25th May. 2021 @ Elab seminar

Self-introduction,

or a biased view of what theoretical cosmologists are recently interested in

Yuichiro TADA

Clab, Nagoya U.

Mikura, YT, Yokoyama — EPL **132**, 3 (2020) **Highlights**

YT & Yokoyama — PRD **100**, no. 2, 023537 (2019)

Fujita, Kawasaki, YT, Takesako — JCAP **12**, 036 (2013)

Yuichiro TADA（多田 祐一郎）

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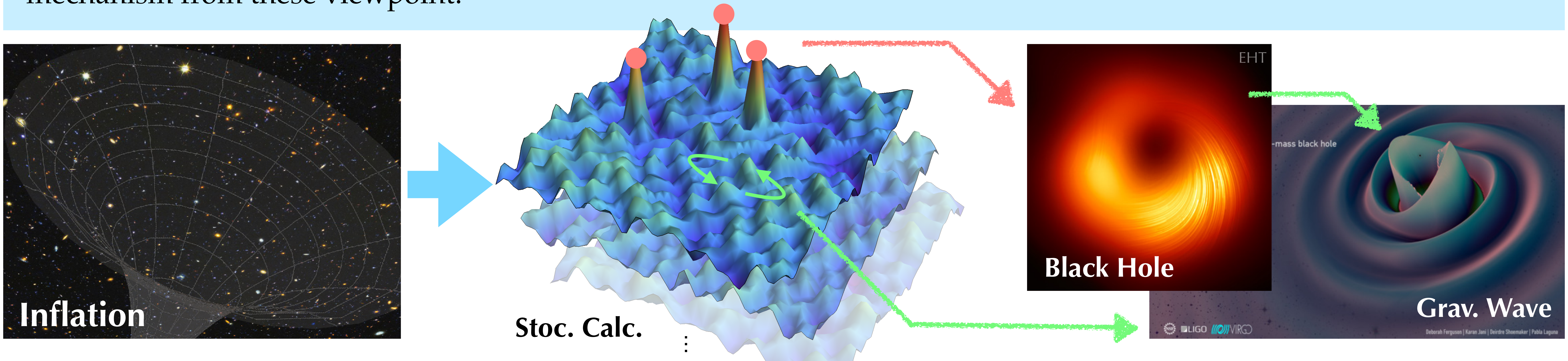
2017 Mar.	Ph.D. (Science)	The University of Tokyo (IPMU & ICRR)
2017 Apr.	PD researcher	Institut d'Astrophysique de Paris
2018 Apr.	JSPS fellow (PD)	Nagoya University (C-lab.)
2021 Apr.	Designated Asst. Prof. (YLC)	Nagoya University (IAR & C-lab.)

Research Topic: Approach to Cosmic Inflation in light of Stochastic Calc., Prim. Black Hole, and Grav. Wave

Our universe is thought to start with an accelerated expansion phase called **Inflation**. It can source various cosmic structures (e.g., galaxy) from quantum fluctuation, but its expansion mechanism has not been explained. As a possible sourced object, **Primordial Black Hole** (原始ブラックホール) has attracted attention as a candidate of **Dark Matter** (暗黒物質). **Gravitational Wave** (重力波) is also attractive because it can be directly detected now. I have proposed a powerful algorithm to evaluate their production by applying **Stochastic Calculus** (確率解析), and am approaching to the inflation mechanism from these viewpoint.



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Research Topic

Our universe is thoug … source various cosmic
structures (e.g., galaxy … explained. As a possible
sourced object, **Primo** … **Dark Matter** (暗黒物質).
Gravitational Wave (… e proposed a powerful
algorithm to evaluate … roaching to the inflation
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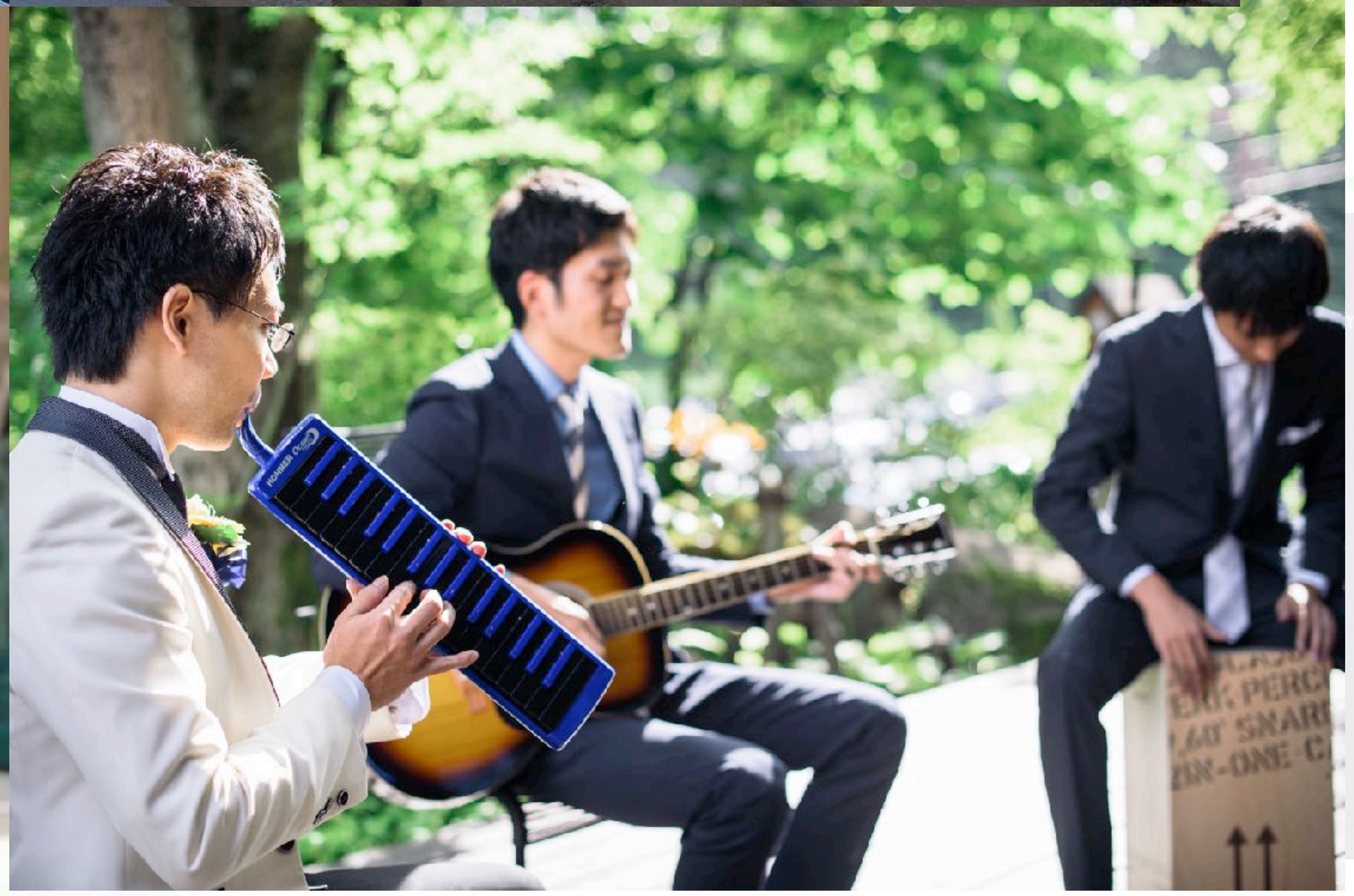


Contents

Inflation

Planck (CMB obs.)

R^2-model
Starobinsky '80

Primordial Black Hole

LIGO, DM, SMBH, OGLE, Planet 9, ...

or "Other Possibilities"?

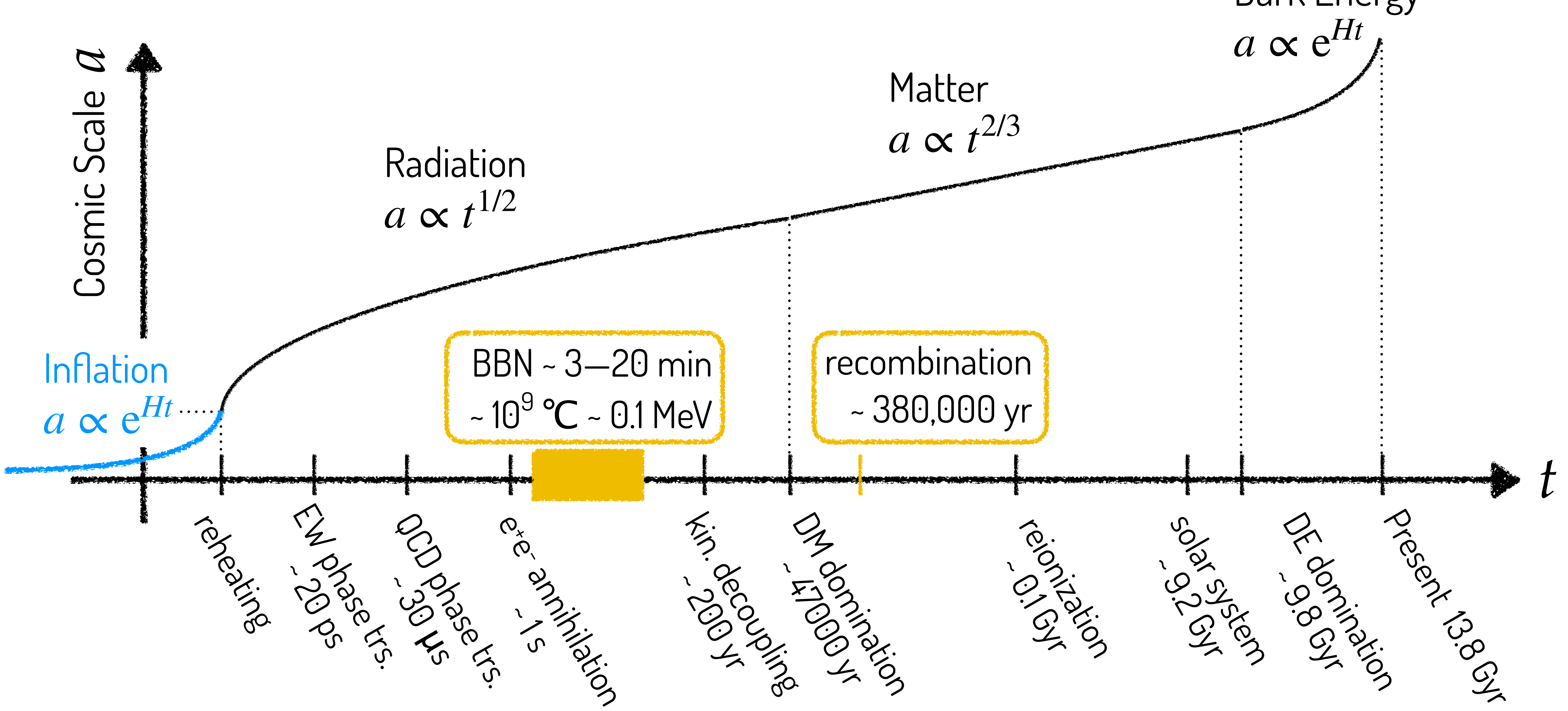
Metric-Affine Gravity
Mikura, YT, Yokoyama '20 & '21

Multistage Inflation
YT & Yokoyama '19, Inomata, Kawasaki, Mukaida, YT, Yanagida '17s

Stochastic Inflation
Fujita, Kawasaki, YT, Takesako '13, Pinol, Renaux-Petel, YT '19 & '21

Thermal History

Why "Inflation"?



Thermal History

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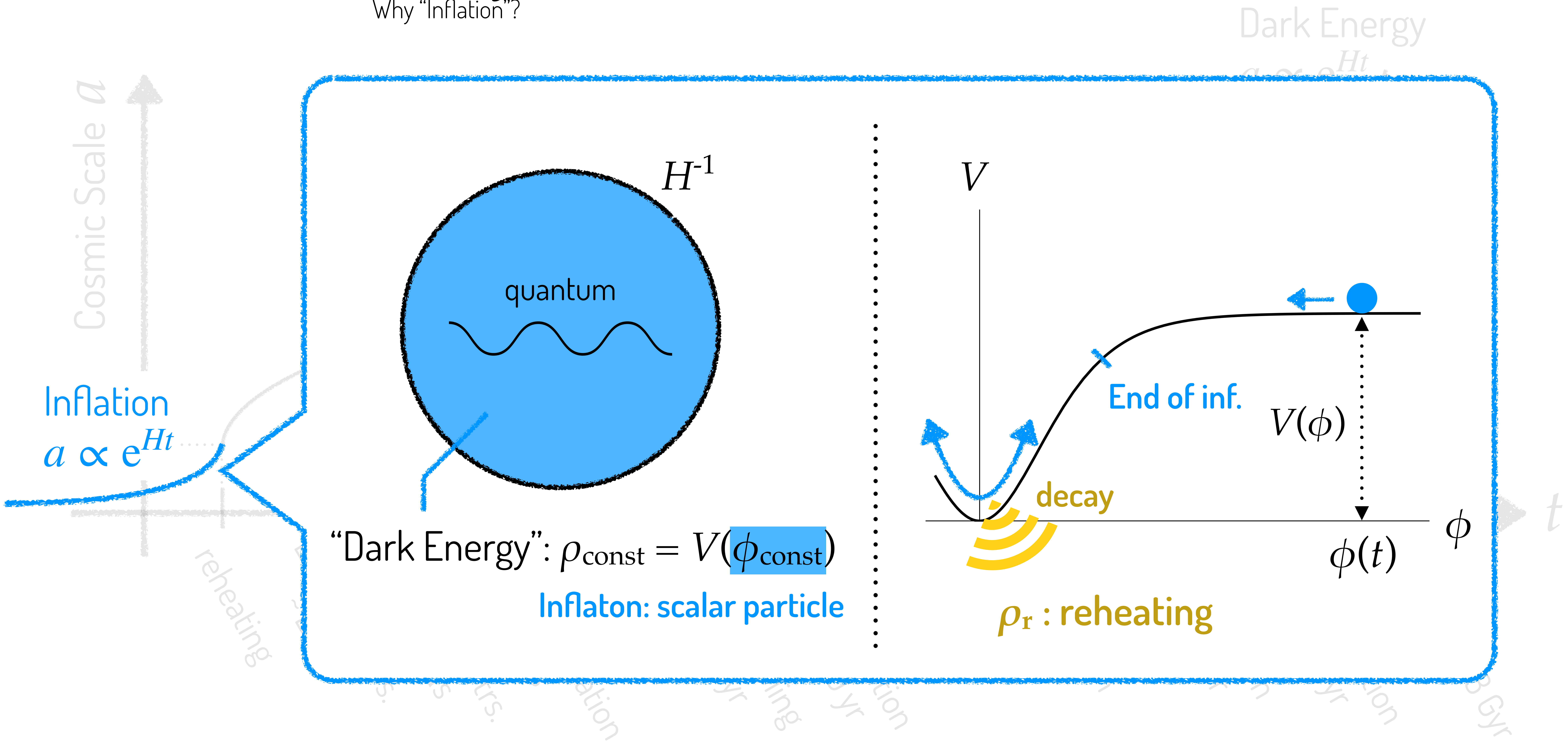

