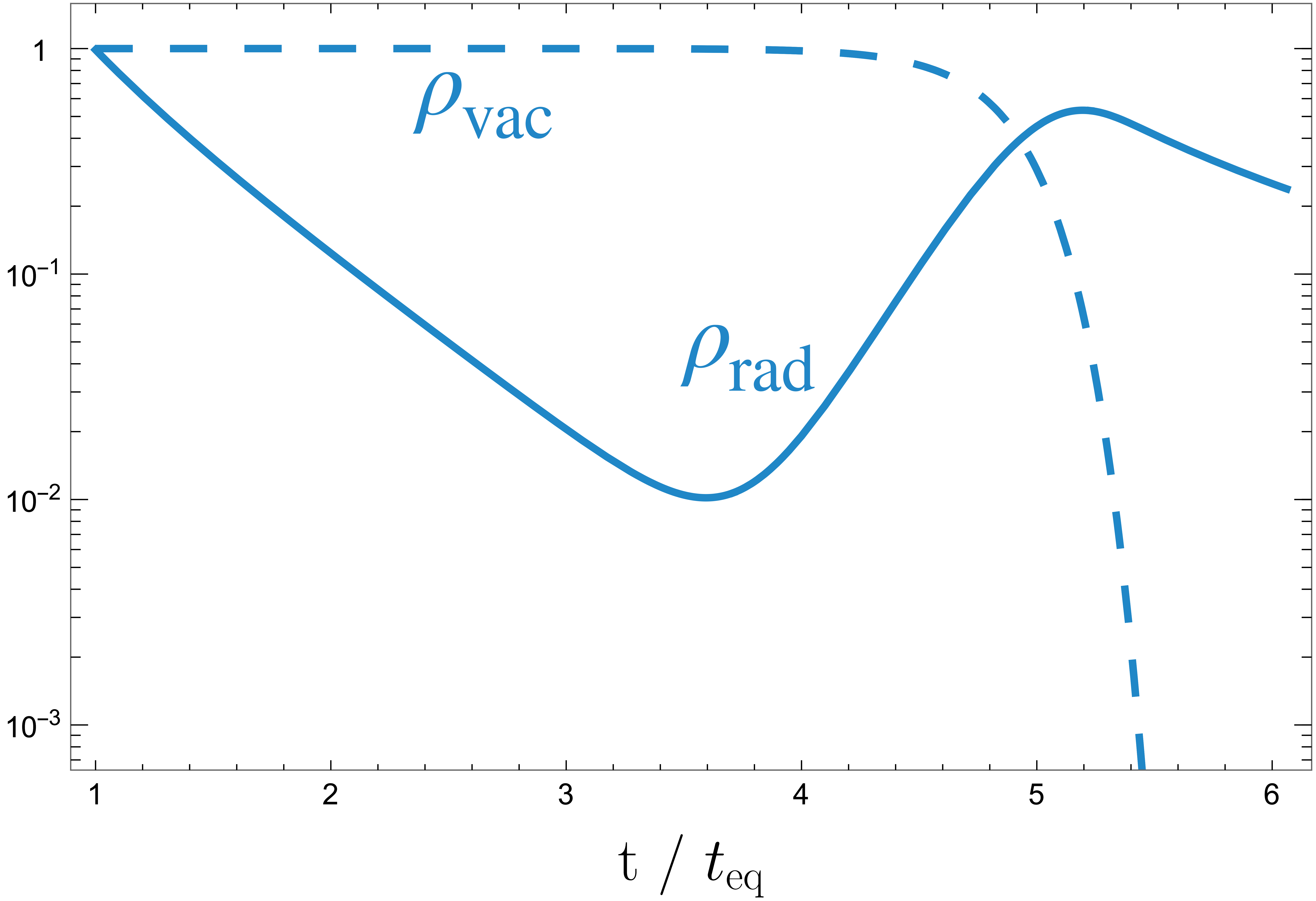
Radiation energy : $$\dot{\rho}_{\rm R}(t;t_{n_i}) + 4H\rho_{\rm R}(t;t_{n_i}) = -\,\dot{\rho}_V(t;t_{n_i})$$

PBH formation threshold : $$\frac{\rho_{\rm R}(t_{\max};t_{n_i})-\rho_{\rm R}(t_{\max};t_c)}{\rho_{\rm R}(t_{\max};t_c)} \simeq 0.45\,,$$

YG, Volansky 2305:04942



YG, Volansky 2305:04942



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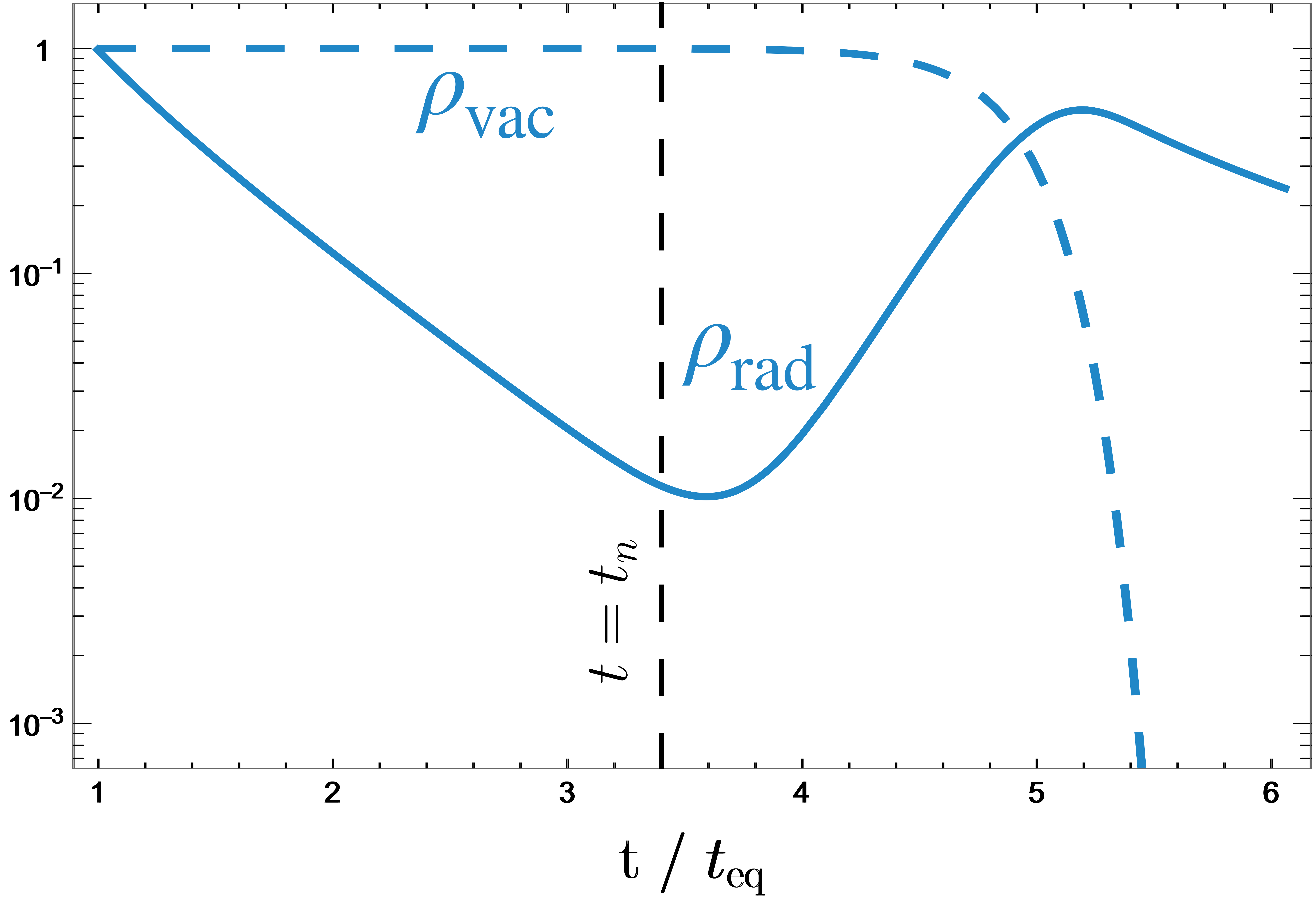

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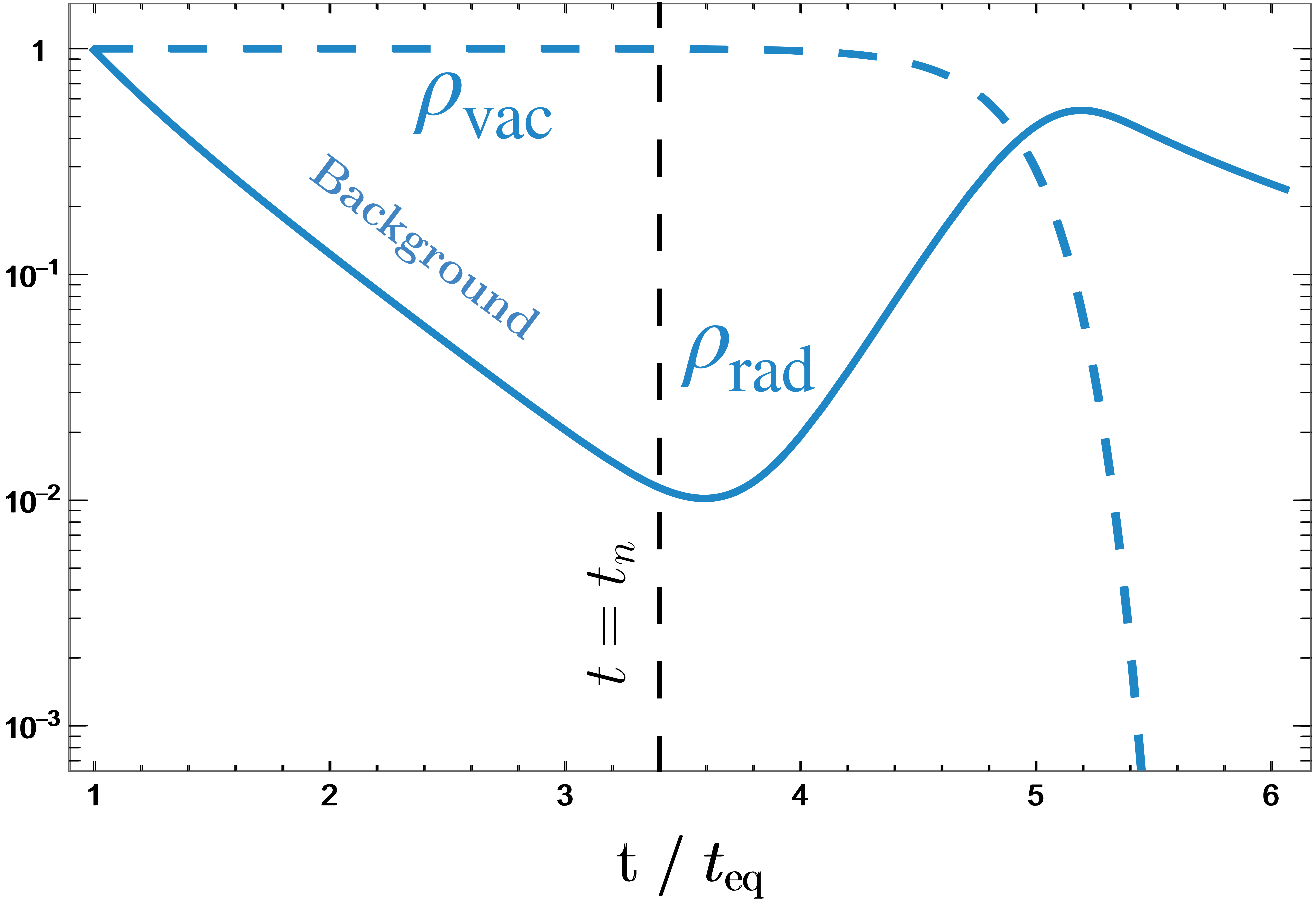