Thermal History

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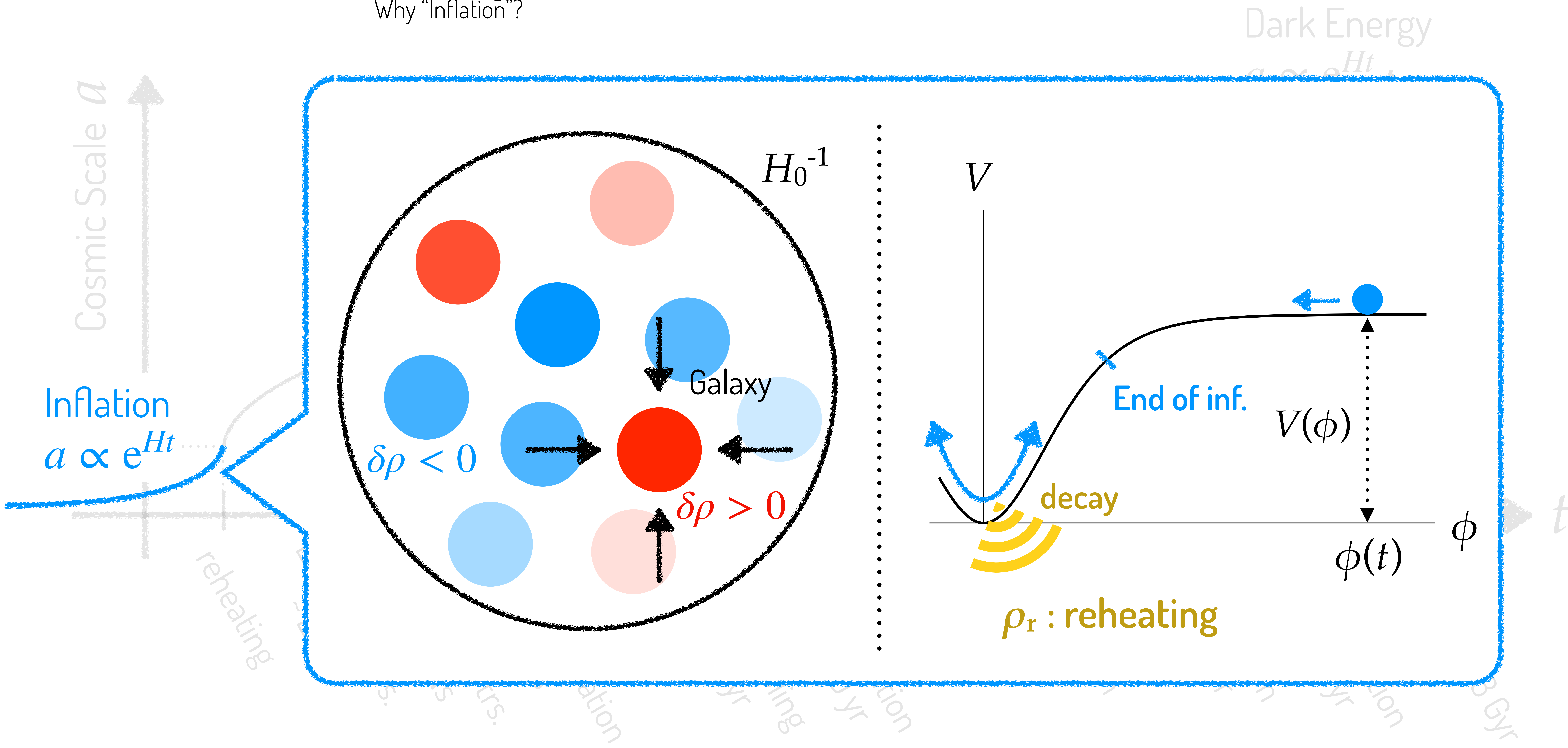
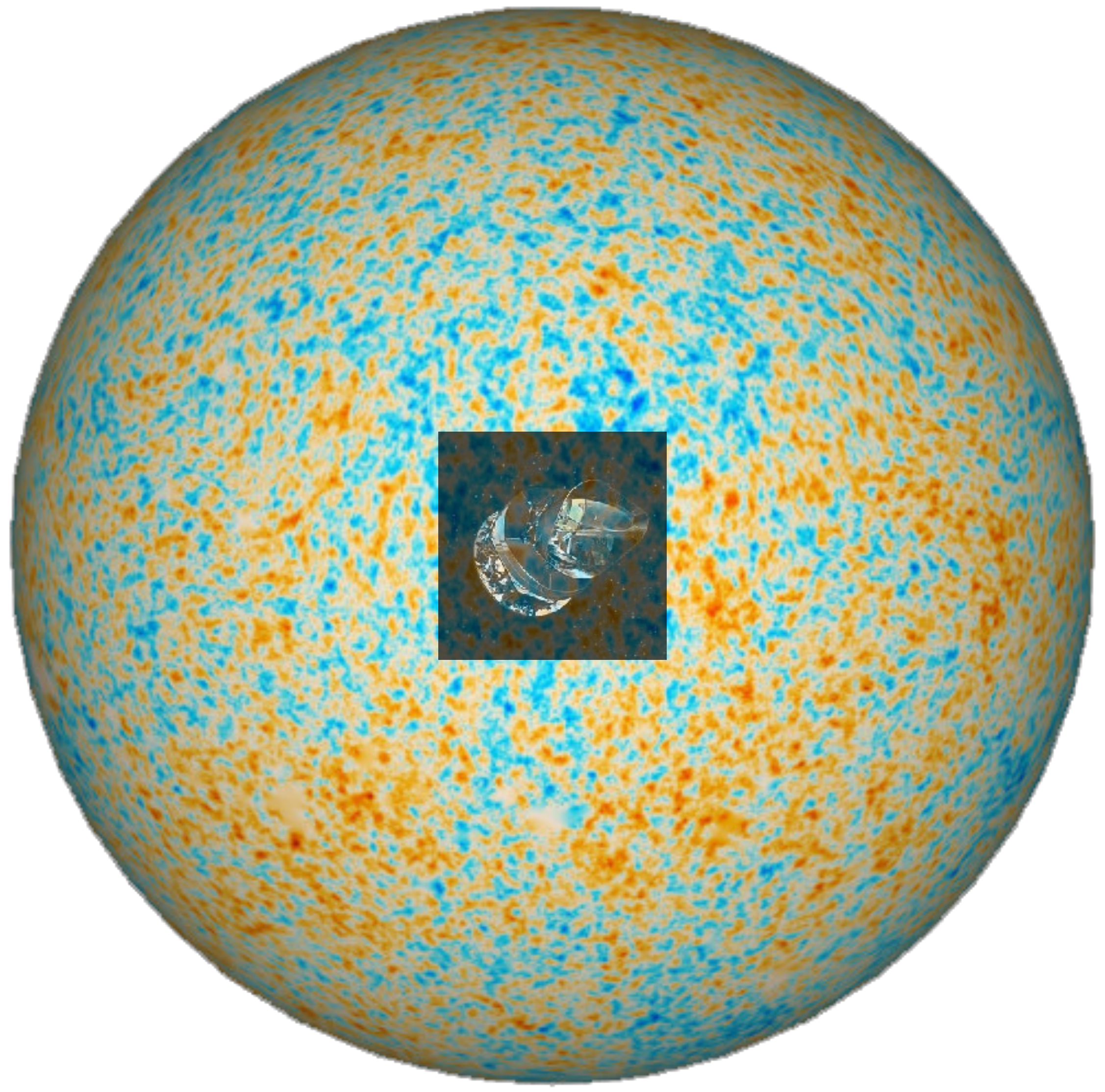
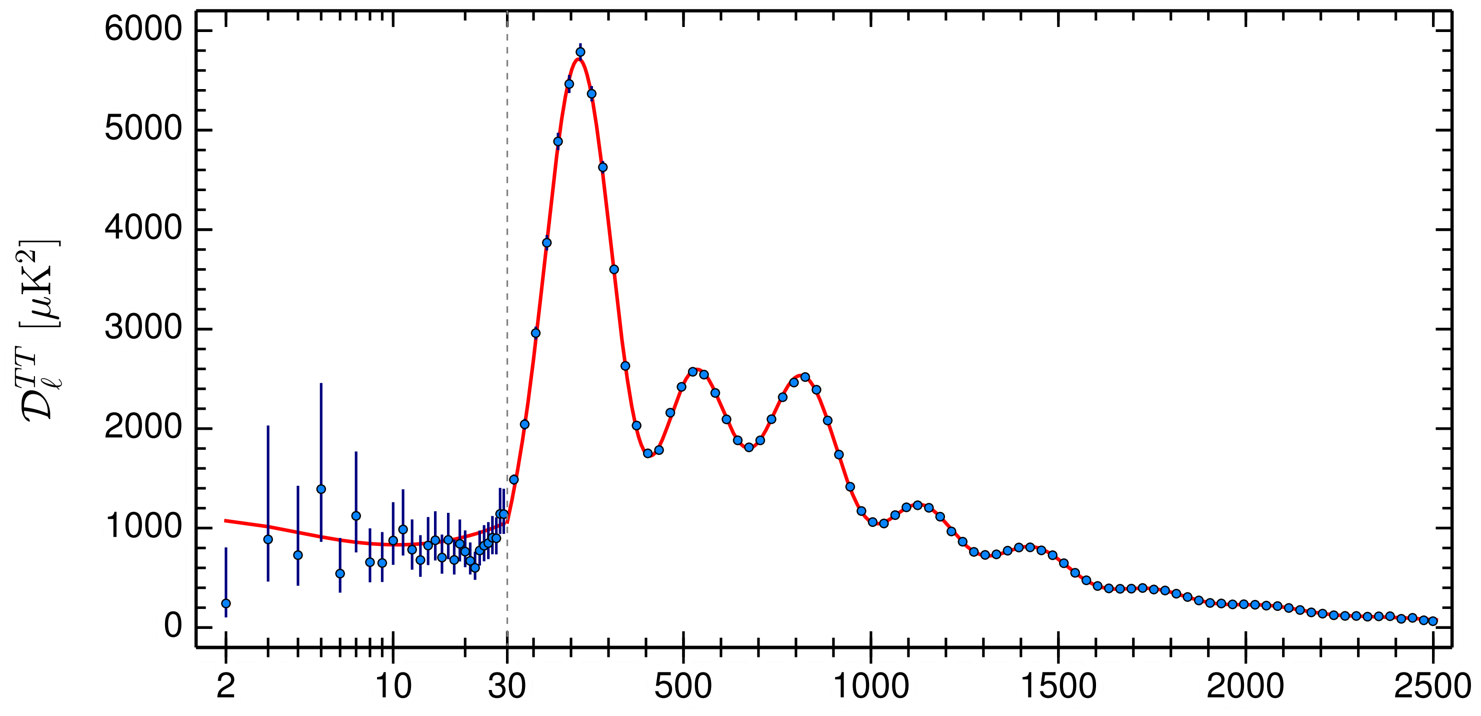


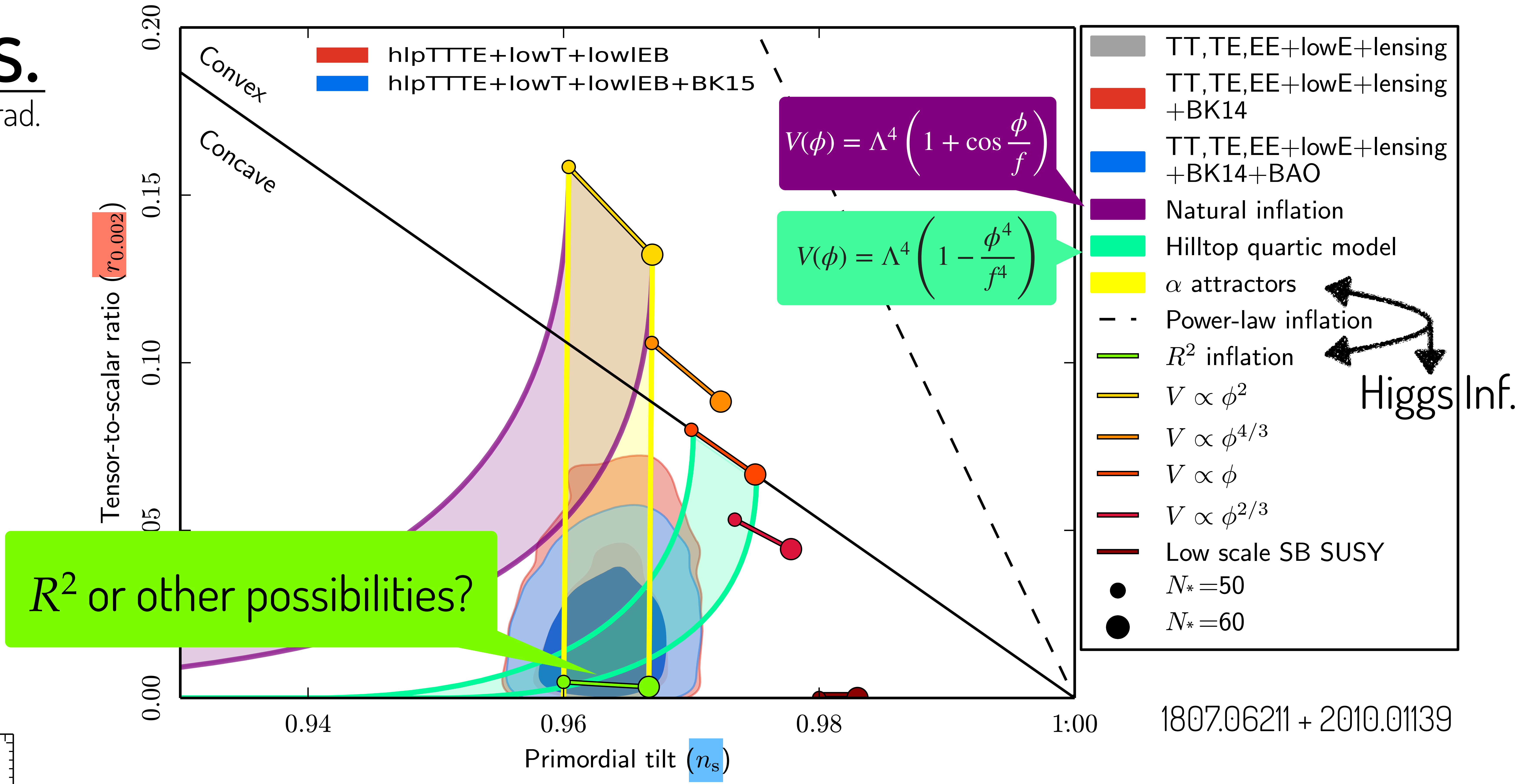
Planck obs.

CMB: remnant of plasma rad.





ℓ : Sph. Harm. Exp.



1807.06211 + 2010.01139

$$\mathcal{P}_\zeta(k) = \frac{(k^3/2\pi^2)\langle\zeta_{\mathbf{k}}\zeta_{\mathbf{k}'}\rangle}{(2\pi)^3\delta^{(3)}(\mathbf{k}-\mathbf{k}')} \propto k^{n_s-1}, \qquad r = \frac{\mathcal{P}_h}{\mathcal{P}_\zeta}$$

$$\mathrm{d}^2 s = -\left(1+2\Psi(t,\mathbf{x})\right) + a^2\left[\left(1-2\Psi(t,\mathbf{x})\right)\delta_{ij} + h_{ij}(t,\mathbf{x})\right]\mathrm{d}x^i\mathrm{d}x^j$$

tensor

scalar $\zeta = -\Psi + \frac{\delta\rho}{3(\rho+P)}$

R^2 inflation

Starobinsky '80

$$S_J[g] = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\,f(R)$$

auxiliary

$$\Leftrightarrow\ S_J[g,z] = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\,\left[f(z)+f'(z)(R-z)\right] \qquad \because\ \frac{1}{\sqrt{-g}}\frac{\delta S_J}{\delta z} = f''(z)(R-z)\ \to\ z=R$$

field trs.

$$g_{\mu\nu}\to\tilde{g}_{\mu\nu} = \frac{\omega}{M_{\mathrm{Pl}}}g_{\mu\nu}, \quad \omega = \frac{f'(z)}{M_{\mathrm{Pl}}}, \quad R = \frac{\omega}{M_{\mathrm{Pl}}}\left(\tilde{R}-6\sqrt{\frac{\omega}{M_{\mathrm{Pl}}}}\,\tilde{\Box}\sqrt{\frac{M_{\mathrm{Pl}}}{\omega}}\right)$$

$$S_E[\tilde{g},\omega] = \int \mathrm{d}^4x\sqrt{-\tilde{g}}\left[\frac{1}{2}M_{\mathrm{Pl}}^2R - \frac{3M_{\mathrm{Pl}}^2}{4\omega^2}(\partial_\mu\omega)^2 - \frac{M_{\mathrm{Pl}}^3(\omega z - f(z)/M_{\mathrm{Pl}})}{2\omega^2}\right]$$

dynamical scalar!

R^2 inflation

$$f(R) = M_{\mathrm{Pl}}^2R+\beta R^2: \quad S_E[g,\chi] = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}M_{\mathrm{Pl}}^2R - \frac{1}{2}(\partial_\mu\chi)^2 - \frac{M_{\mathrm{Pl}}^2}{2\beta}\left(1-\mathrm{e}^{-\sqrt{\frac{2}{3}}\frac{\chi}{M_{\mathrm{Pl}}}}\right)^2\right]$$

Conformal inf.

Kallosh & Linde '13

ghost

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{12}(\chi^2-\phi^2)R+\frac{1}{2}(\partial_\mu\chi)^2-\frac{1}{2}(\partial_\mu\phi)^2-\frac{1}{4}F\left(\frac{\phi}{\chi}\right)(\chi^2-\phi^2)^2\right]$$

local conformal + global (pseudo) SO(1,1)

$$\begin{cases} g_{\mu\nu}\to\tilde{g}_{\mu\nu}=e^{-2\sigma(x)}g_{\mu\nu}, & \tilde{R}=e^{2\sigma}(R-\cancel{e^{\sigma}\Box e^{-\sigma}}) \\ \phi\to\tilde{\phi}=e^{\sigma(x)}\phi, & \partial_\mu\tilde{\phi}=e^{\sigma}\partial_\mu\phi+\cancel{\phi\partial_\mu e^{\sigma}} \end{cases}$$

Gauge fixing: $\chi^2-\phi^2=6M_{\rm Pl}^2$

pNG boson

$$\begin{cases} \sqrt{6}M_{\rm Pl}\cosh\frac{\varphi}{\sqrt{6}M_{\rm Pl}} \\ \sqrt{6}M_{\rm Pl}\sinh\frac{\varphi}{\sqrt{6}M_{\rm Pl}} \end{cases}$$

$\longrightarrow$ $V(\varphi)\propto\tanh^{2n}\frac{\varphi}{\sqrt{6}M_{\rm Pl}}$ ✓

c.f. α attractor: $V(\varphi)\propto\tanh^{2n}\frac{\varphi}{\sqrt{6\alpha}M_{\rm Pl}}$

nontrivially embedded in superconformal

Metric-Affine Grav.

Geometry = $g_{\mu\nu}$ + $R^{\mu}{}_{\nu\rho\sigma}(\Gamma)$ + $\cancel{T^{\mu}{}_{\nu\rho}}$

- Metric

  norm conserv. in parallel trs.

$$\overset{\Gamma}{\nabla} g_{\mu\nu} = 0 \ \rightarrow \ \Gamma^{\mu}_{\nu\rho} = \frac{1}{2} g^{\mu\sigma}(g_{\nu\sigma,\rho} + g_{\rho\sigma,\nu} - g_{\nu\rho,\sigma})$$

$$\Downarrow$$

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{1}{2} M_{\mathrm{Pl}}^2\, g^{\mu\nu} R_{\mu\nu}\left(\Gamma(g)\right)$$

- Metric-Affine

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{1}{2} M_{\mathrm{Pl}}^2\, g^{\mu\nu} R_{\mu\nu}(\Gamma)$$

$$\Downarrow$$

EL constraint

$$\frac{\delta S}{\delta \Gamma} = 0 \ \rightarrow \ \Gamma^{\mu}_{\nu\rho} = \frac{1}{2} g^{\mu\sigma}(g_{\nu\sigma,\rho} + g_{\rho\sigma,\nu} - g_{\nu\rho,\sigma})$$

. . . .

$$S = \int \mathrm{d}^4x \sqrt{-g}\, f\left(R(g)\right) \qquad S = \int \mathrm{d}^4x \sqrt{-g}\, f\left(g^{\mu\nu} R_{\mu\nu}(\Gamma)\right)$$

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \phi^2 R(g) \qquad S = \int \mathrm{d}^4x \sqrt{-g}\, \phi^2 g^{\mu\nu} R_{\mu\nu}(\Gamma)$$

Conf. inf. in MAG

Mikura, YT, Yokoyama '20 & '21

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{12\alpha}(\chi^2 - \phi^2) R(g,\Gamma) + \frac{1}{2}(D_\mu \chi)^2 - \frac{1}{2}(D_\mu \phi)^2 - \frac{1}{4} F\left(\frac{\phi}{\chi}\right)(\chi^2 - \phi^2)^2 \right]$$

$$\begin{cases} g_{\mu\nu} \to \tilde{g}_{\mu\nu} = e^{-2\sigma(x)} g_{\mu\nu}, \\ \Gamma \to \tilde{\Gamma} = \Gamma, \end{cases} \qquad \tilde{R} = \tilde{g}^{\mu\nu} R_{\mu\nu}(\tilde{\Gamma}) = e^{2\sigma(x)} R$$

$D_\mu = \partial_\mu - \frac{1}{8} Q_\mu$ (auxiliary) gauge field

$$Q_\mu = -g^{\alpha\beta} \nabla_\mu g_{\alpha\beta} \to \tilde{Q}_\mu = Q_\mu + 8\partial_\mu \sigma$$

Gauge fixing: $\chi^2 - \phi^2 = 6\alpha M_{\mathrm{Pl}}^2$

$$\begin{cases} \sqrt{6\alpha} M_{\mathrm{Pl}} \cosh \dfrac{\varphi}{\sqrt{6\alpha} M_{\mathrm{Pl}}} \\ \sqrt{6\alpha} M_{\mathrm{Pl}} \sinh \dfrac{\varphi}{\sqrt{6\alpha} M_{\mathrm{Pl}}} \end{cases} \longrightarrow \quad V(\varphi) \propto \tanh^{2n} \frac{\varphi}{\sqrt{6\alpha} M_{\mathrm{Pl}}}$$

c.f. MAG + conf. + O(2)

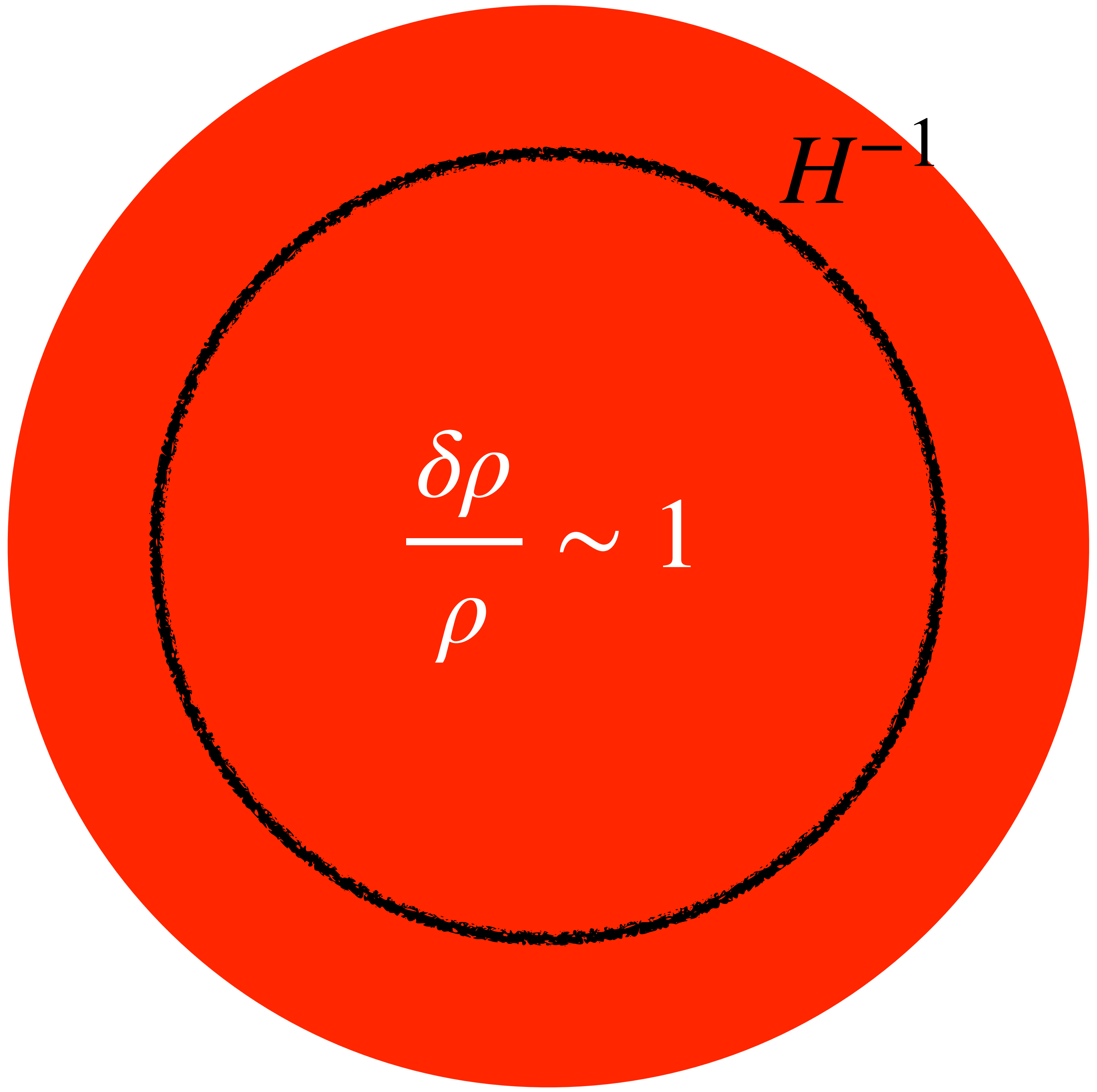
→ natural inf. $V(\varphi) \propto 1 + \cos \frac{\varphi}{f}$

Primordial Black Hole

Primordial BH

Carr & Hawking '74

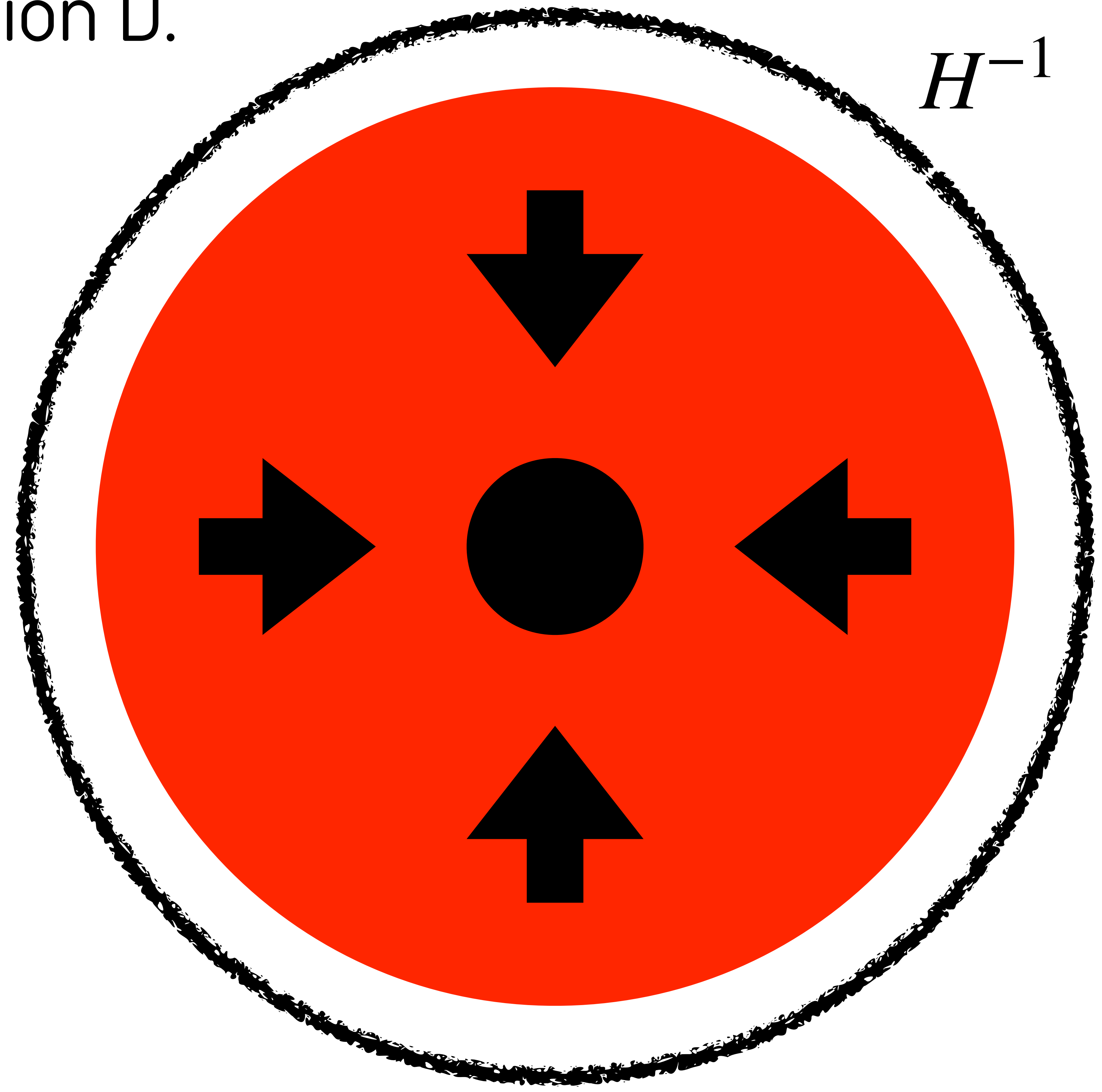
Radiation D.



Primordial BH

Carr & Hawking '74

Radiation D.