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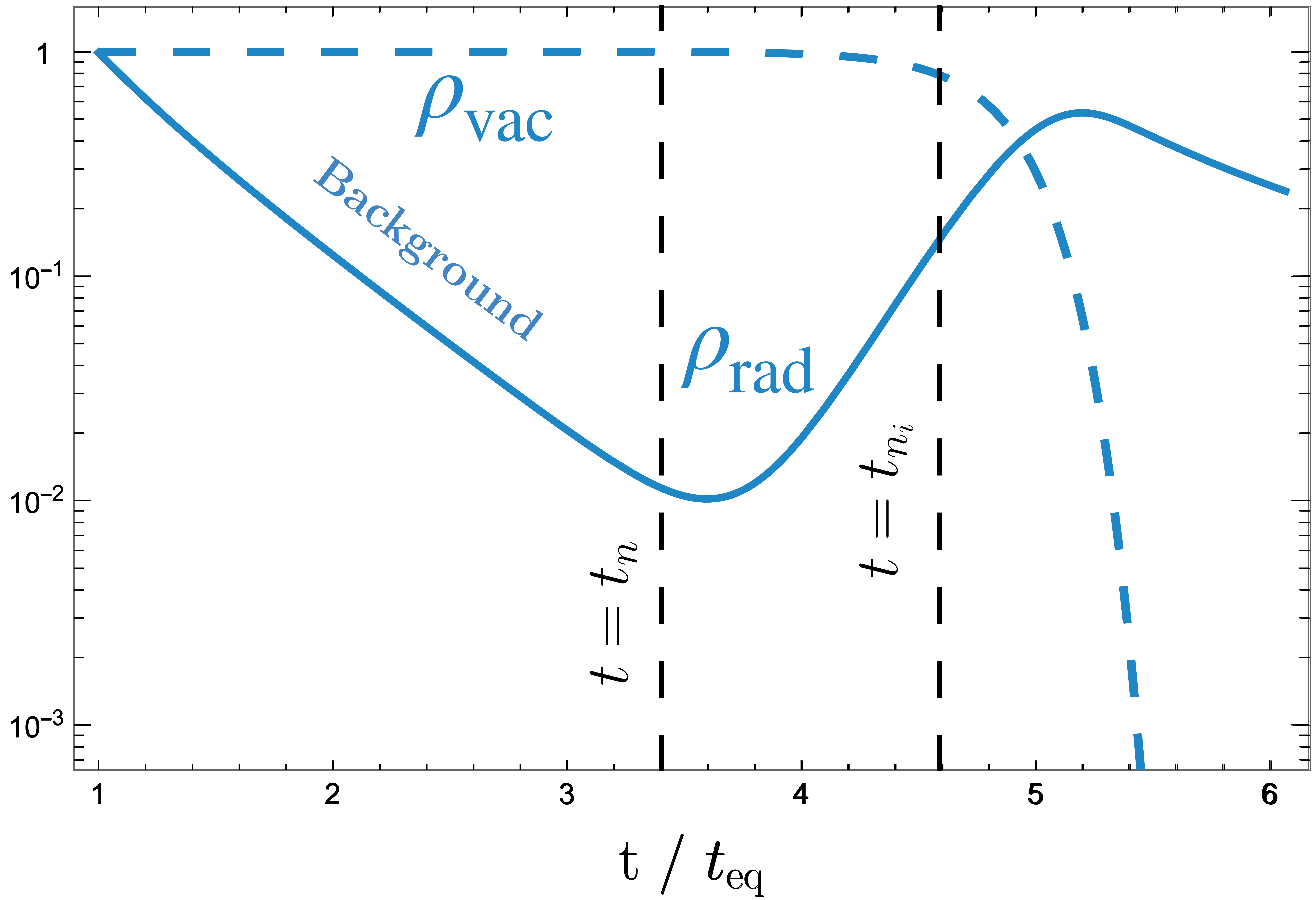

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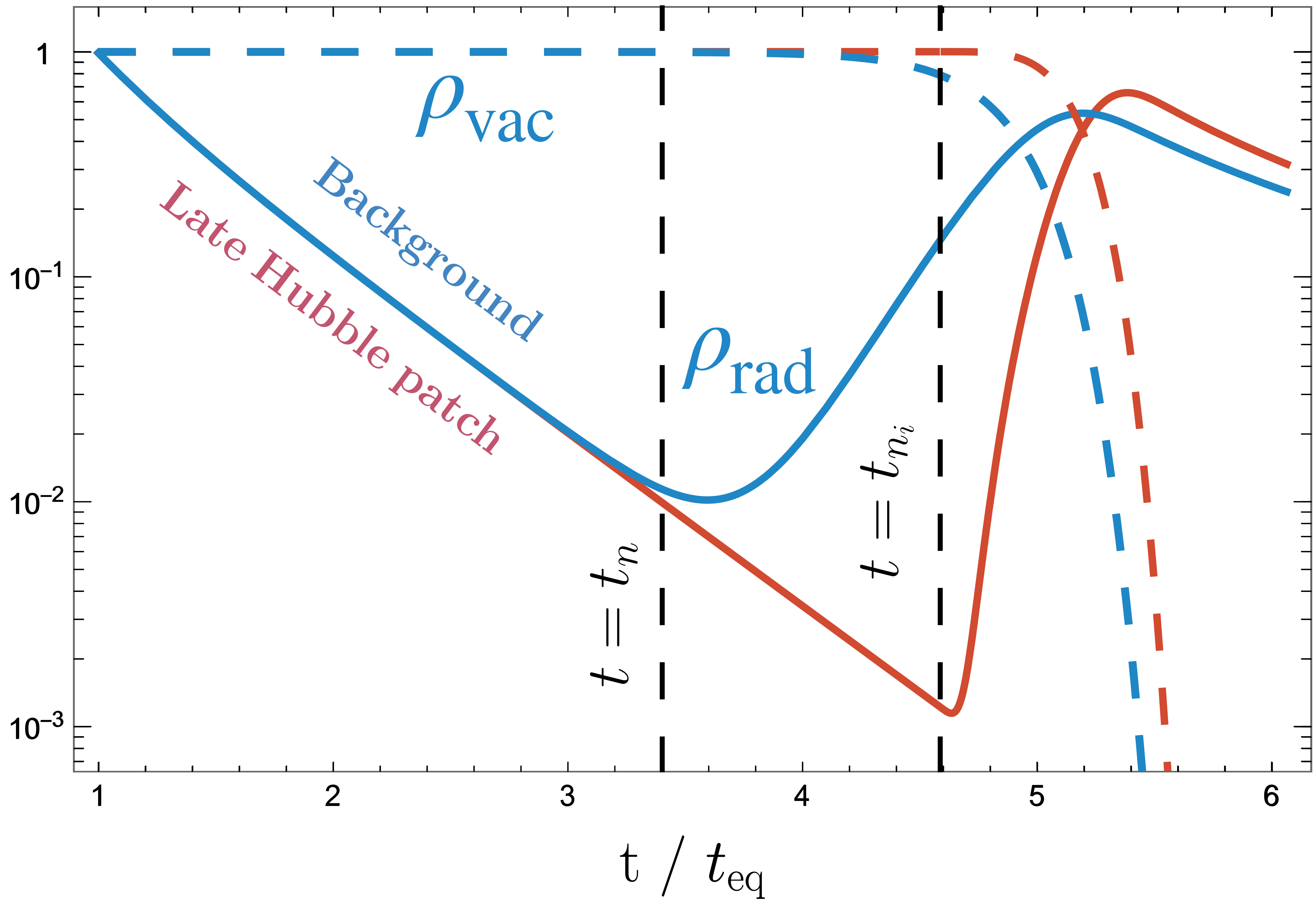

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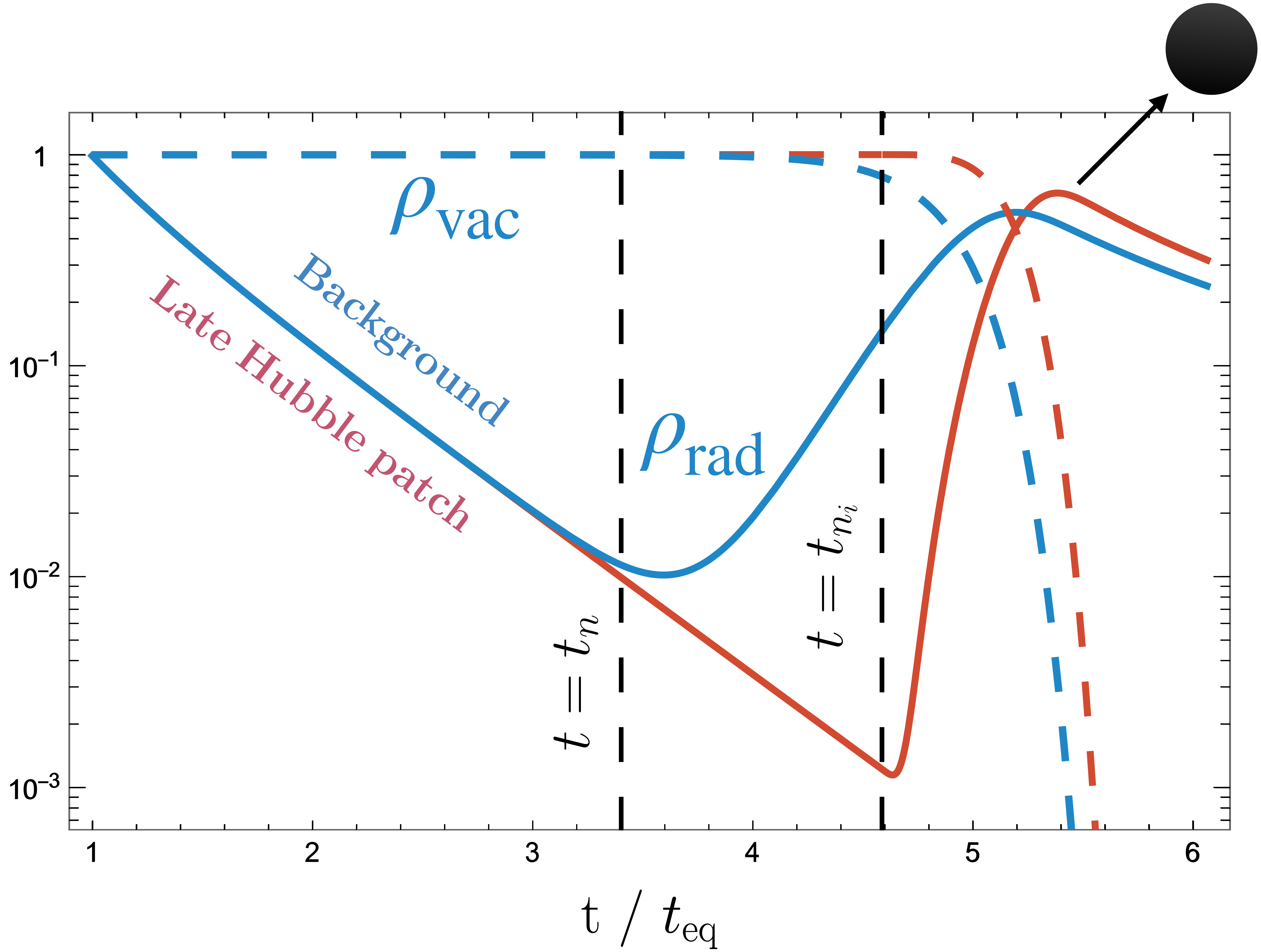