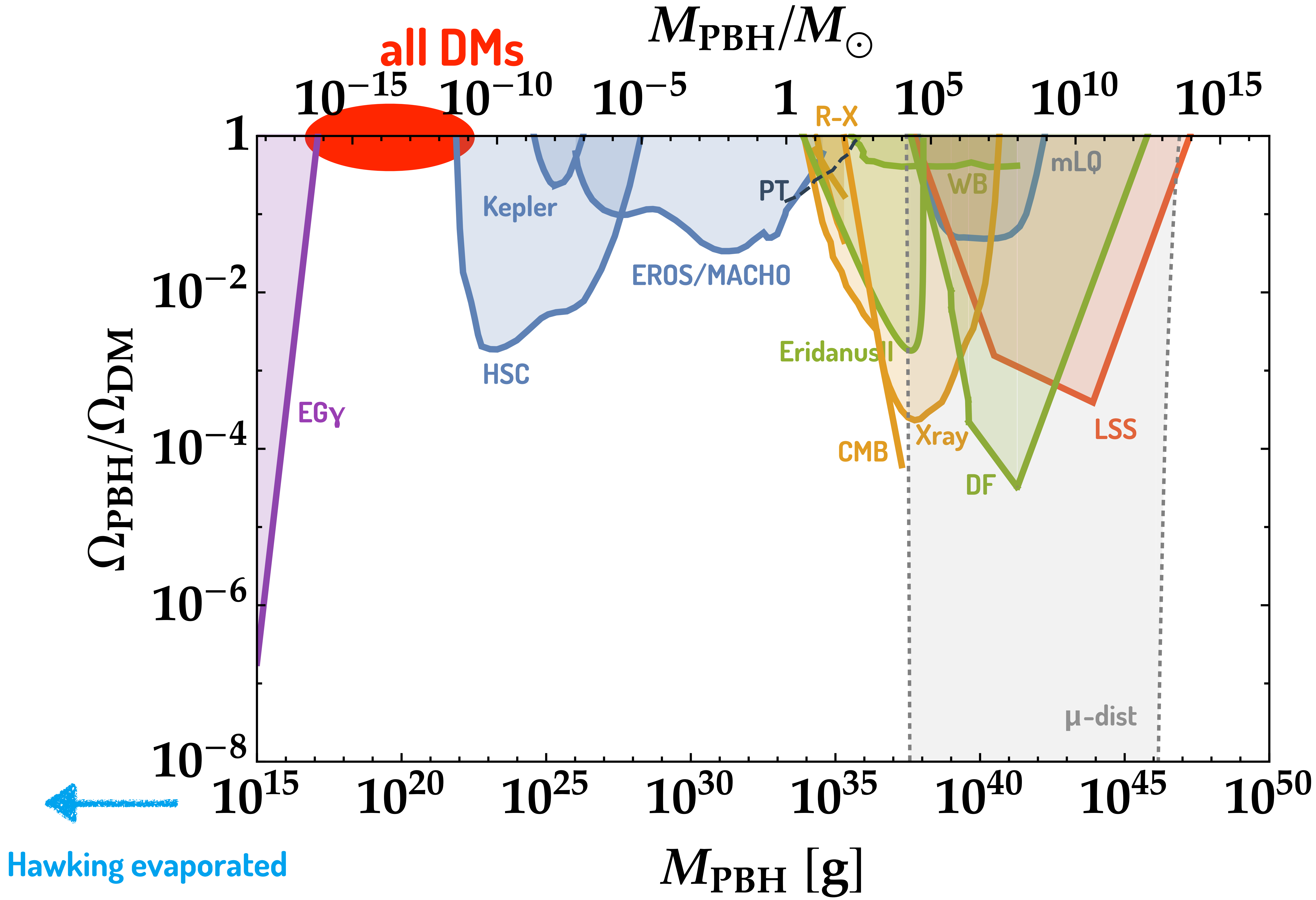


- almost arbitrary mass

  c.f. stellar BH $\gtrsim M_\odot$

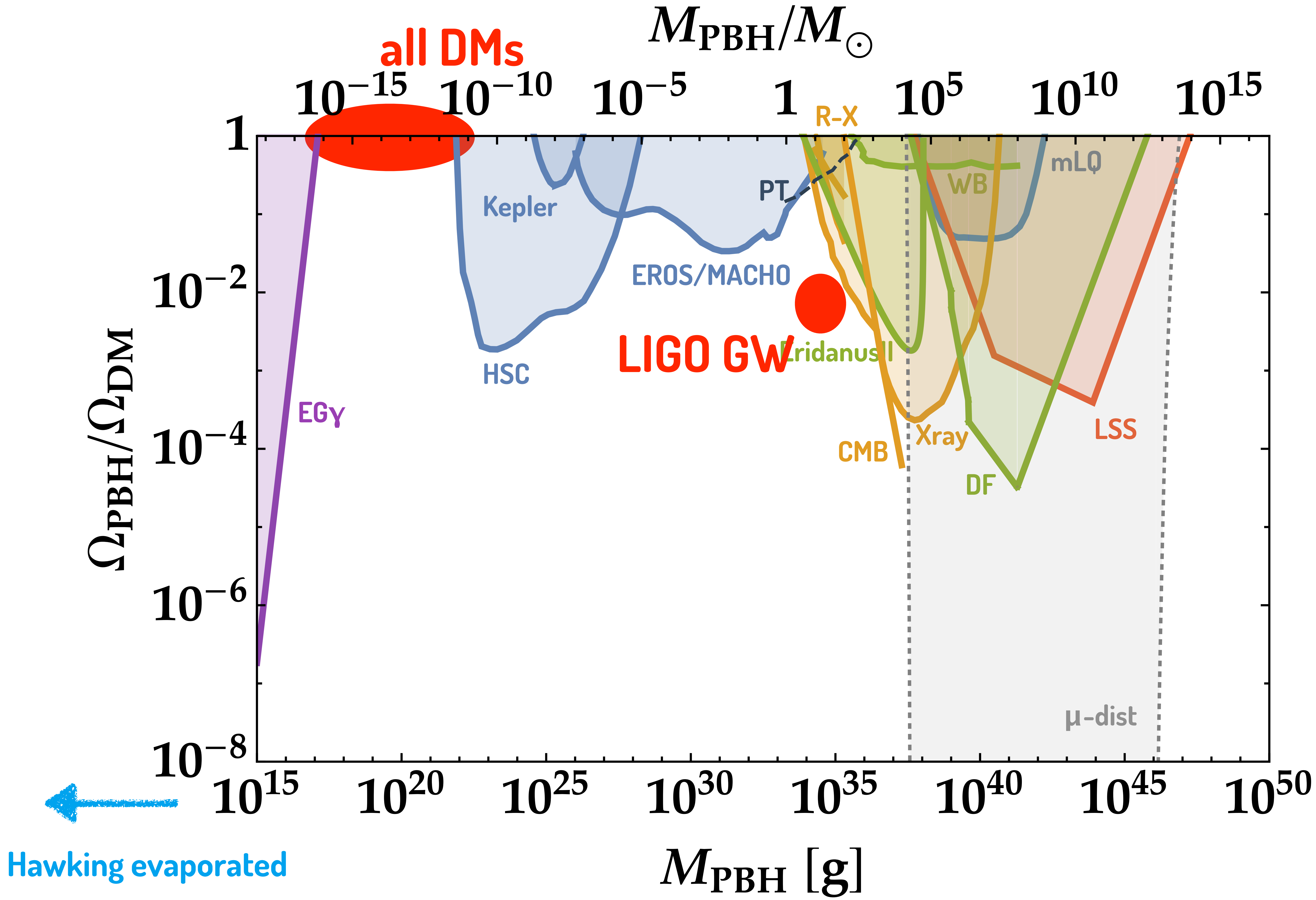
- almost zero spin

Motivations of PBH



- Gravitational Lensing
- Dynamical Friction
- Accretion γ
- Prim. PTB
- Hawking γ

Motivations of PBH



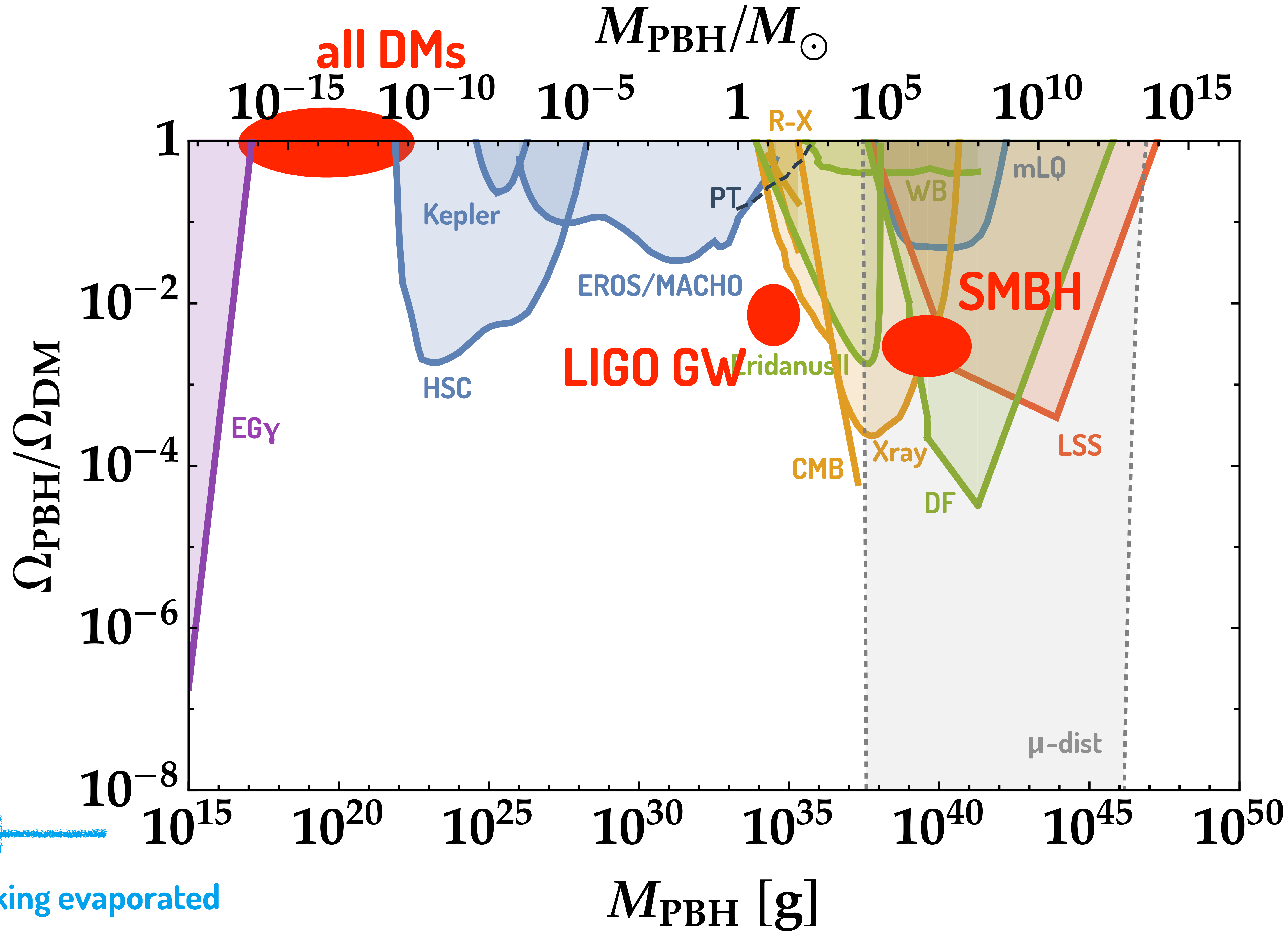
Massive than stellar BHs found

small spin

Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	$\chi_{\rm eff}$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$

LIGO/Virgo 2018

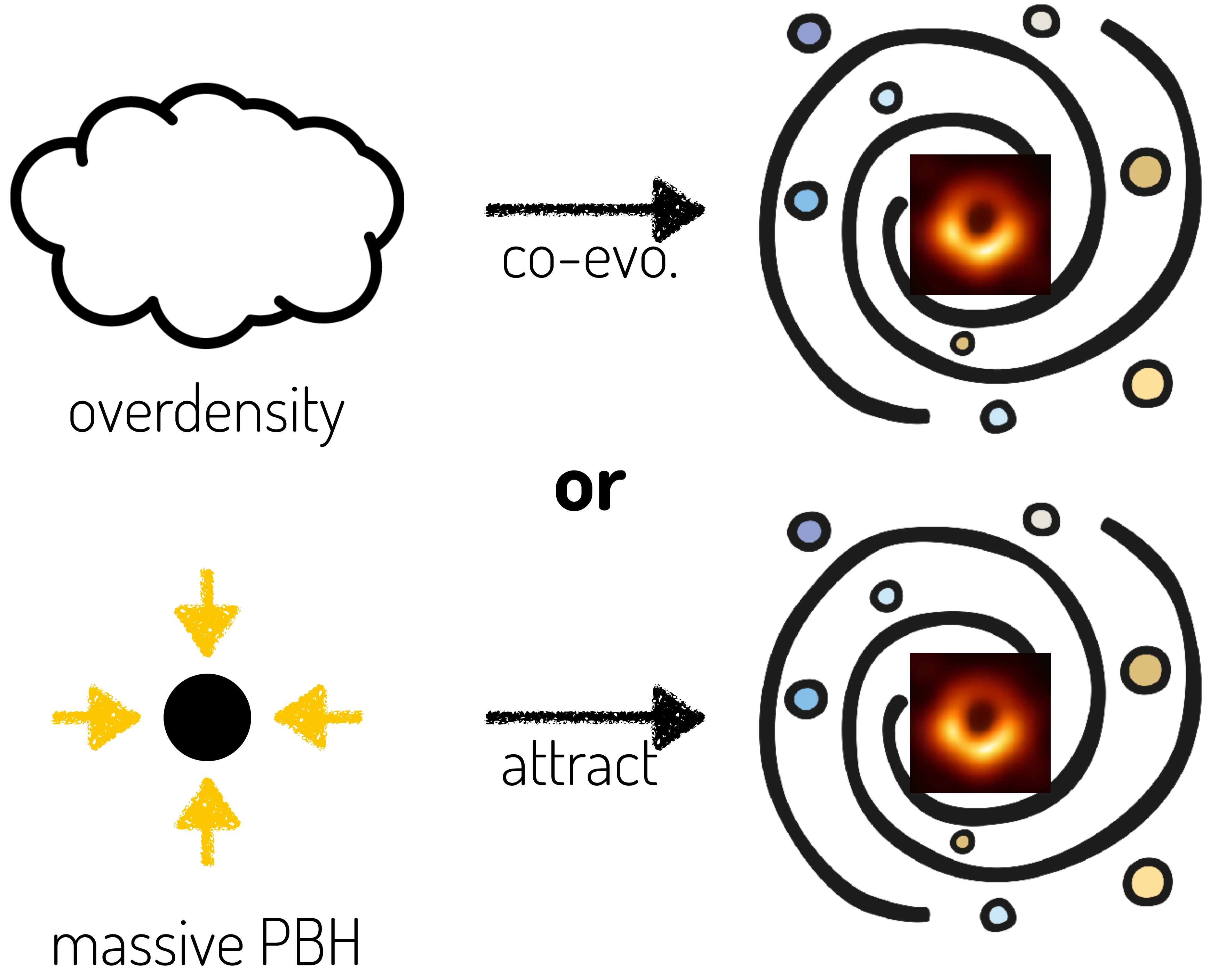
Motivations of PBH



Hawking evaporated

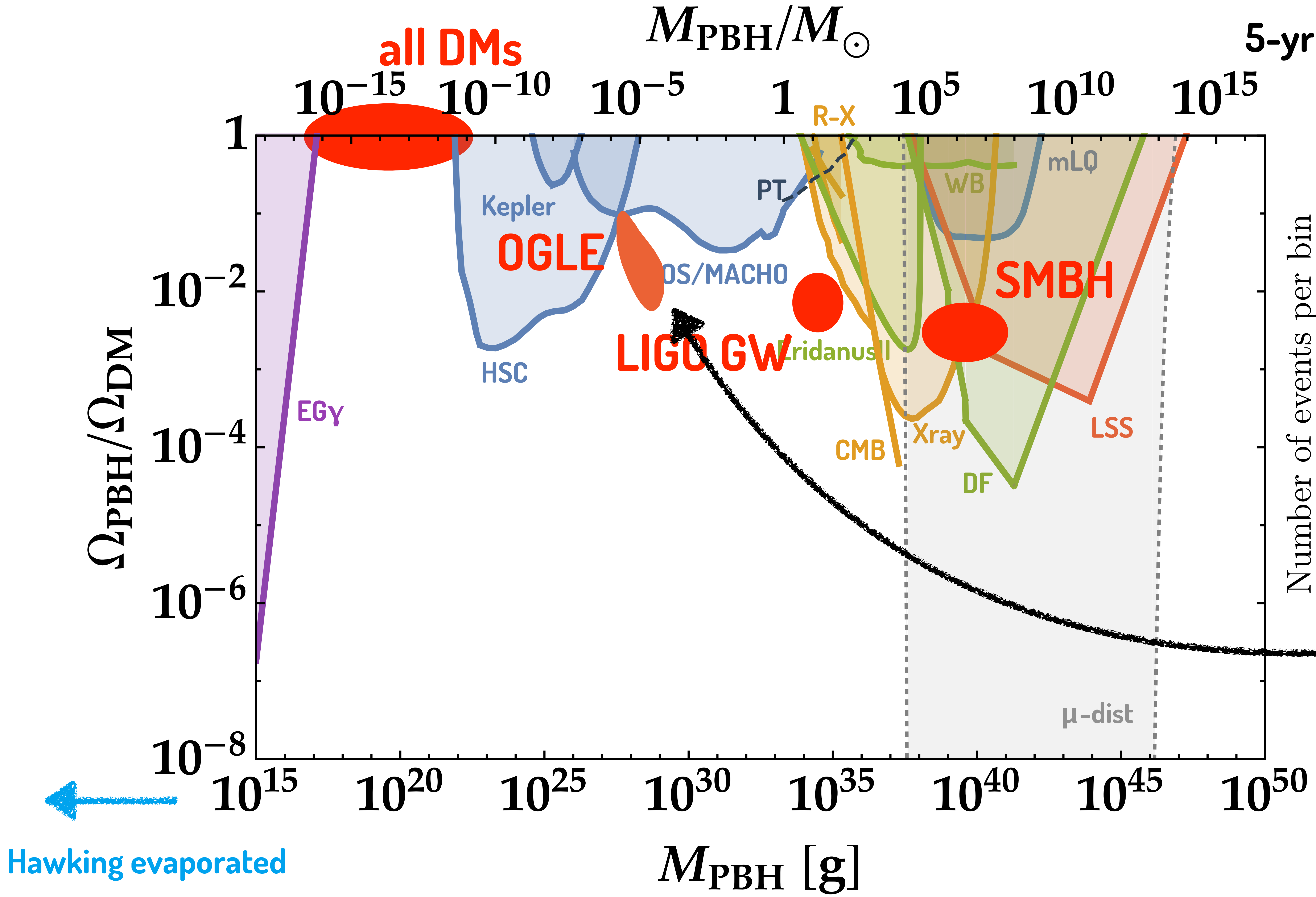
Supermassive Black Hole

~ $10^{5\text{–}10}\,M_\odot$ SMBH in each galaxy



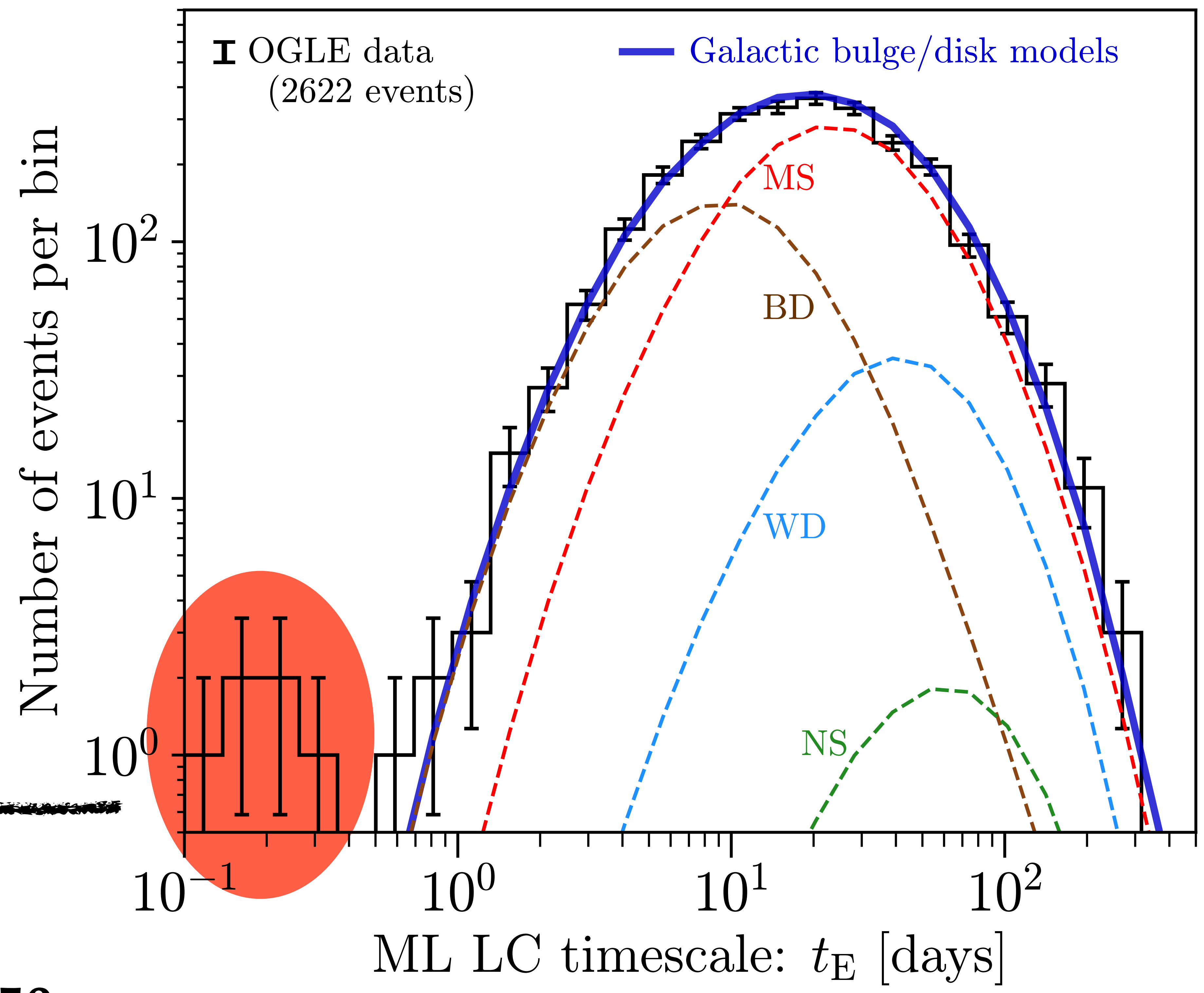
Bean & Magueijo 2002
Carr & Silk 2018

Motivations of PBH

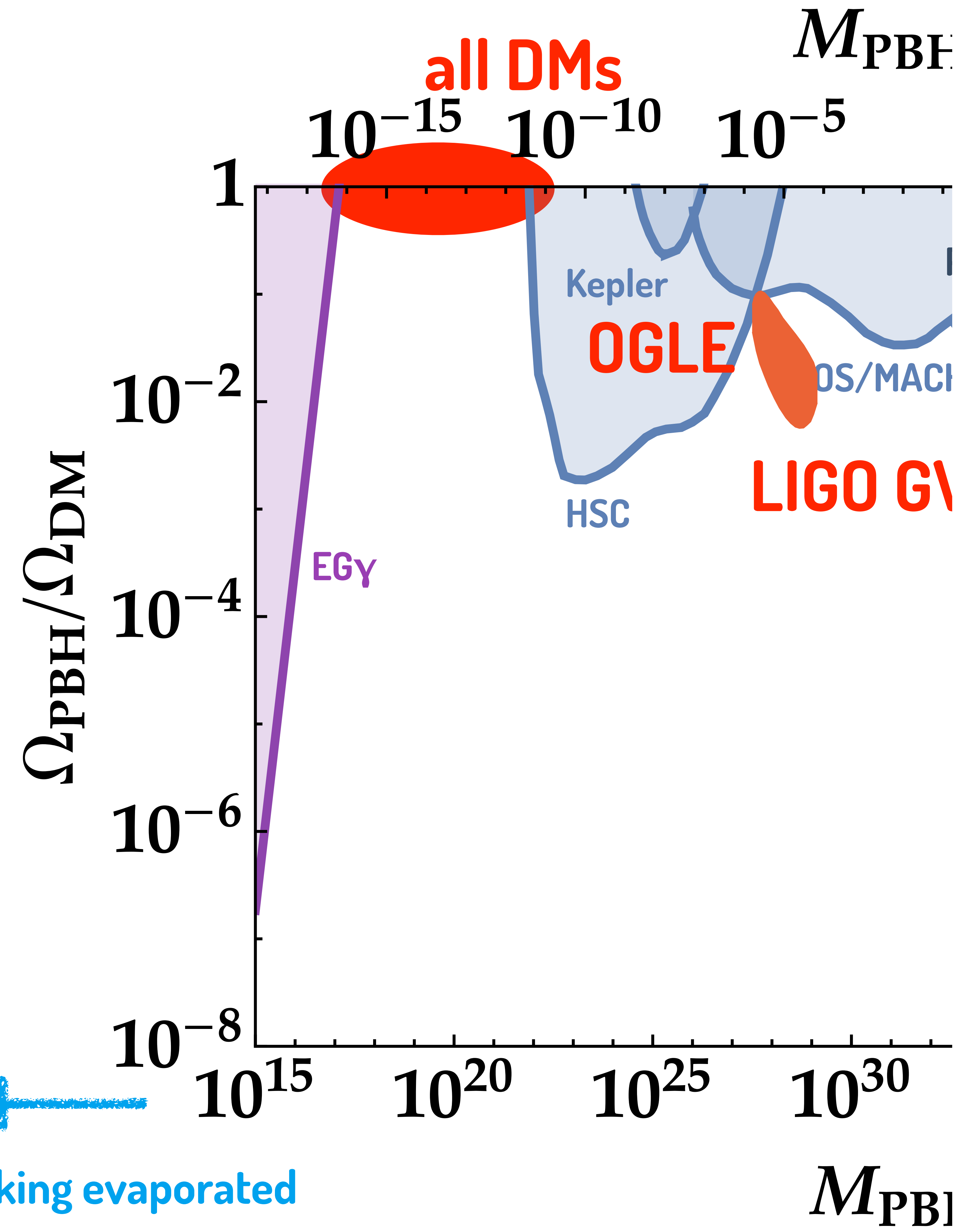


5-yr Optical Gravitational Lensing Experiment (OGLE)

Niikura+ 2019



Motivations of PBH



Hawking evaporated

PHYSICAL REVIEW LETTERS **125,** 051103 (2020)

Editors' Suggestion Featured in Physics

What If Planet 9 Is a Primordial Black Hole?

Jakub Scholtz[1] and James Unwin[2]

[1]*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom*
[2]*Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607, USA and Department of Physics, University of California, Berkeley and Theoretical Physics Group, LBNL and Mathematics Sciences Research Institute, Berkeley, California 94720, USA*

Introduction.—As of this year, two gravitational anomalies of similar mass but very different origins remain to be explained. First, there is a growing body of observational anomalies connected to the orbits of trans-Neptunian objects (TNOs) [1–3]. These observations have been taken as evidence of a new ninth planet in our Solar System, called Planet 9 (P9), with mass $M_9 \sim 5$–$15 M_\oplus$ and orbiting around the Sun at a distance of 300–1000 AU [4]. Second, gravitational anomalies have also been recently observed by the Optical Gravitational Lensing Experiment (OGLE). OGLE reported an excess of six ultrashort microlensing events with crossing times of 0.1–0.3 days [5]. The lensing objects are located toward the galactic bulge, roughly 8 kpc away. These events correspond to lensing by objects of mass $M \sim 0.5 M_\oplus - 20 M_\oplus$ [6] and could be interpreted as an unexpected population of free floating planets (FFPs) or as primordial black holes (PBHs).

Supplementary Material

A. Size of the PBH

The Schwarzschild radius of a black hole is given by

$$r_{\rm BH} = \frac{2GM_{\rm BH}}{c^2} \simeq 4.5{\rm cm}\left(\frac{M_{\rm BH}}{5M_\oplus}\right) . \qquad (15)$$

In Figure 1 we provide an exact scale image of a $5M_\oplus$ PBH. The associated DM halo however extends to the stripping radius $r_{t,\odot} \sim 8$AU, this would imply a DM halo which extends roughly the distance from Earth to Saturn (both in real life and relative to the image).

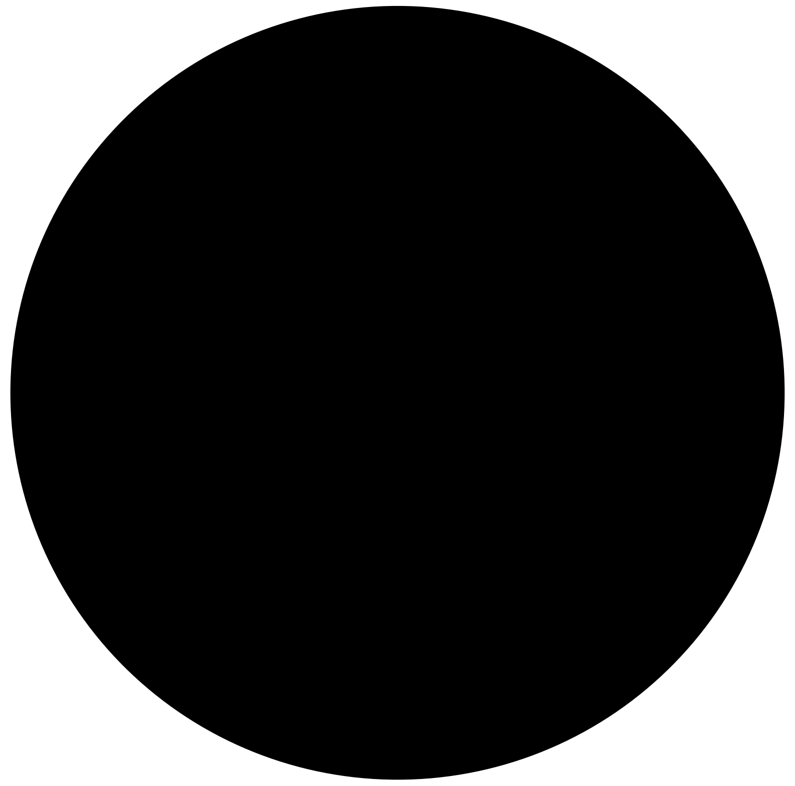
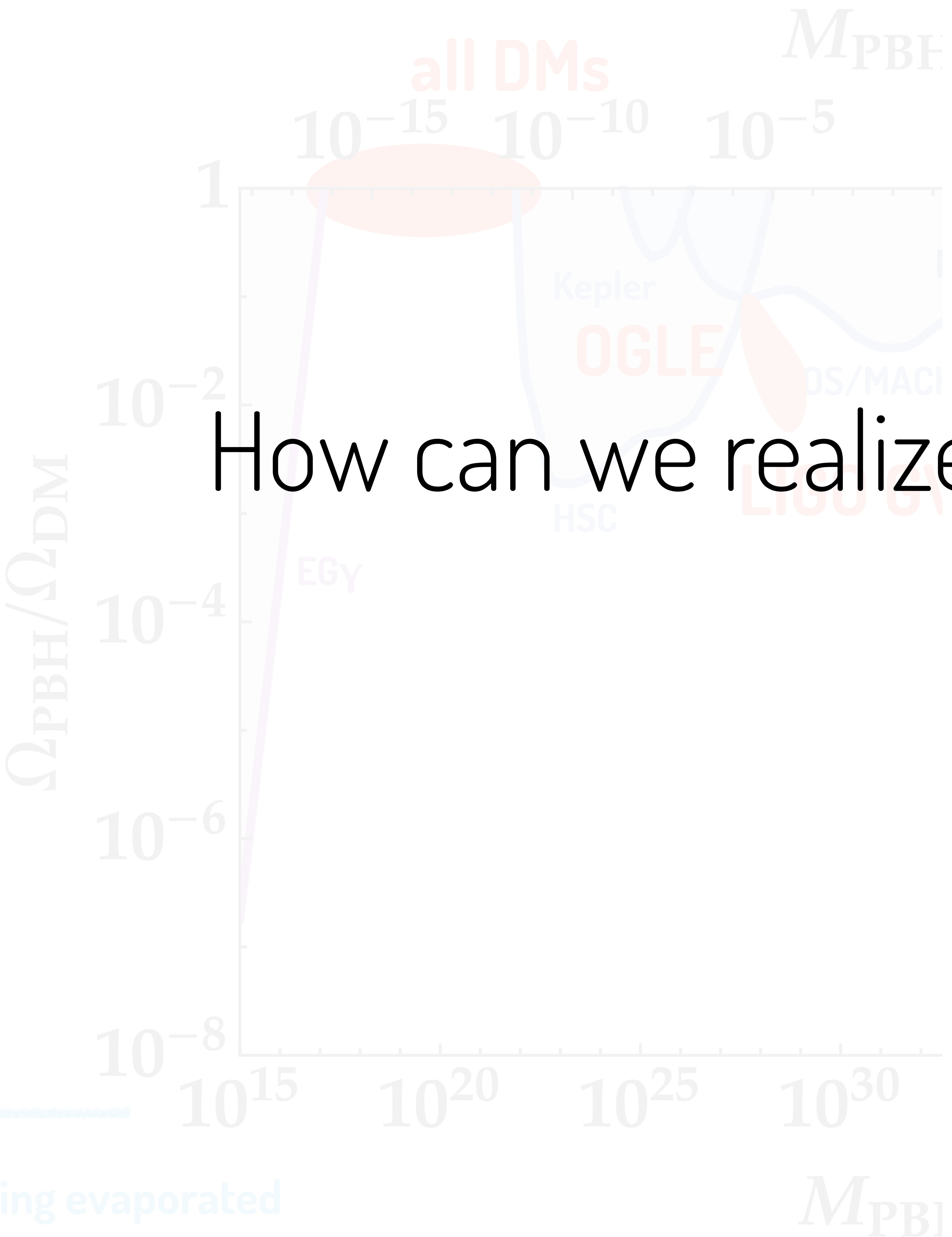
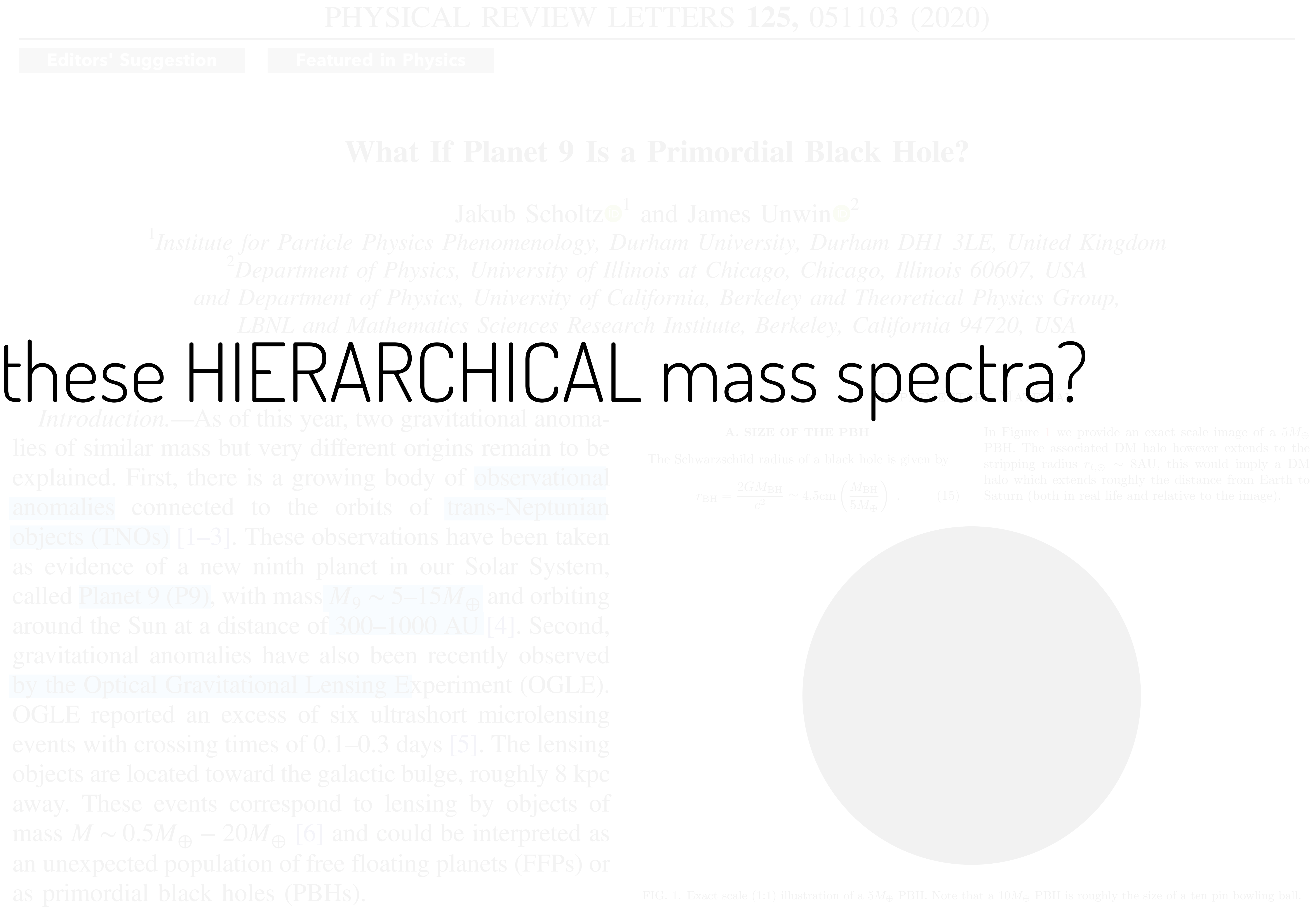