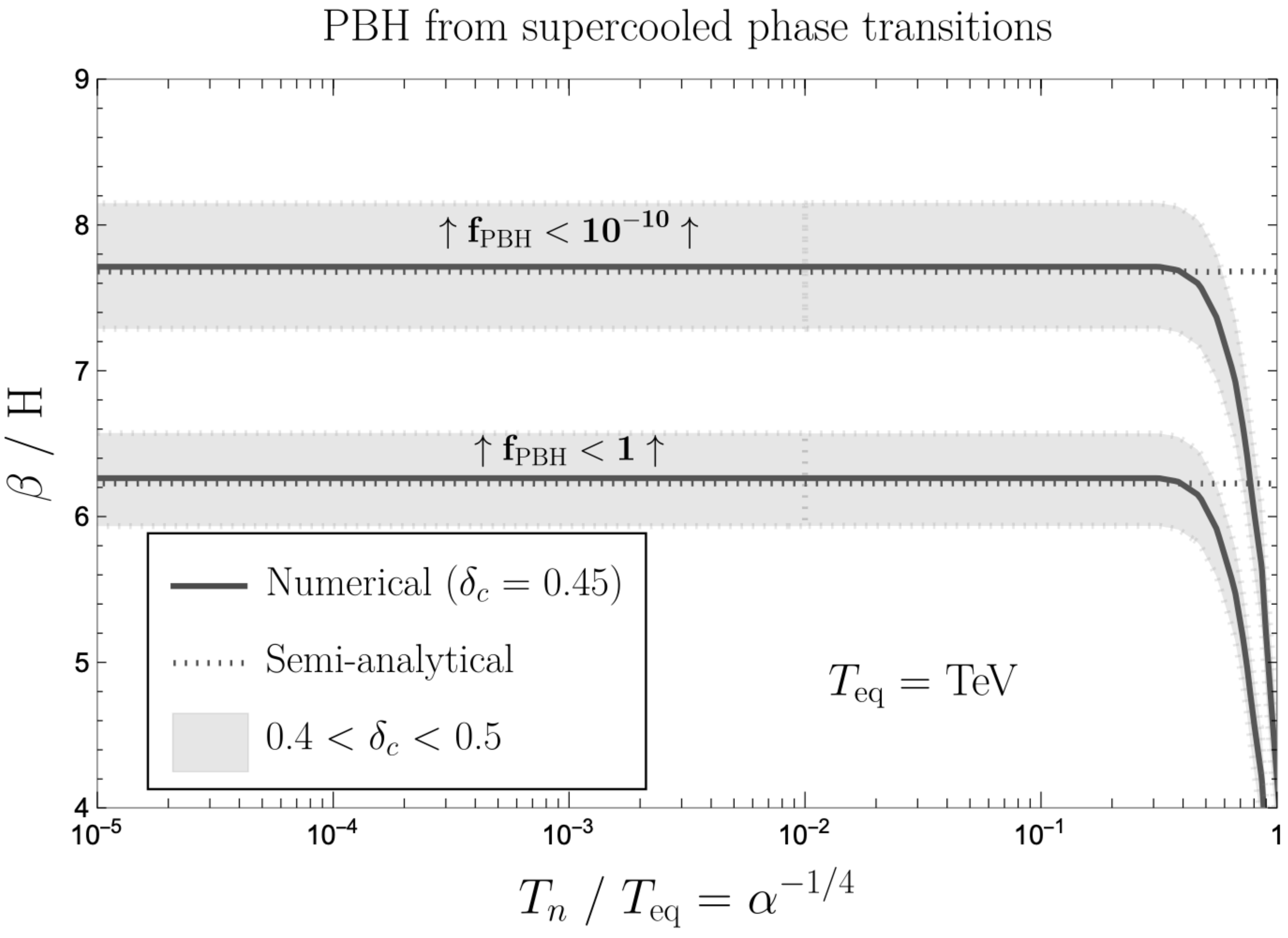
Tunneling rate :

$$\Gamma = \Gamma_0 e^{\beta t}$$

$$\beta \equiv \frac{d \log \Gamma}{dt}$$

$\beta^{-1} \simeq$ PT duration

$\simeq$ bubble size



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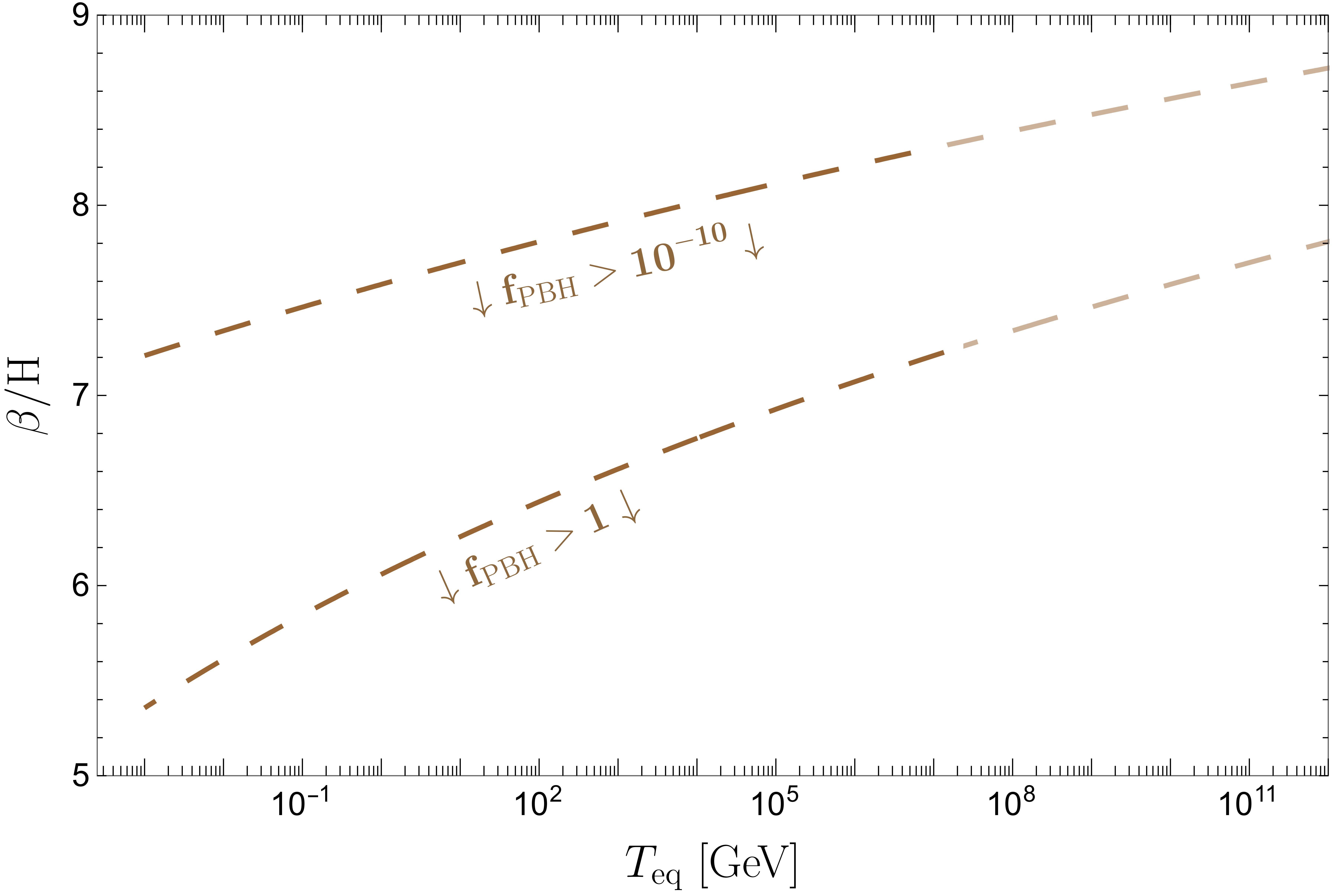

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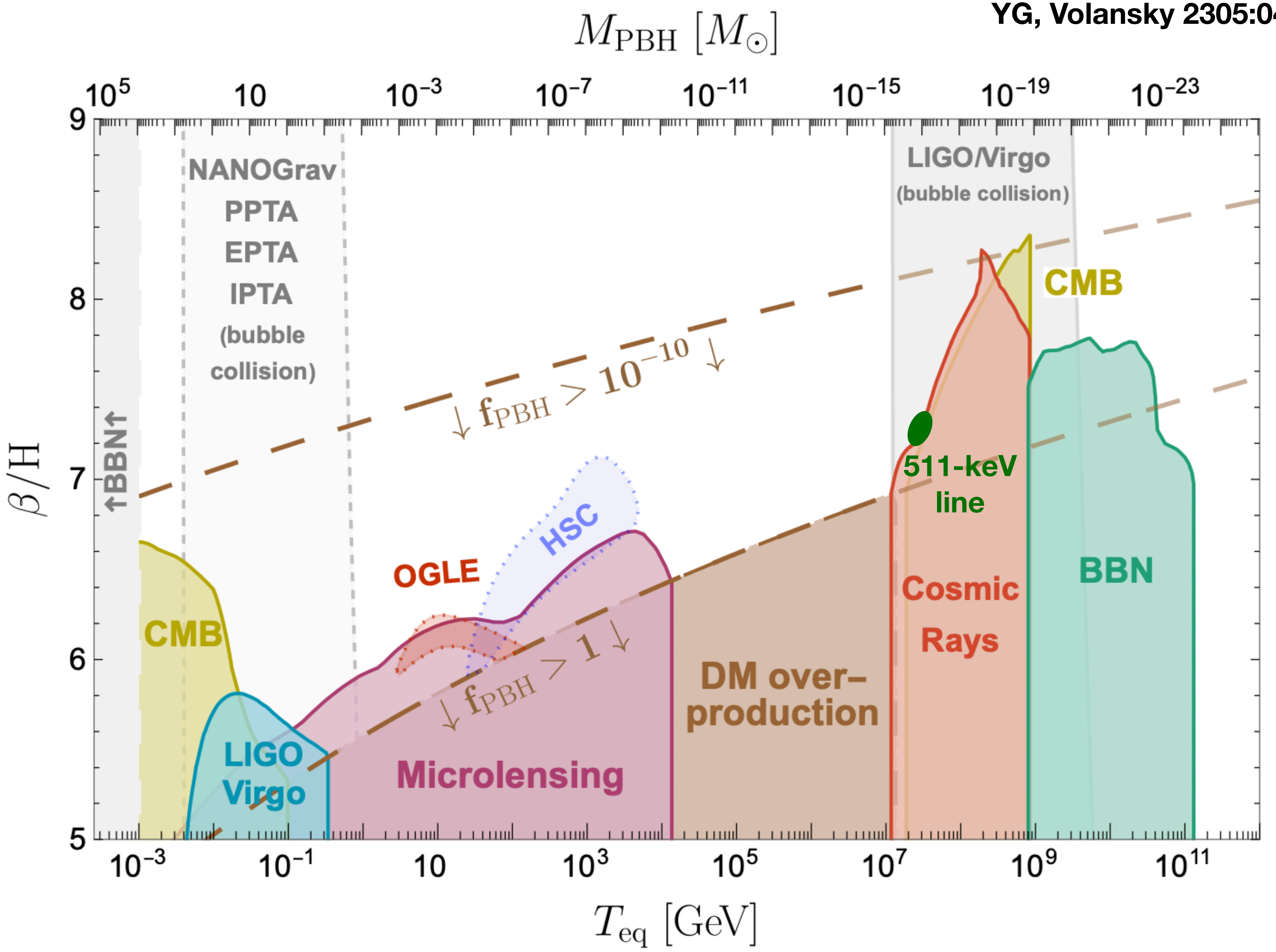