FIG. 1. Exact scale (1:1) illustration of a $5M_\oplus$ PBH. Note that a $10M_\oplus$ PBH is roughly the size of a ten pin bowling ball.

Motivations of PBH





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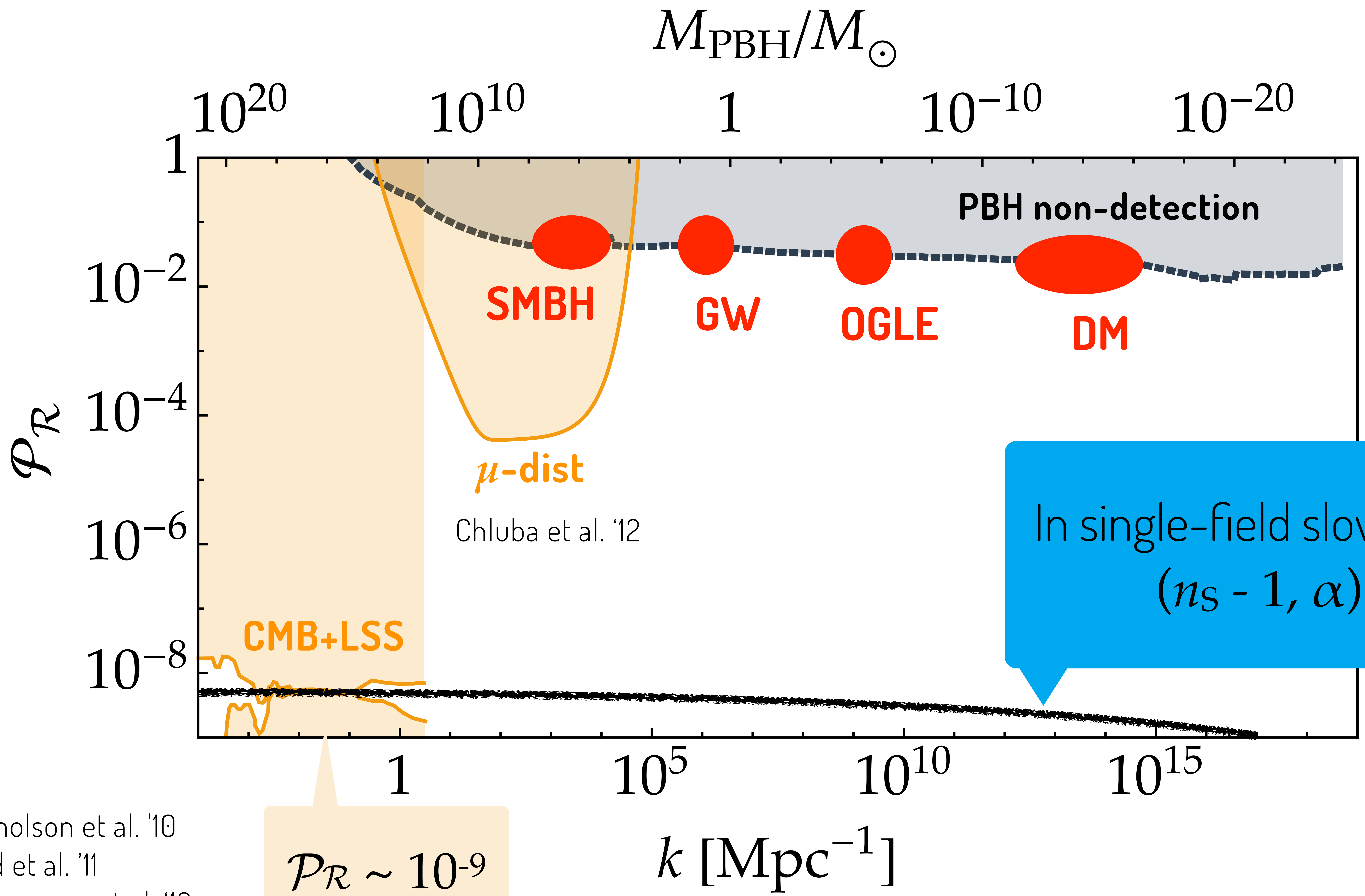
A. SIZE OF THE PBH

How can we realize these HIERARCHICAL mass spectra?

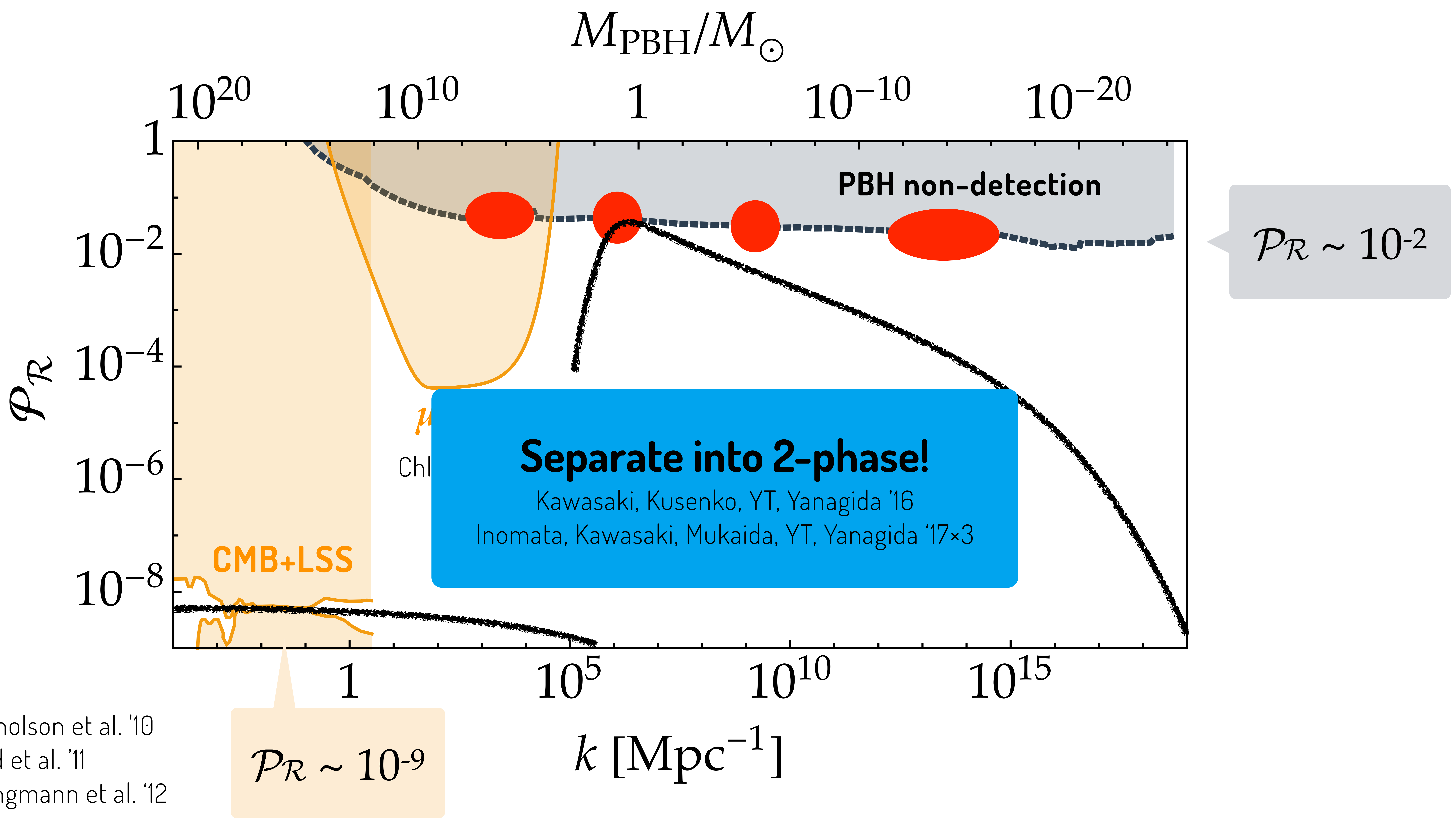


$\mathcal{P}_\mathcal{R} \sim 10^{-2}$

In single-field slow-roll inflation,
$(n_S - 1, \alpha) \sim \mathcal{O}(\varepsilon)$

Nicholson et al. '10
Bird et al. '11
Bringmann et al. '12

$\mathcal{P}_\mathcal{R} \sim 10^{-9}$



Separate into 2-phase!

Kawasaki, Kusenko, YT, Yanagida '16

Inomata, Kawasaki, Mukaida, YT, Yanagida '17×3

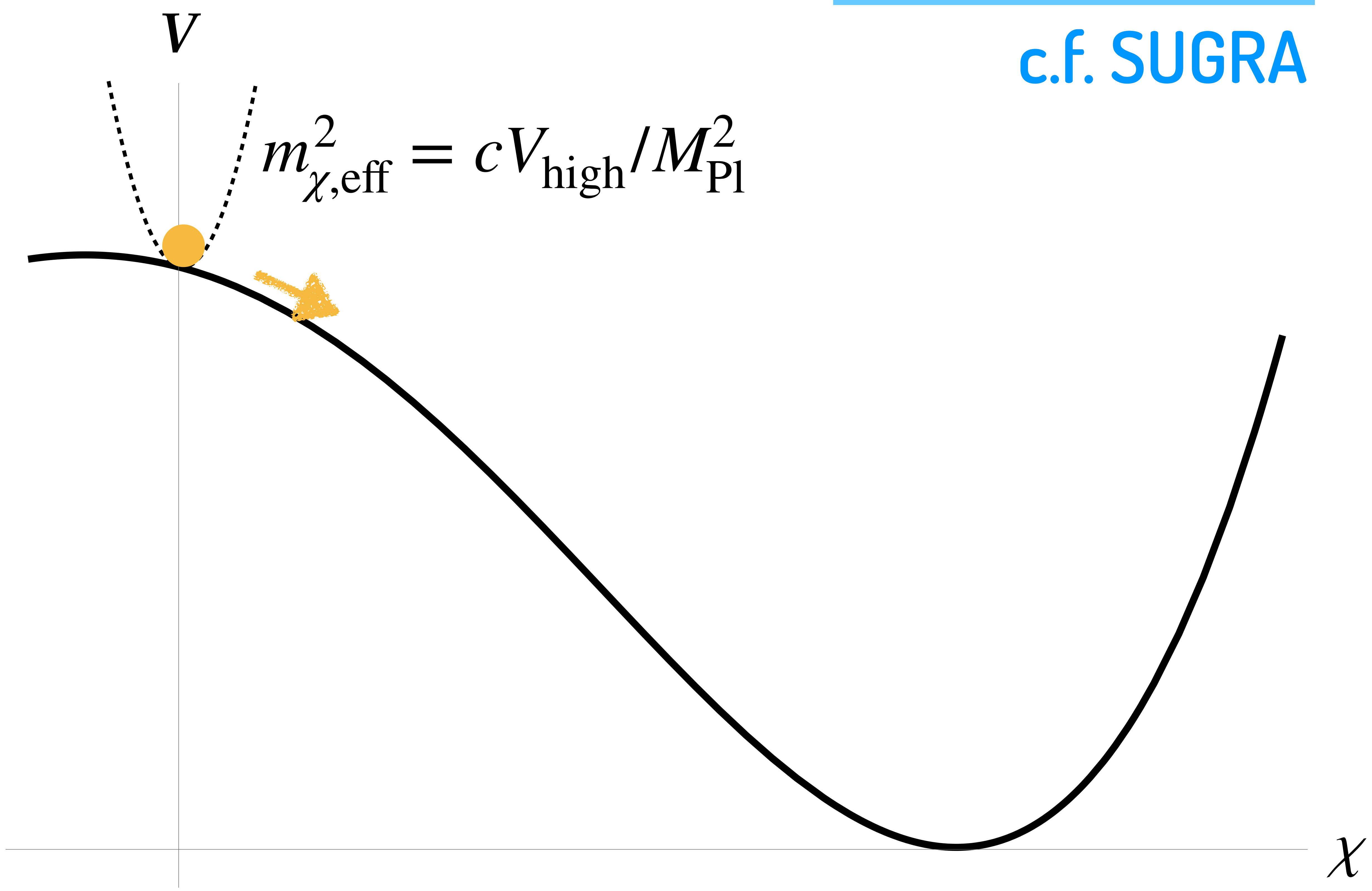
Nicholson et al. '10
Bird et al. '11
Bringmann et al. '12

Double Inflation

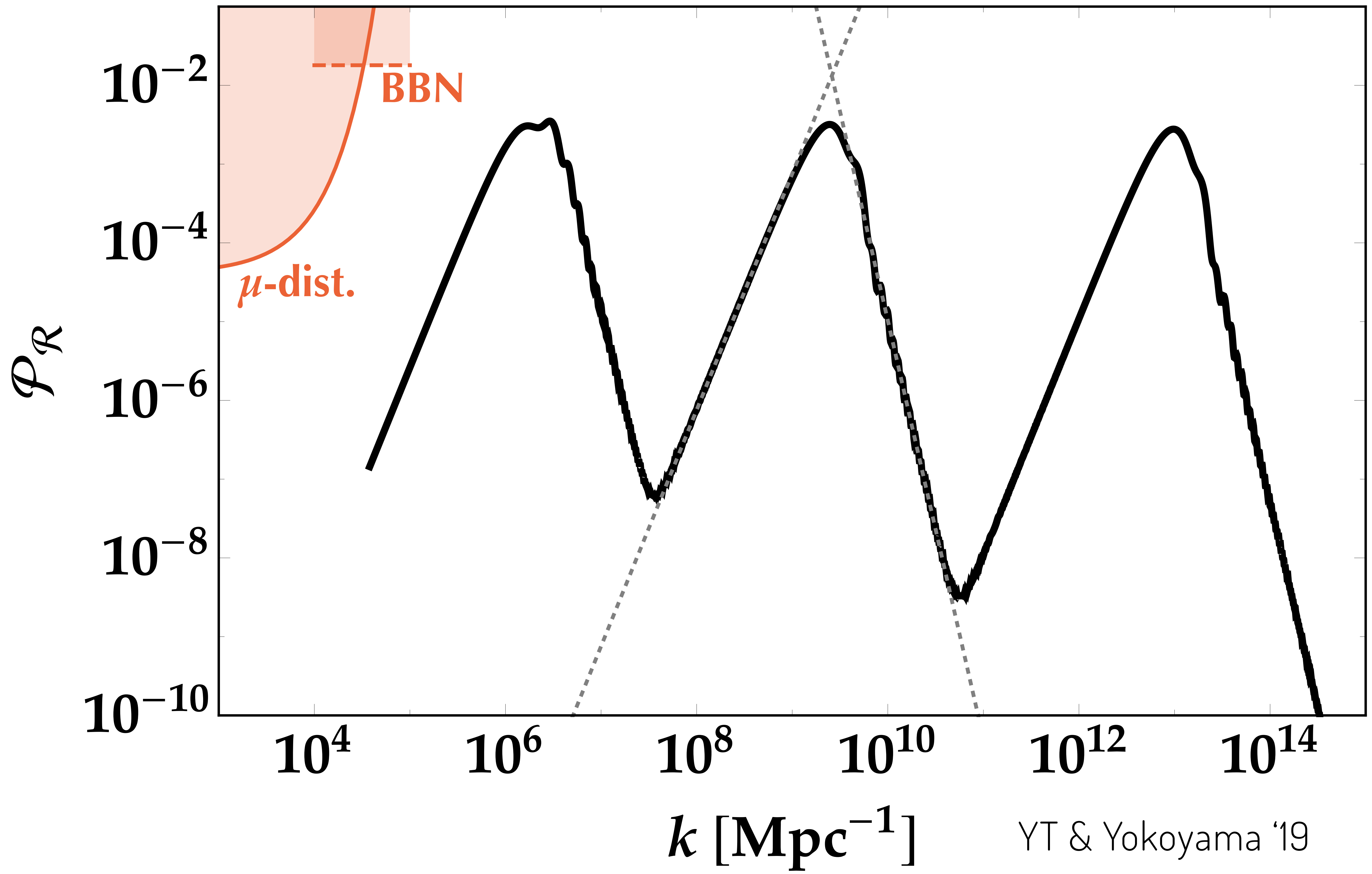
Kumekawa, Moroi, Yanagida '94
Izawa, Kawasaki, Yanagida '97
Kawasaki, Sugiyama, Yanagida '98

$$V(\phi,\chi) = \underset{\gg}{V_{\rm high}(\phi) + V_{\rm hill}(\chi)} + \boxed{\frac{c}{2}V_{\rm high}(\phi)\frac{\chi^2}{M_{\rm Pl}}}$$

c.f. SUGRA



Extreme case



YT & Yokoyama '19

- 4 hilltop inflation

$$V_{\text{hill}} = \sum_{i=1}^{4} V_{\text{hill},i}$$

$$+$$

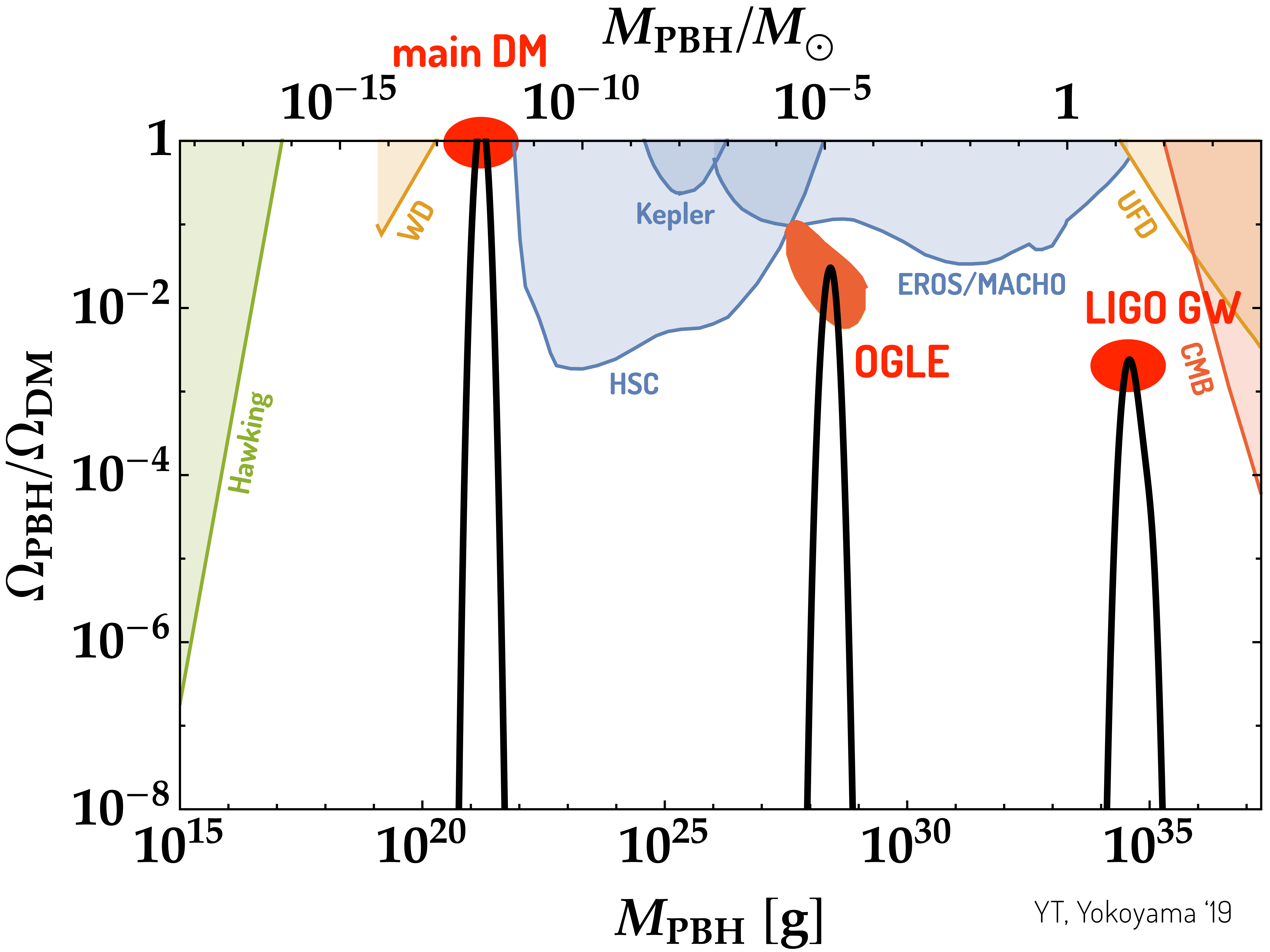
- Stabilizer

$$V_{\text{stab}} = \sum_{i \neq j} \frac{c_{ij}}{2} V_{\text{hill},i} \frac{\phi_j^2}{M_{\text{Pl}}^2}$$

not long inflation

⇕

strong scale dependence



YT, Yokoyama '19

Implication to String Theory?

dS swampland conjecture   Ooguri & Vafa+ '18

"dS vacua will be unstable in UV-complete theories"

$$\epsilon_V = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \gtrsim \mathcal{O}(1) \quad \text{or} \quad \eta_V = M_{\rm Pl}^2 \frac{V''}{V} \lesssim -\mathcal{O}(1)$$

each inf. phase CANNOT continue long ➡ enough inf. in total by multistage

* CMB scale?   Kogai & YT '20

❌ inflaton   ❌ curvaton   △ modulated reheating

Stochastic Inflation

Ptb. approach

coordinate so that ptb. only in Metric!

auxiliary auxiliary

$$\mathrm{d}^2 s = -\underbrace{\hat{\mathcal{N}}^2(t,\mathbf{x})}_{\text{auxiliary}}\mathrm{d}^2 t + a^2(t)\mathrm{e}^{2\hat{\zeta}(t,\mathbf{x})}(\underbrace{\hat{\beta}^i(t,\mathbf{x})}_{\text{auxiliary}}\mathrm{d}t + \mathrm{d}x^i)^2, \quad \phi(t,\mathbf{x}) = \phi_0(t)$$

$$\downarrow$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}M_{\mathrm{Pl}}R - \frac{1}{2}(\partial_\mu\phi)^2 - V(\phi)\right] = S^{(0)} + S^{(2)}[\zeta] + S^{(3)}[\zeta] + \cdots$$

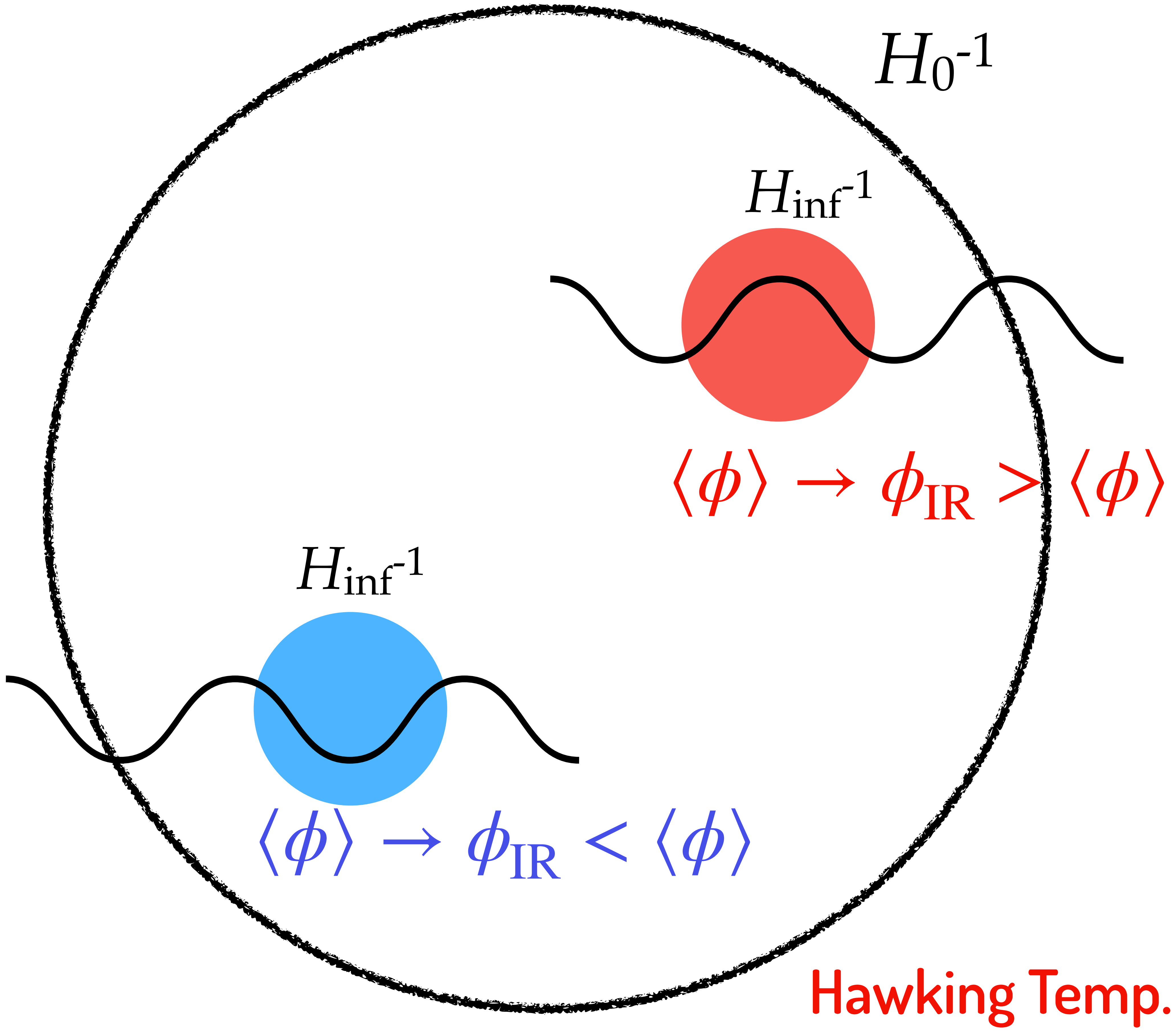
$$\downarrow$$

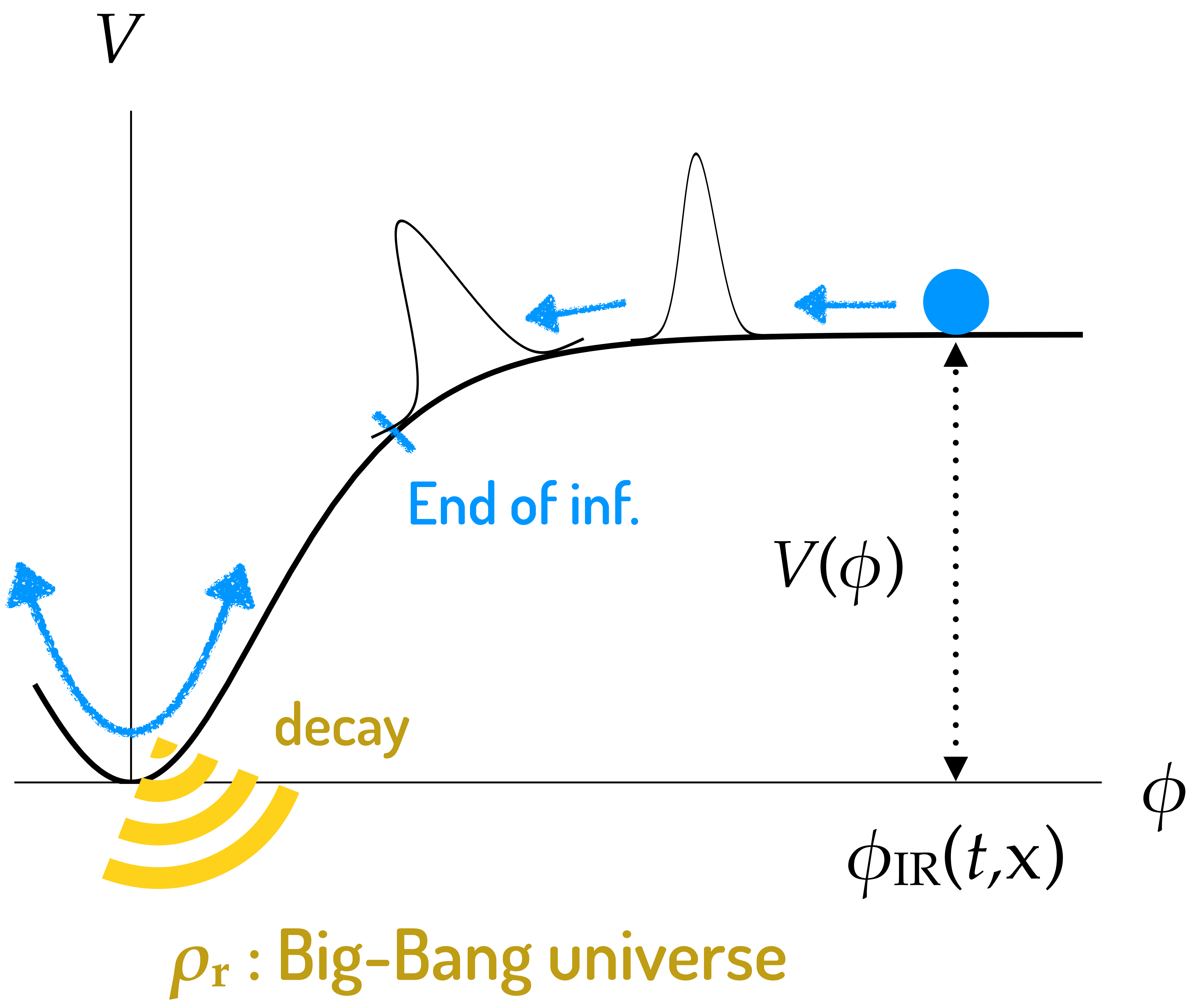
$$\langle\zeta(t,\mathbf{x})\zeta(t,\mathbf{y})\rangle = \langle 0_{\mathrm{in}}\,|\,\zeta(t,\mathbf{x})\zeta(t,\mathbf{y})\,|\,0_{\mathrm{in}}\rangle$$

$$= \left\langle\left[\bar{T}\exp\left(i\int^t H_I\mathrm{d}t'\right)\right]\zeta^I(t,\mathbf{x})\zeta^I(t,\mathbf{y})\left[T\exp\left(-i\int^t H_I\mathrm{d}t'\right)\right]\right\rangle$$

Stochastic Form.