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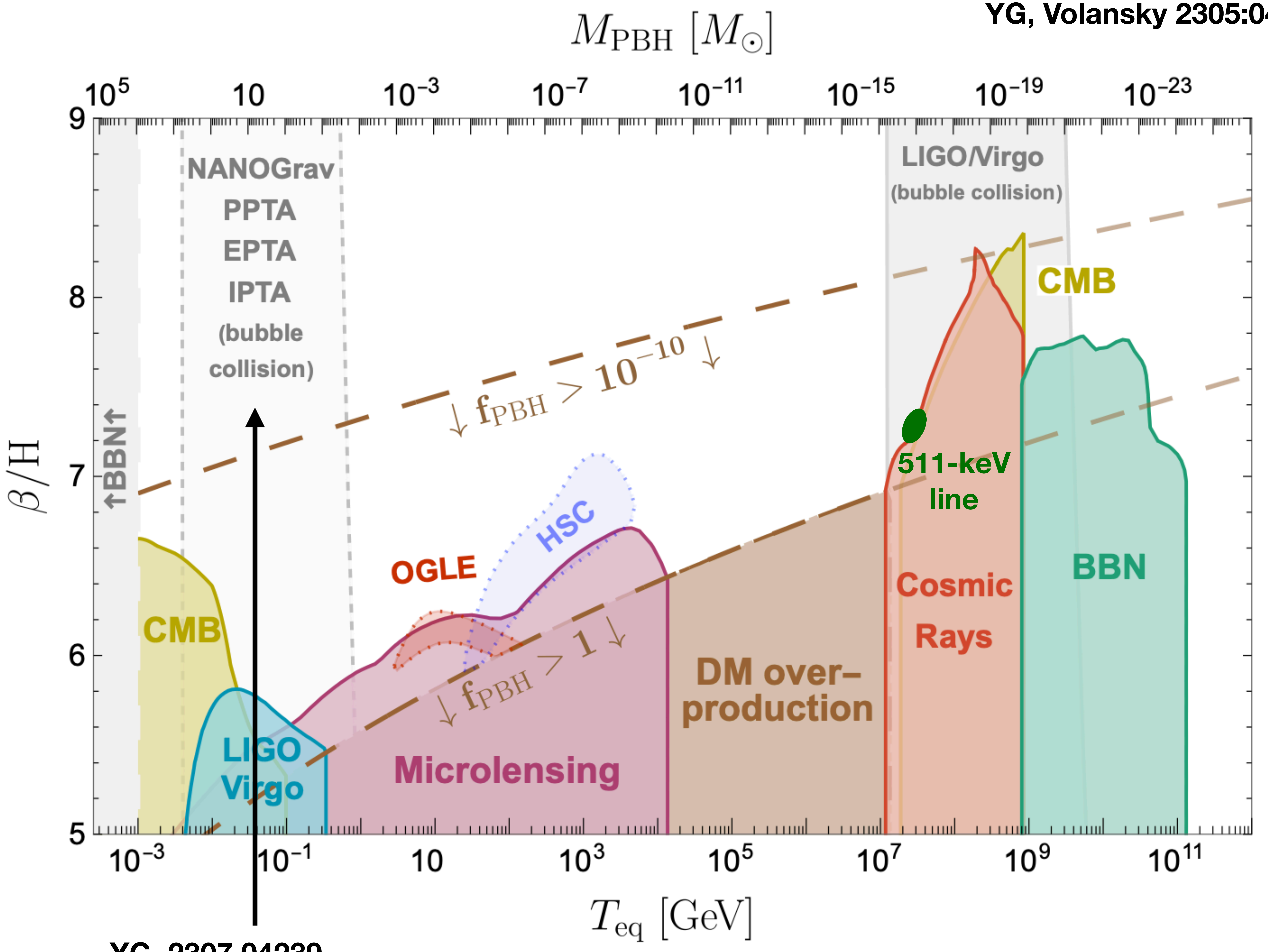

YG, 2307.04239,
Phys.Rev.Lett. 131 (2023) 17

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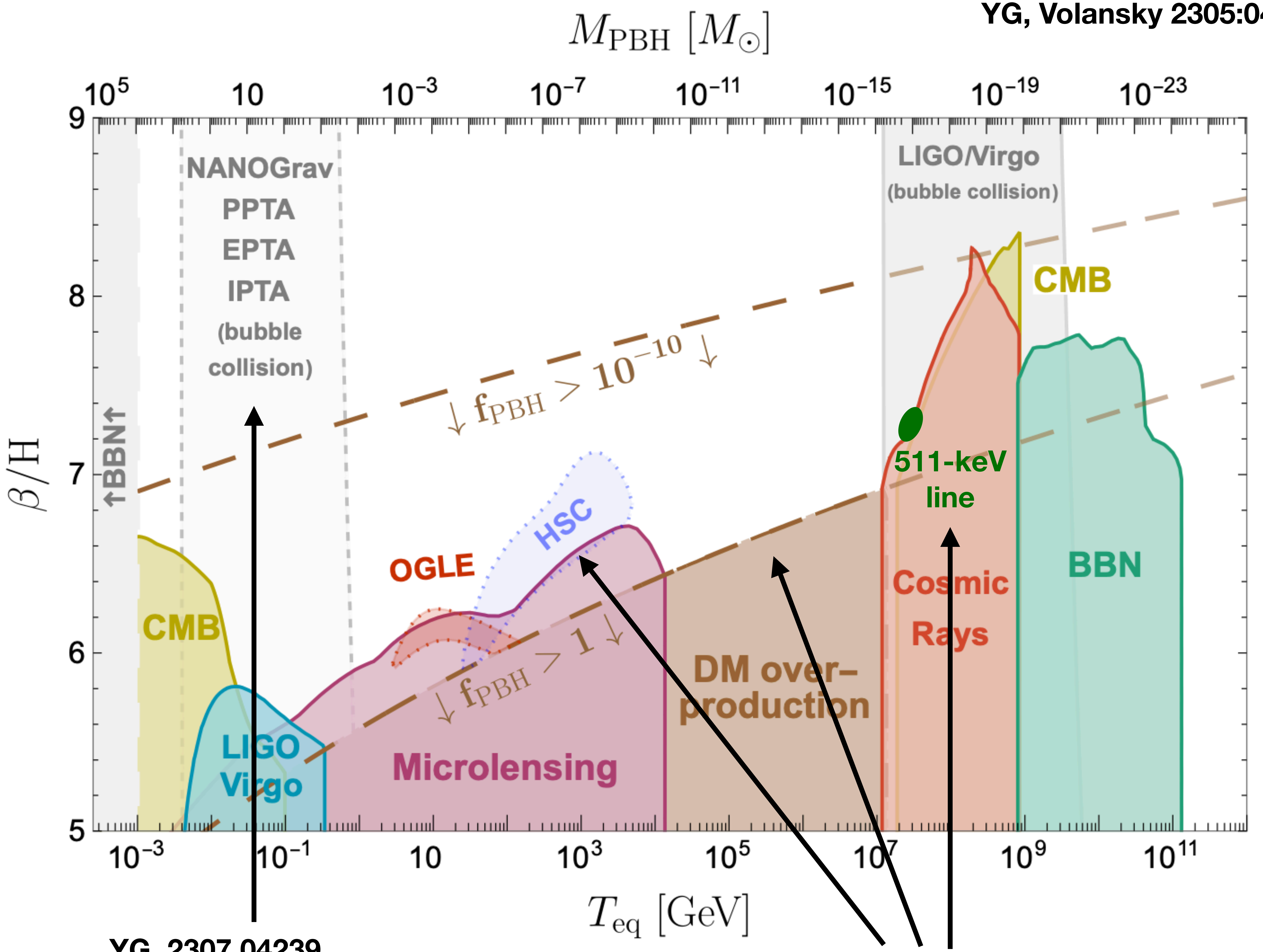
YG, Volansky 2305:04942



YG, 2307.04239, Phys.Rev.Lett. 131 (2023) 17

YG, 2311.13640

PBH from conformal Higgs

YG, 2311.13640

PBH from conformal Higgs

YG, 2311.13640

$$V_{\rm tree}(|\Phi|,|H|) = \lambda_h |H|^4 + \lambda_\phi |\Phi|^4 - \lambda_{h\phi} |\Phi|^2 |H|^2$$

PBH from conformal Higgs

YG, 2311.13640

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$$V_{T=0}(\phi) = \beta_\lambda \frac{\phi^4}{4}\left[\log\left(\frac{\phi}{v_\phi}\right) - \frac{1}{4}\right], \quad \beta_\lambda \simeq 6\alpha_{\rm D}^2 .$$

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PT completion rate:

$$\beta/H \simeq 100 g_{\rm D}^3 - 4$$

PBH from conformal Higgs

YG, 2311.13640

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PT completion rate:

$$\beta/H \simeq 100 g_{\rm D}^3 - 4$$

PT supercooling amount:

$$\log(T_{\rm eq}/T_n) \simeq g_{\rm D}^{-3}$$

PBH from conformal Higgs

YG, 2311.13640

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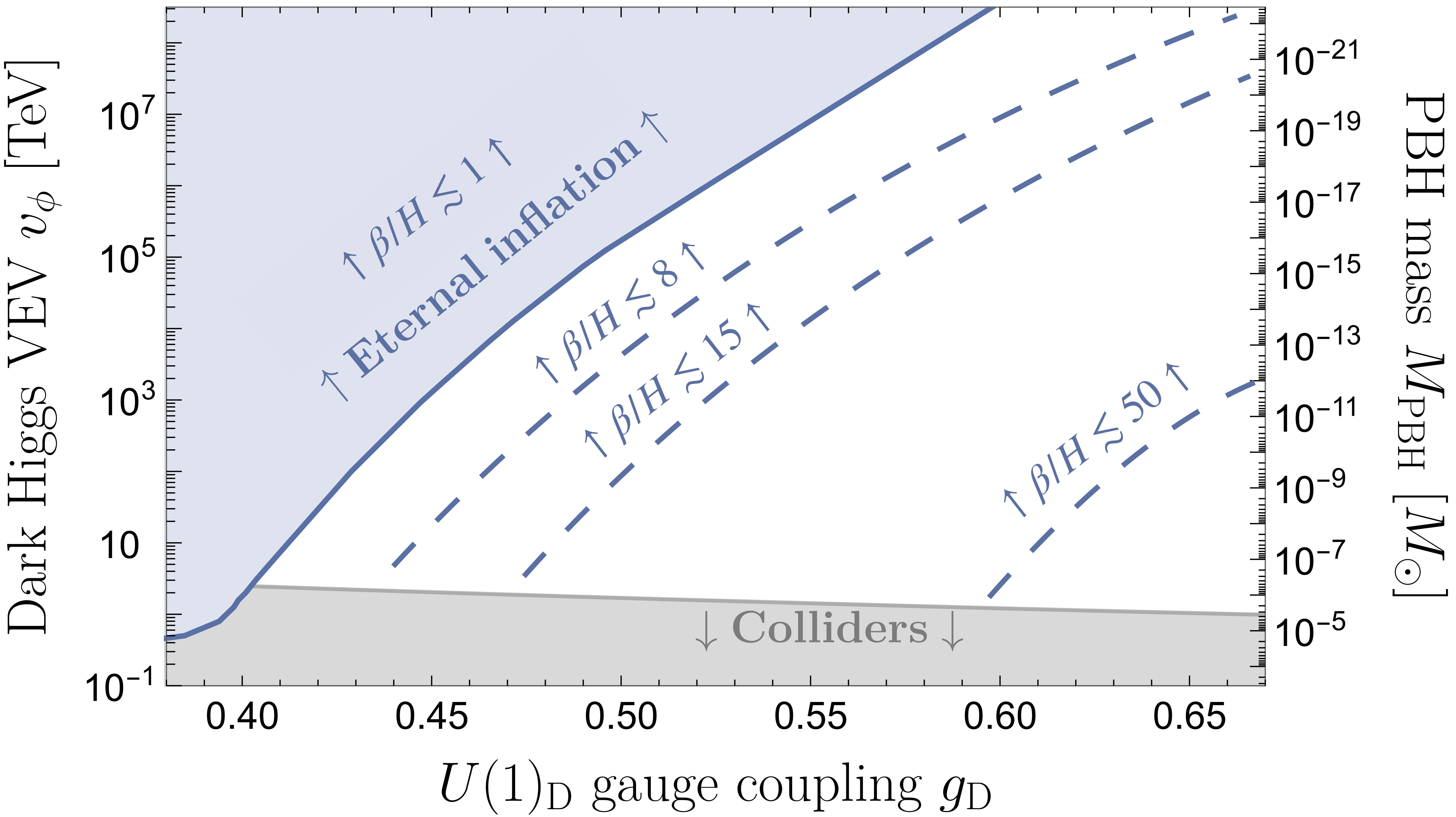
PT completion rate:

$$\beta/H \simeq 100 g_D^3 - 4$$

PT supercooling amount:

$$\log(T_{eq}/T_n) \simeq g_D^{-3}$$



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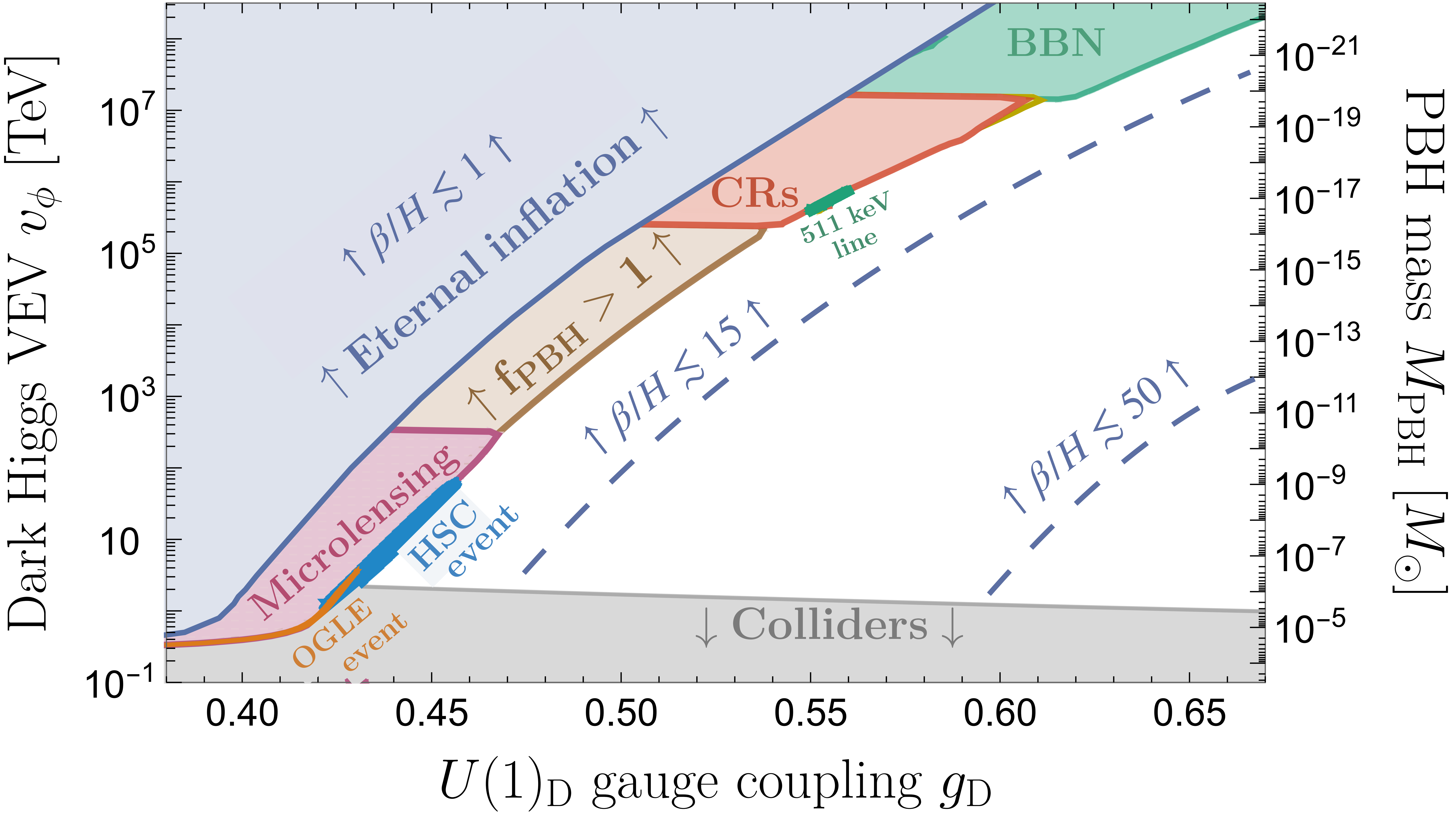

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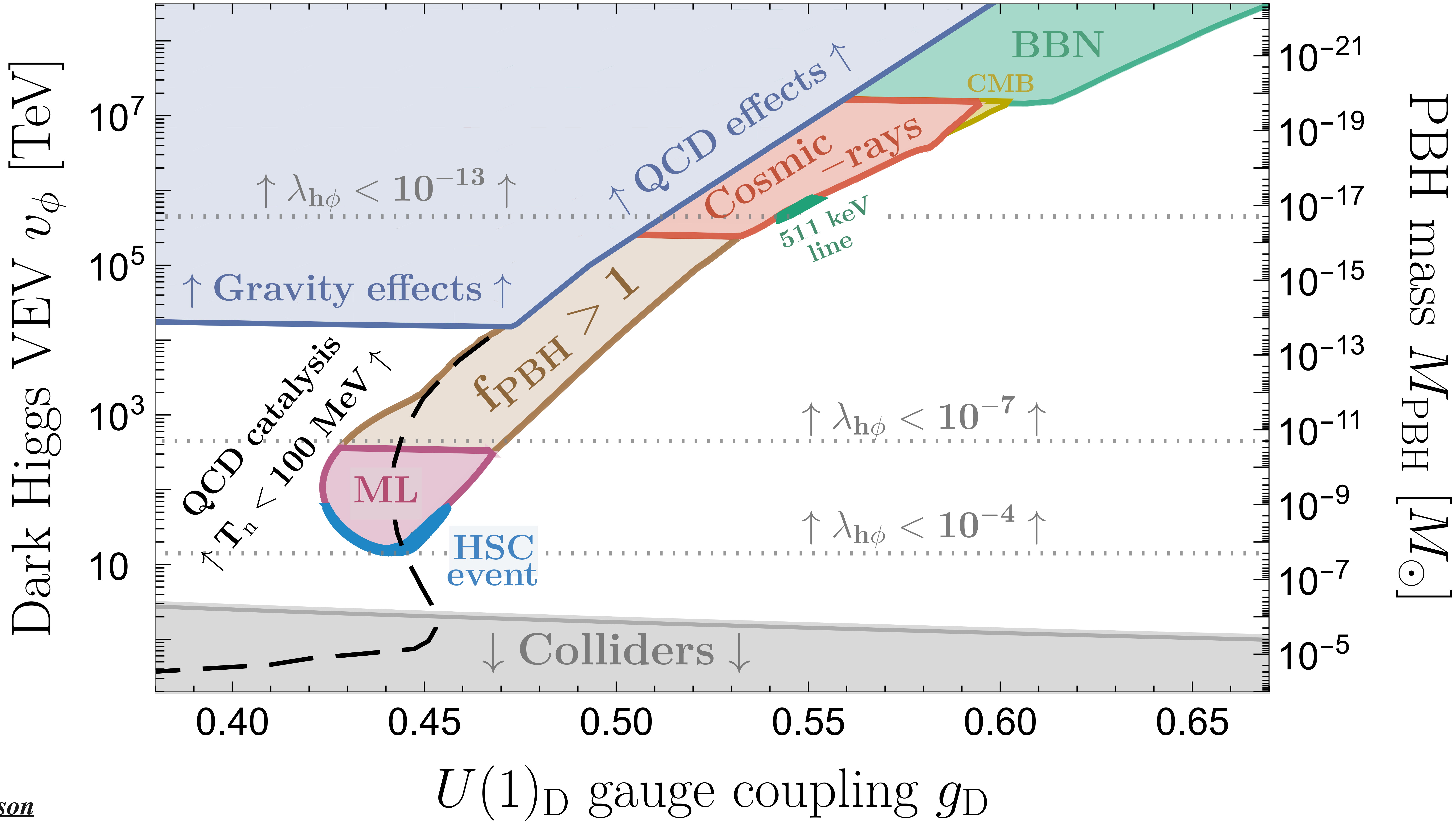

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Witten, Nucl. Phys. B 177, 477 (1981)

Cosmological Consequences of a Light Higgs Boson

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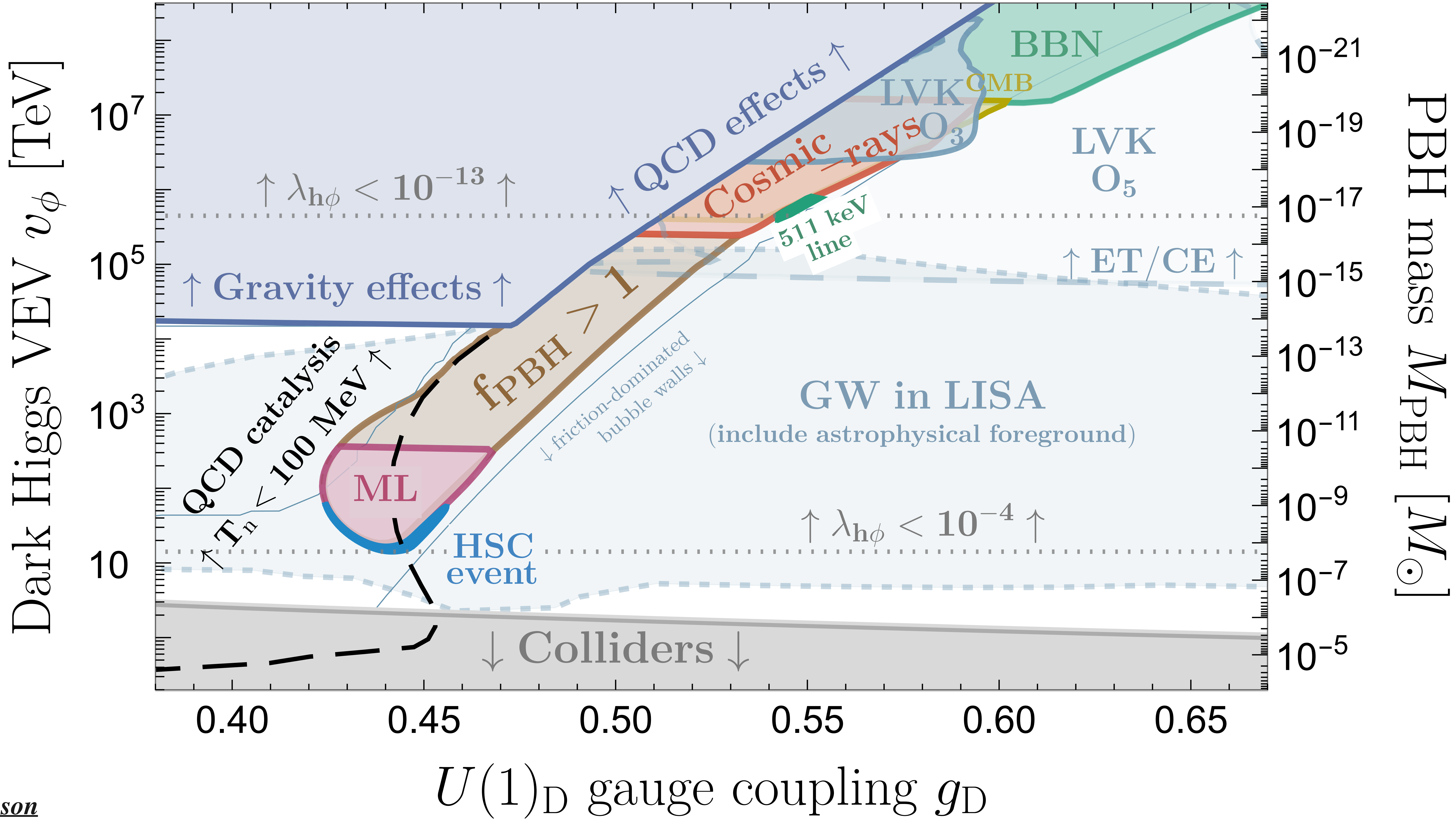

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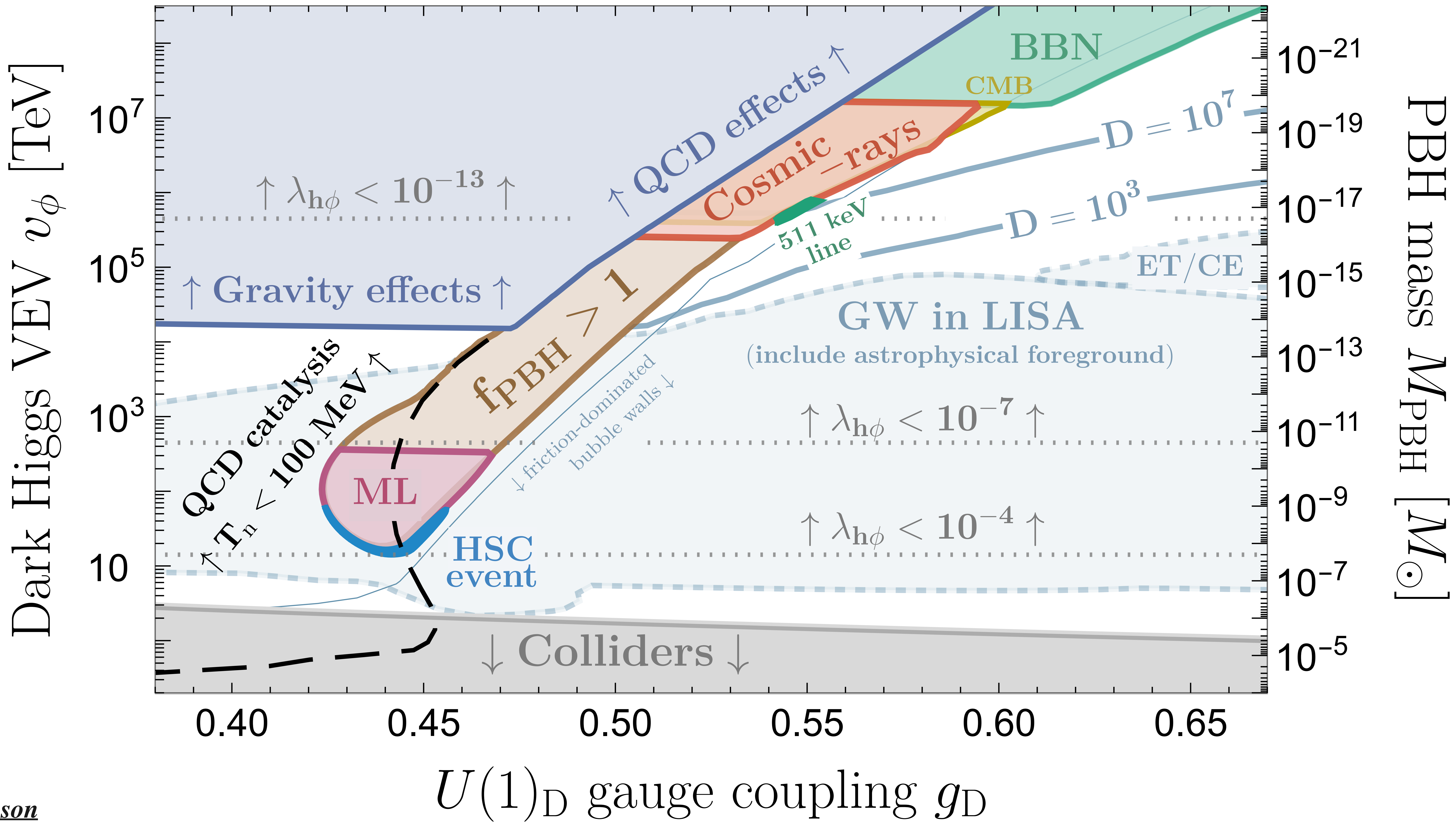
$$\Omega_{\rm GW} \to D^{-4/3}\Omega_{\rm GW}$$

$$D \simeq \frac{T_{\rm dom}}{\sqrt{M_{\rm pl}\Gamma_\phi}} \propto \lambda_{h\phi}$$



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Cosmological Consequences of a Light Higgs Boson

Summary

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YG, Volansky 2305:04942

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YG, 2307.04239, Phys.Rev.Lett. 131 (2023) 17

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YG, 2307.04239, Phys.Rev.Lett. 131 (2023) 17

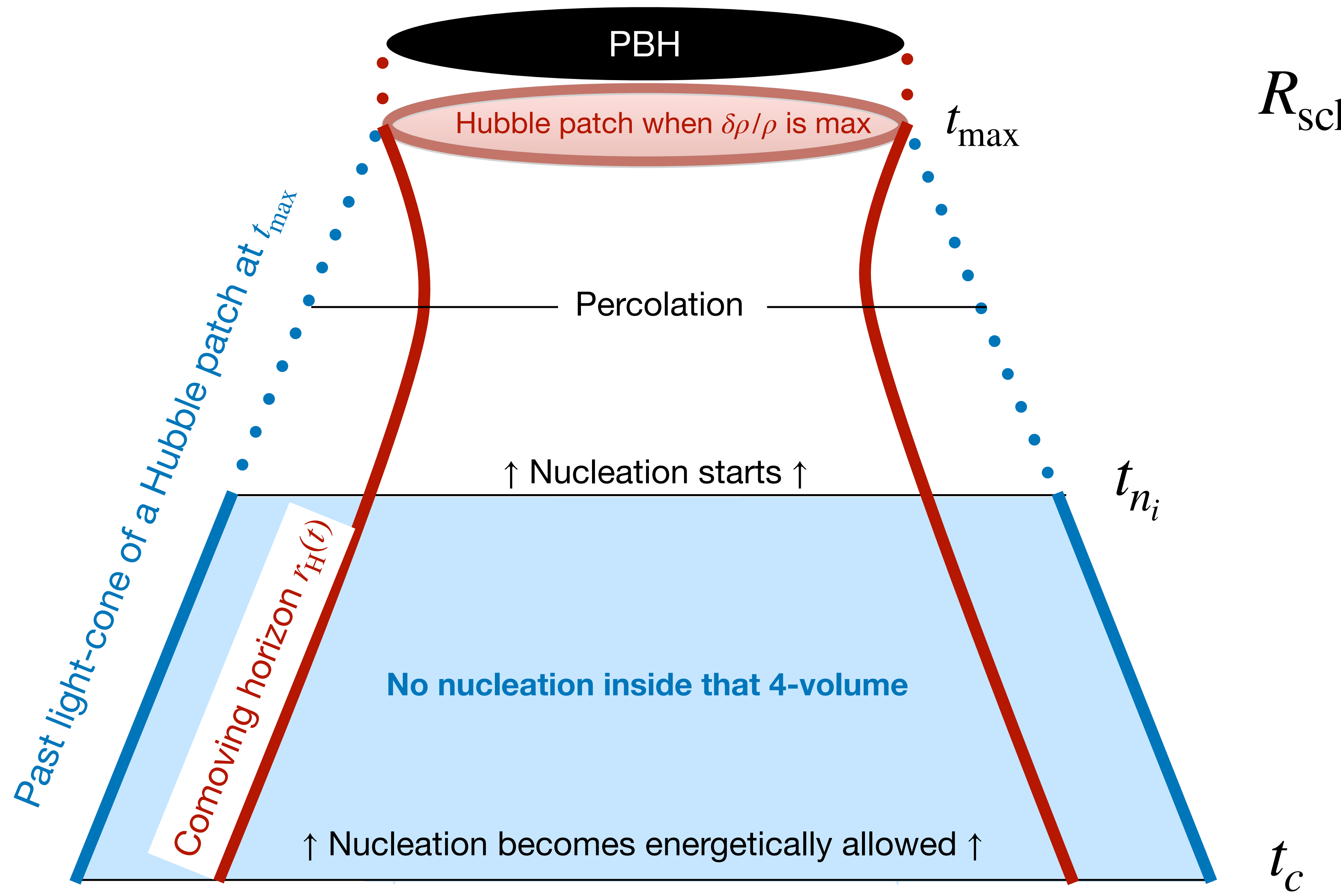
4) Scale-invariant U(1) extension of SM:

Only two additional parameters g_{D} and v_ϕ

YG, 2311.13640

- **Explain HSC lensing anomaly ($v_\phi \sim 20$ TeV)**
- **Explain 100% of DM ($v_\phi \in [300\,\mathrm{TeV},\ 300\,\mathrm{PeV}]$)**
- **Explain 511-keV line ($v_\phi \sim 5 \times 10^8\,\mathrm{GeV}$)**

2023: Primordial Black Holes from Supercooled Phase Transitions,
YG, Volansky, 2305.04942



$$R_{sch} = 2GM_{bulk}$$

1982: Kodama, Sasaki, Sato, Abundance of Primordial Holes Produced by Cosmological First Order Phase Transition (Prog.Theor.Phys. 68 (1982) 1979)

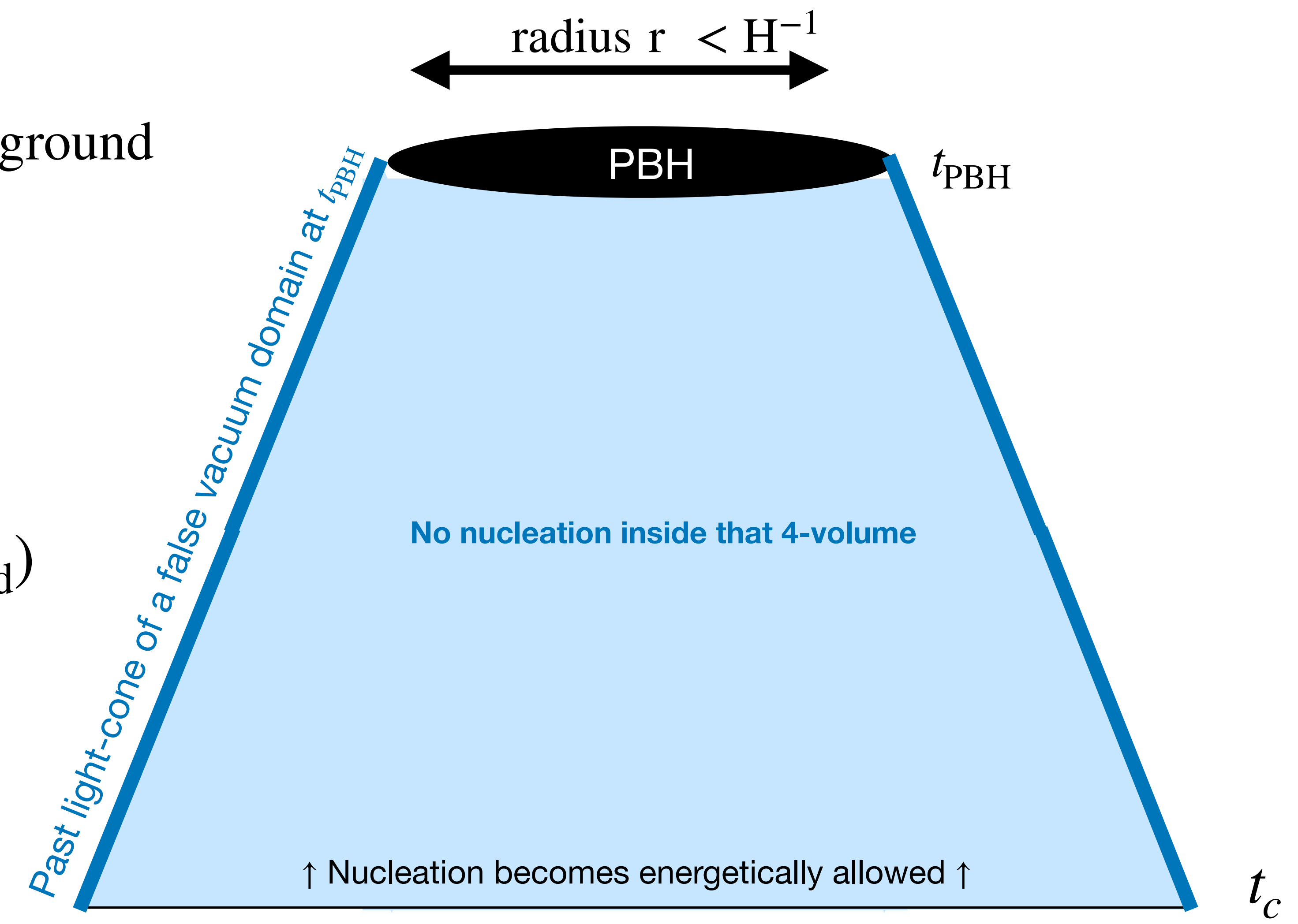
2023: Primordial black holes from strong first-order phase transitions, Lewicki, Toczek, Vaskonen, JHEP 09 (2023) 092, 2305.04924

$$R_{sch} = 2G\delta M$$

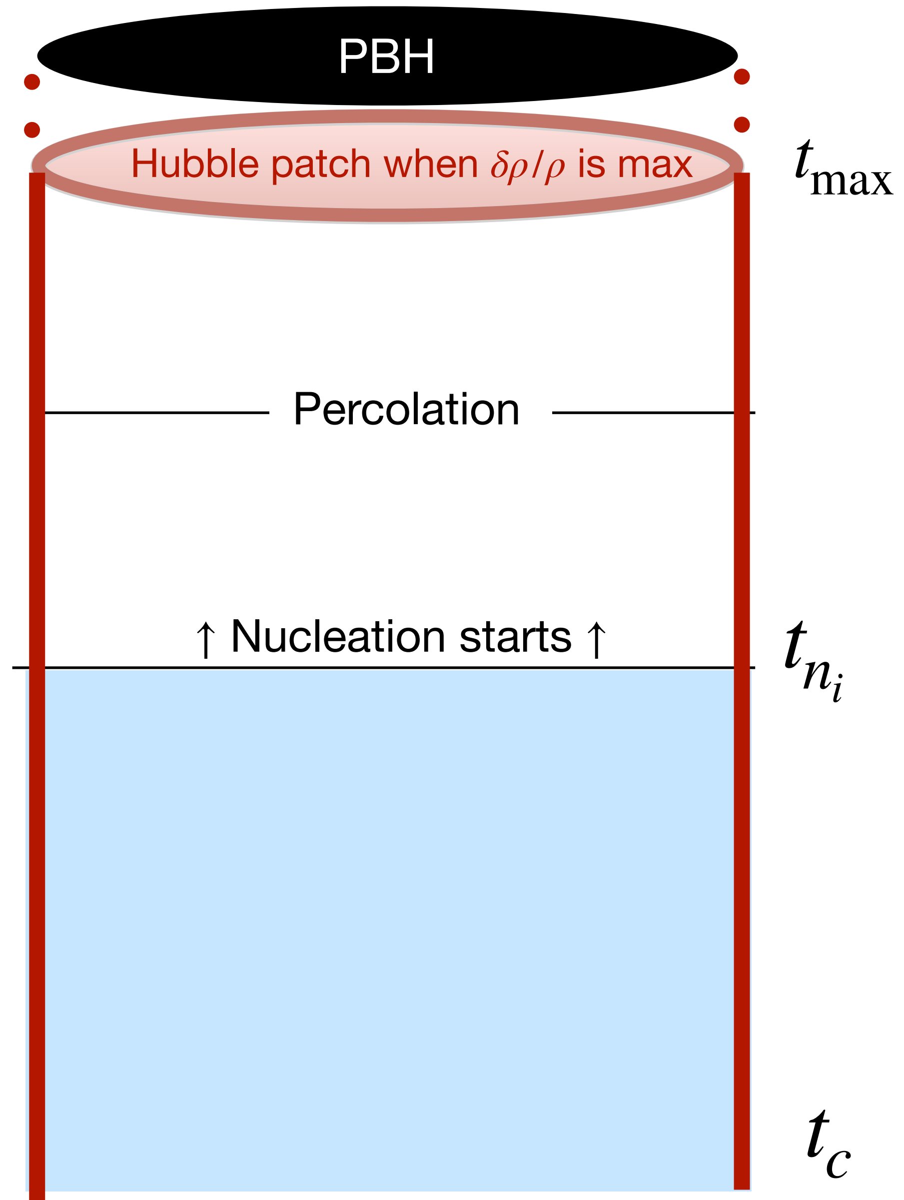
$$\delta M = M_{bulk} + M_{wall} - M_{background}$$

$$M_{bulk} \simeq \frac{4\pi}{3} r^3 \Delta V + 4\pi r^2 \sigma\gamma$$

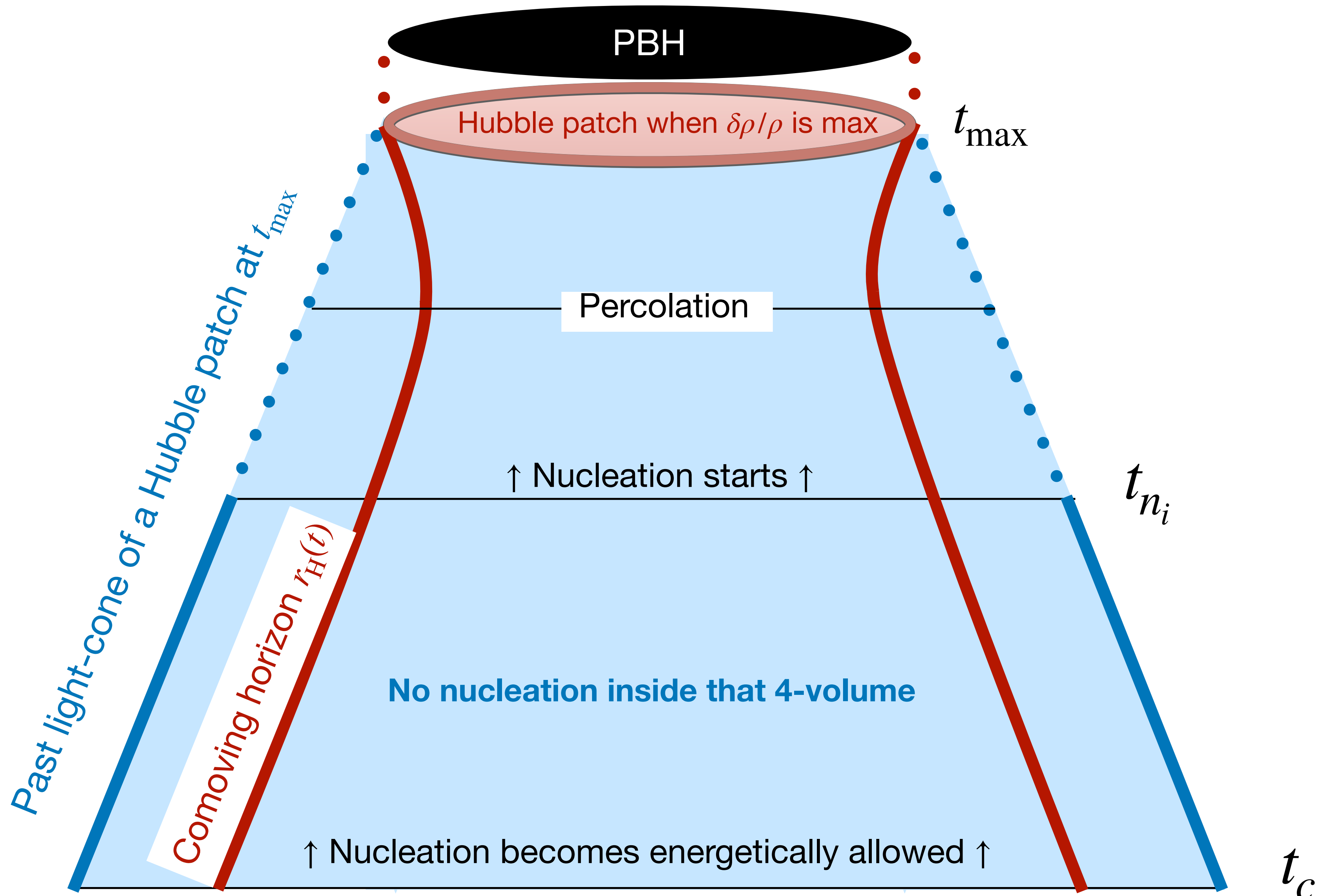
$$M_{background} \simeq \frac{4\pi}{3} r^3 (\rho_{vac} + \rho_{wall} + \rho_{rad})$$



2021: Liu, Bian, Can, Guo, Wang, Primordial black hole production during first-order phase transitions, 2106.05637, *Phys.Rev.D* 105 (2022) 2



2022: Kawana, T. Kim, and P. Lu, PBH Formation from Overdensities in Delayed Vacuum Transitions, 2212.14037



PBH from conformal Higgs

YG, 2311.13640

Scale invariant Higgs + U(1)

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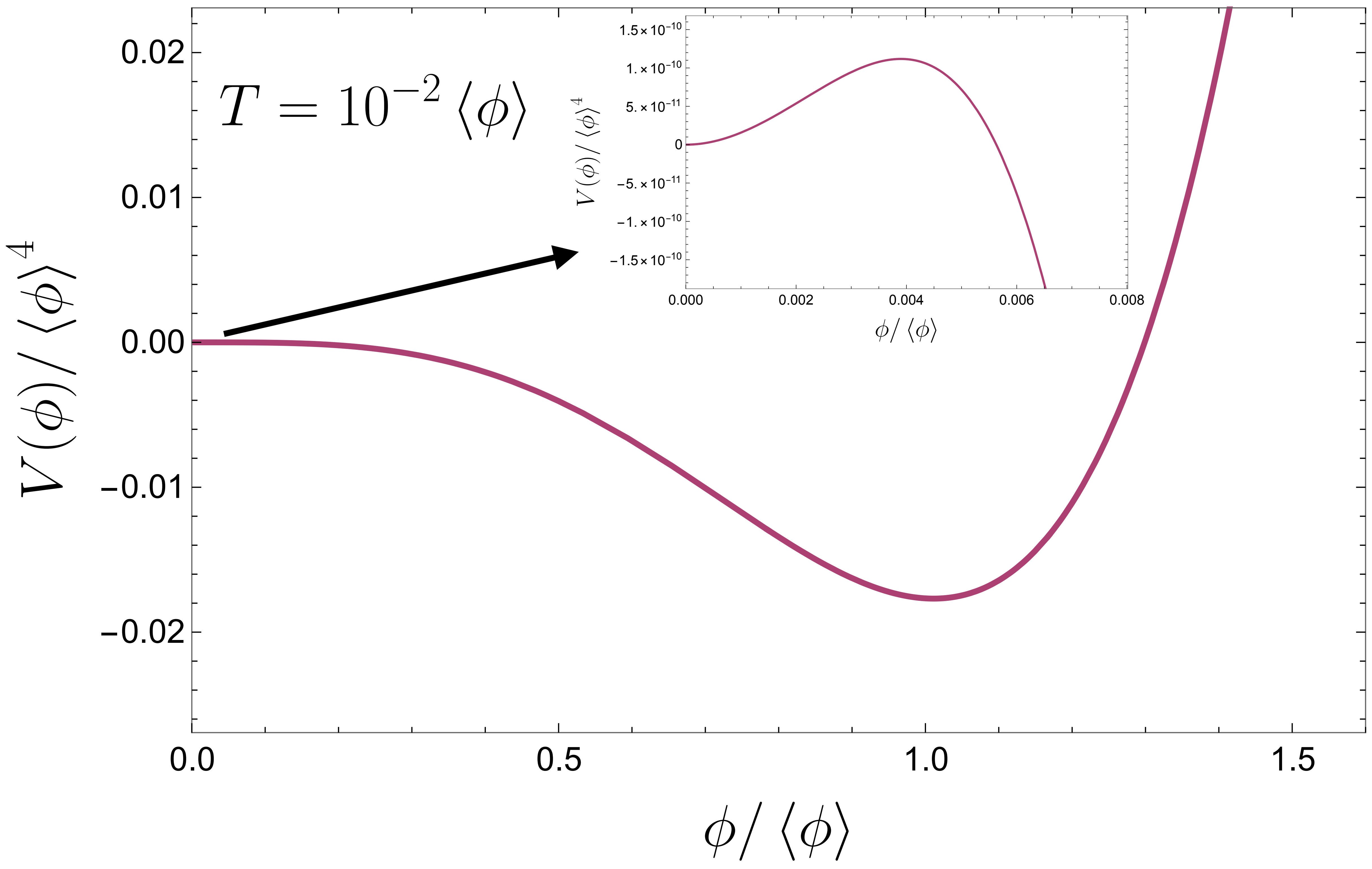
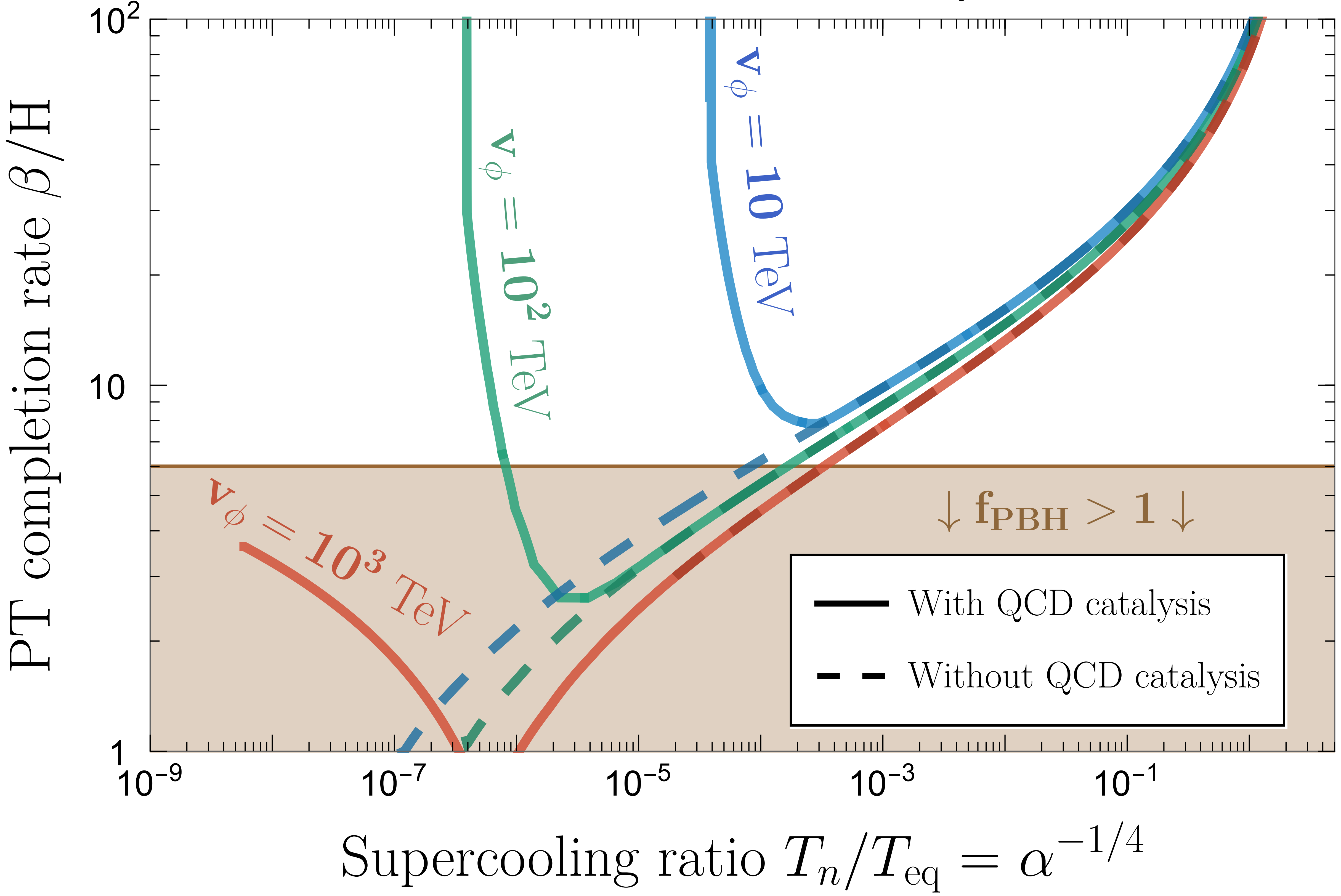
Witten, Nucl. Phys. B 177, 477 (1981)





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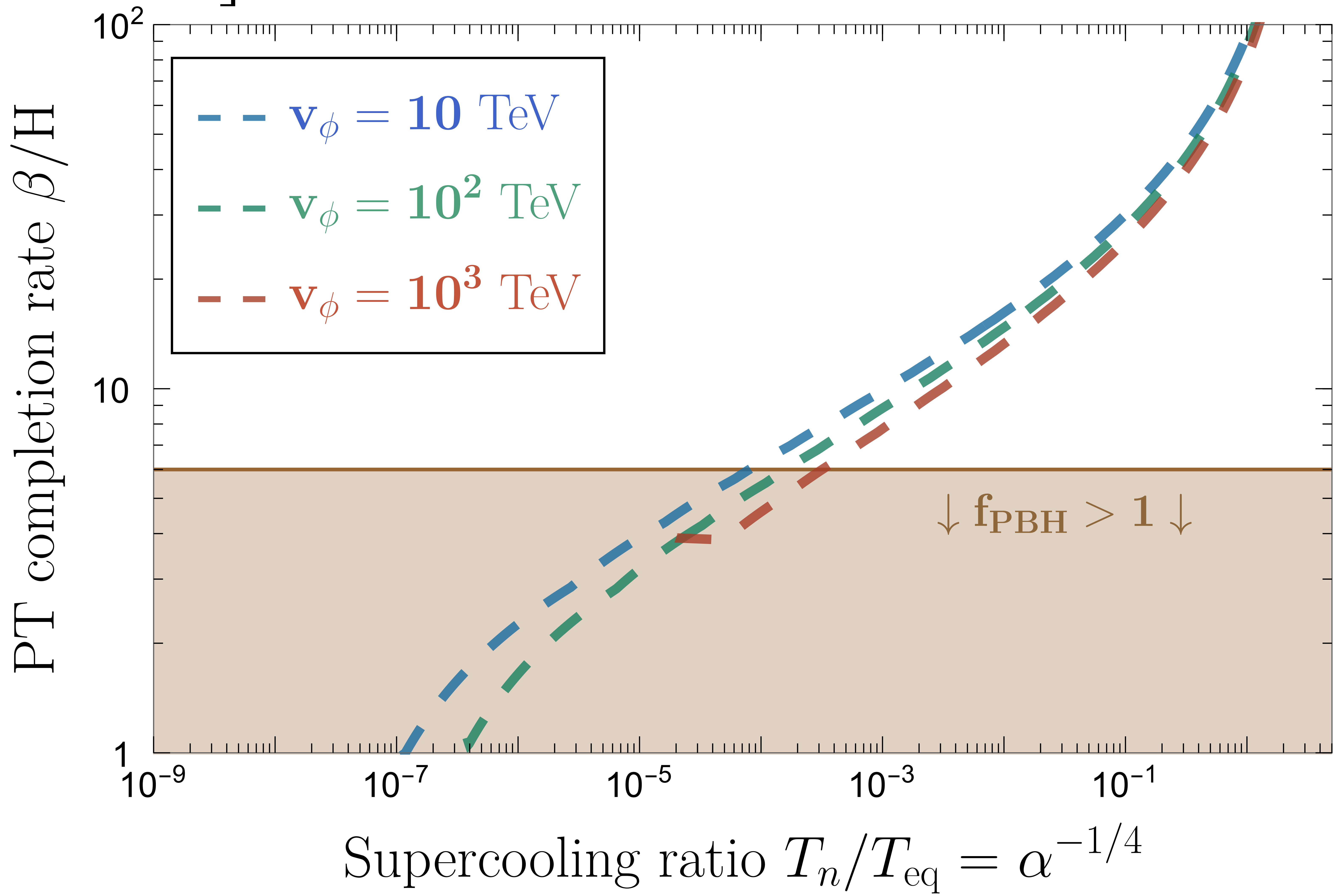

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