Starobinsky '86





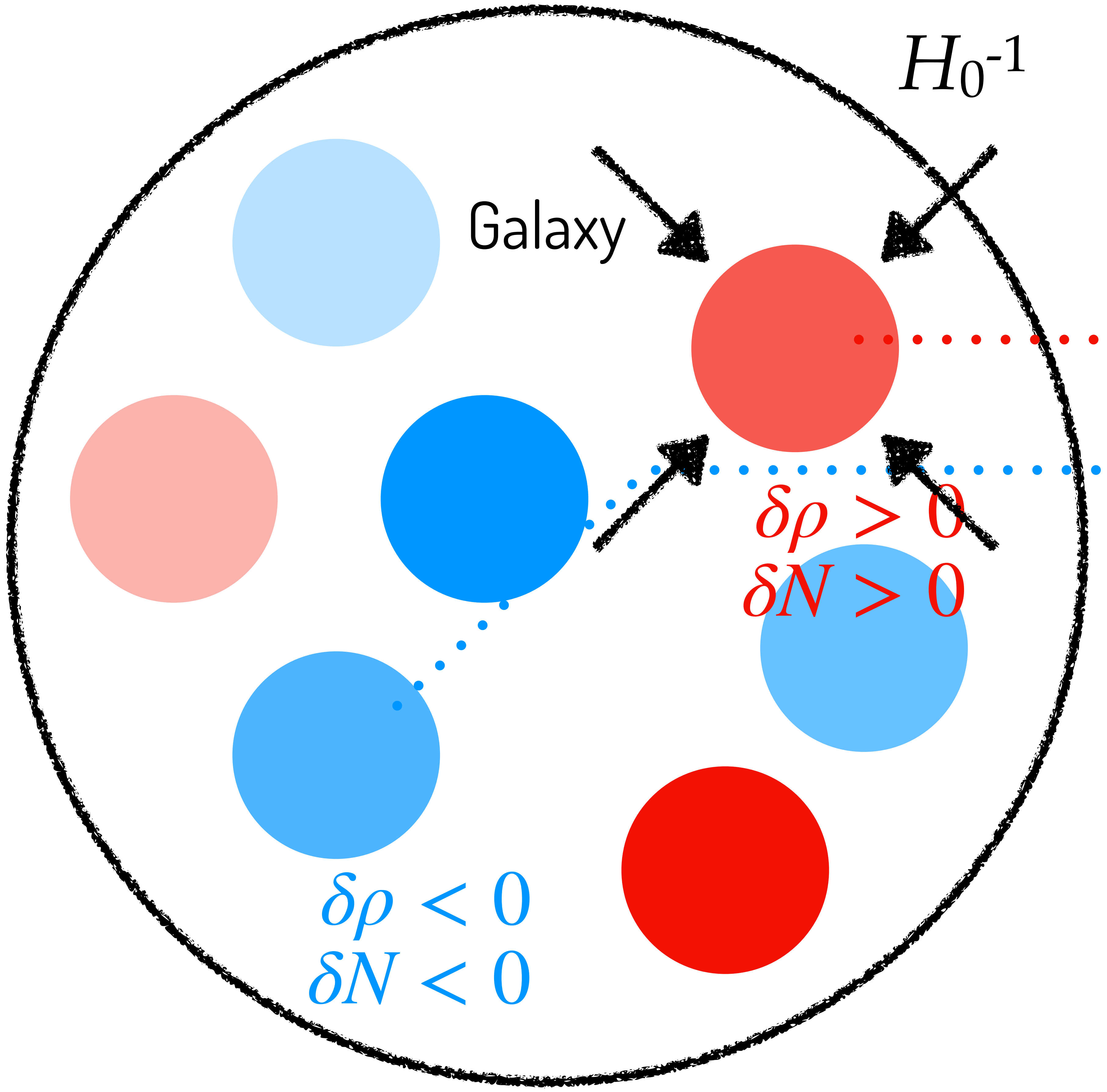
Hawking Temp.

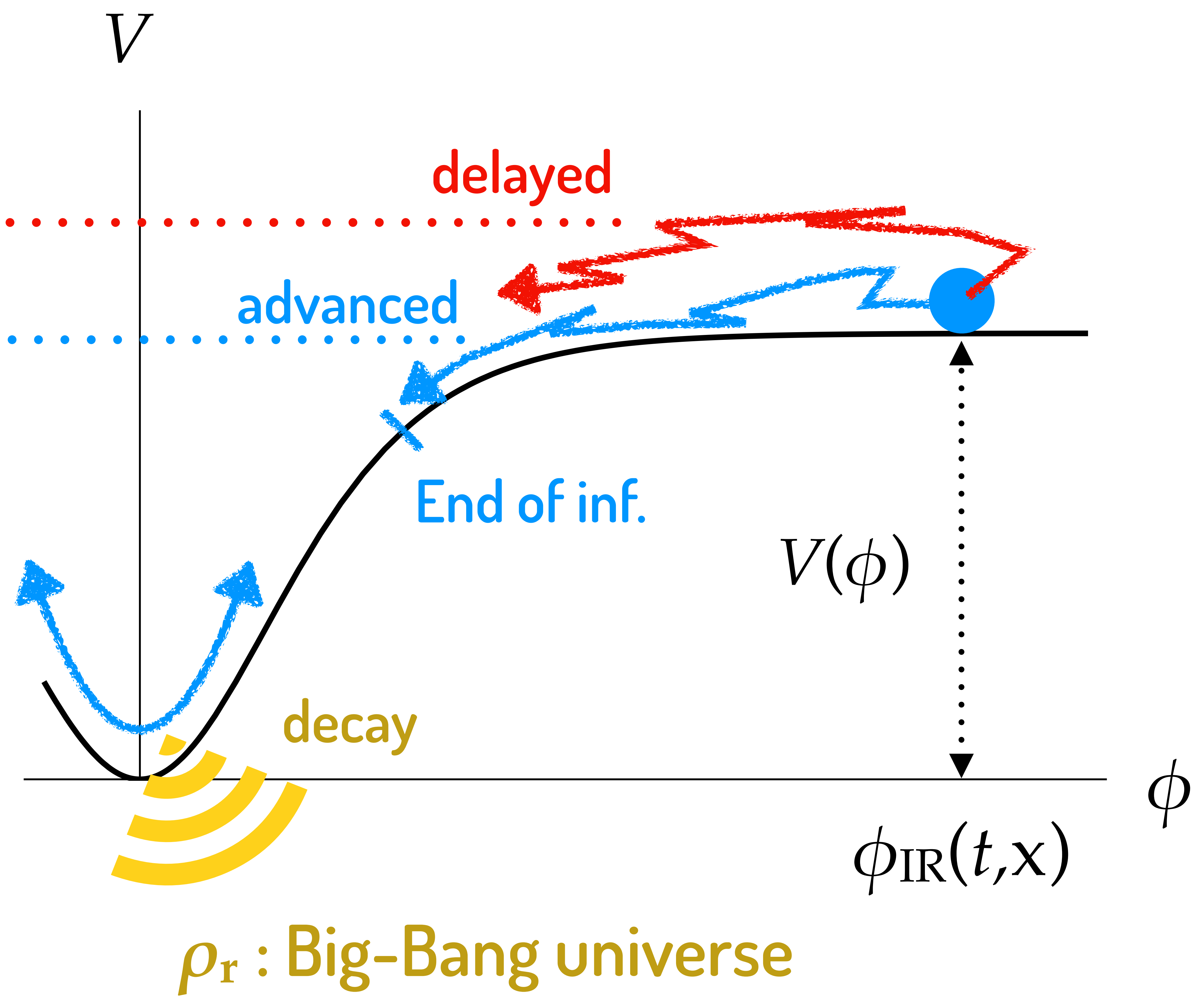
❖ Stochastic EoM: $$\frac{\mathrm{d}\phi_{\rm IR}}{\mathrm{d}N} = -\frac{V'}{3H^2} + \boxed{\frac{H}{2\pi}}\,\boxed{\xi}$$

Gaussian Rand.

(conserved) δN Form.

Starobinsky '85



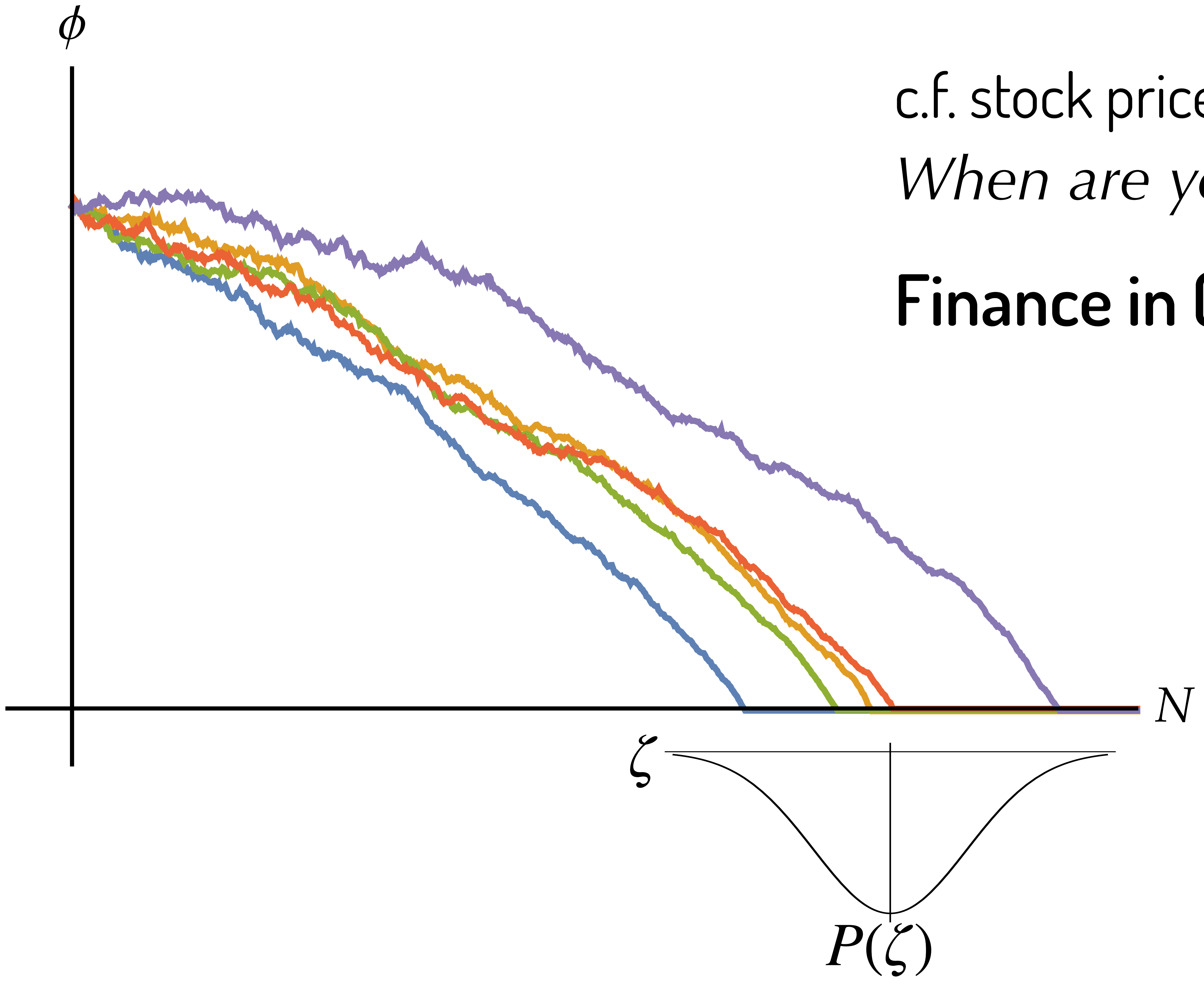


$$\boxed{\zeta = \delta N, \quad N = \int^t H \mathrm{d}t'}$$

Lyth, Malik, Sasaki '05

Stochastic δN

Fujita, Kawasaki, YT, Takesako '13
Vennin & Starobinsky '15

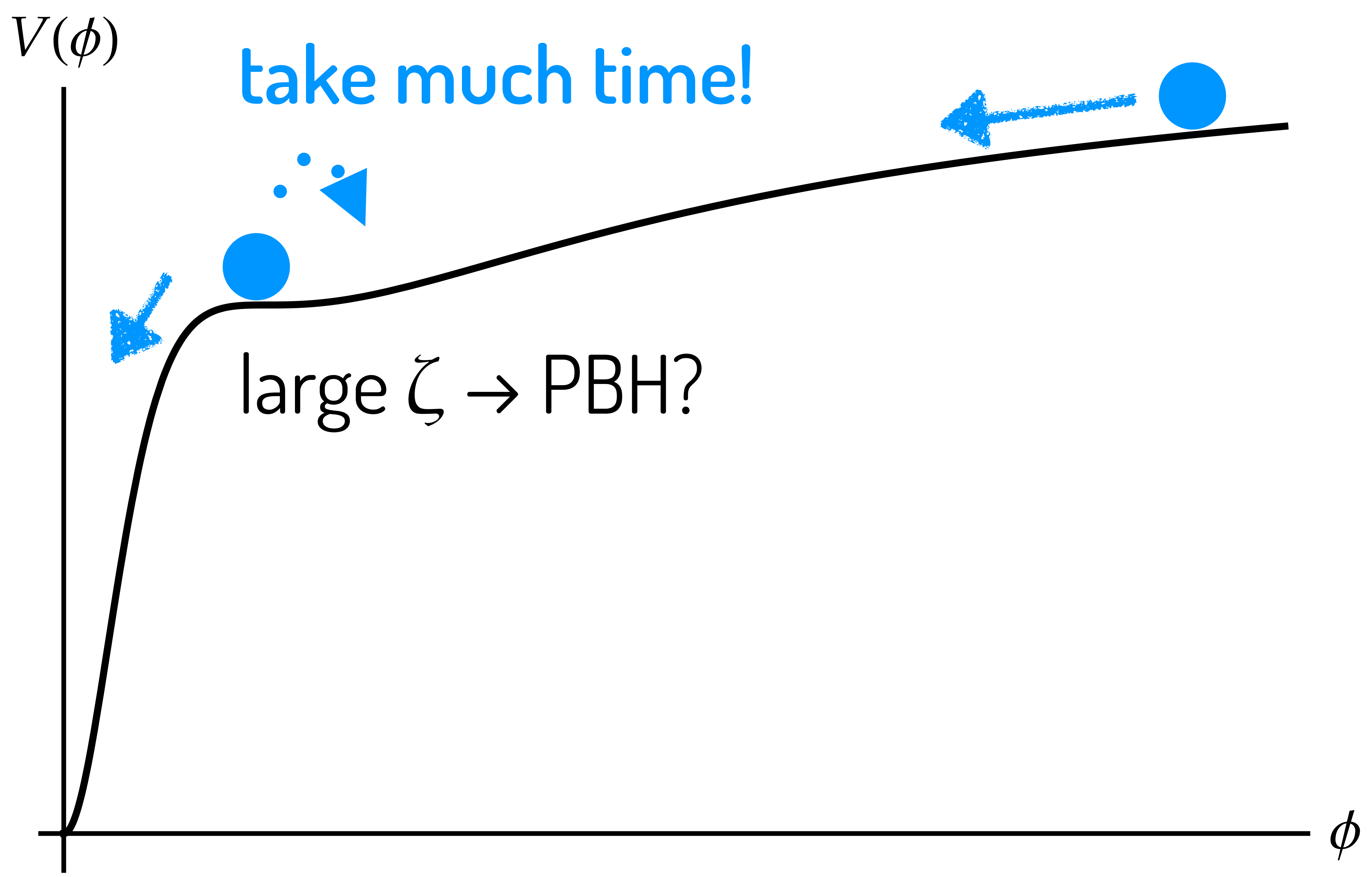


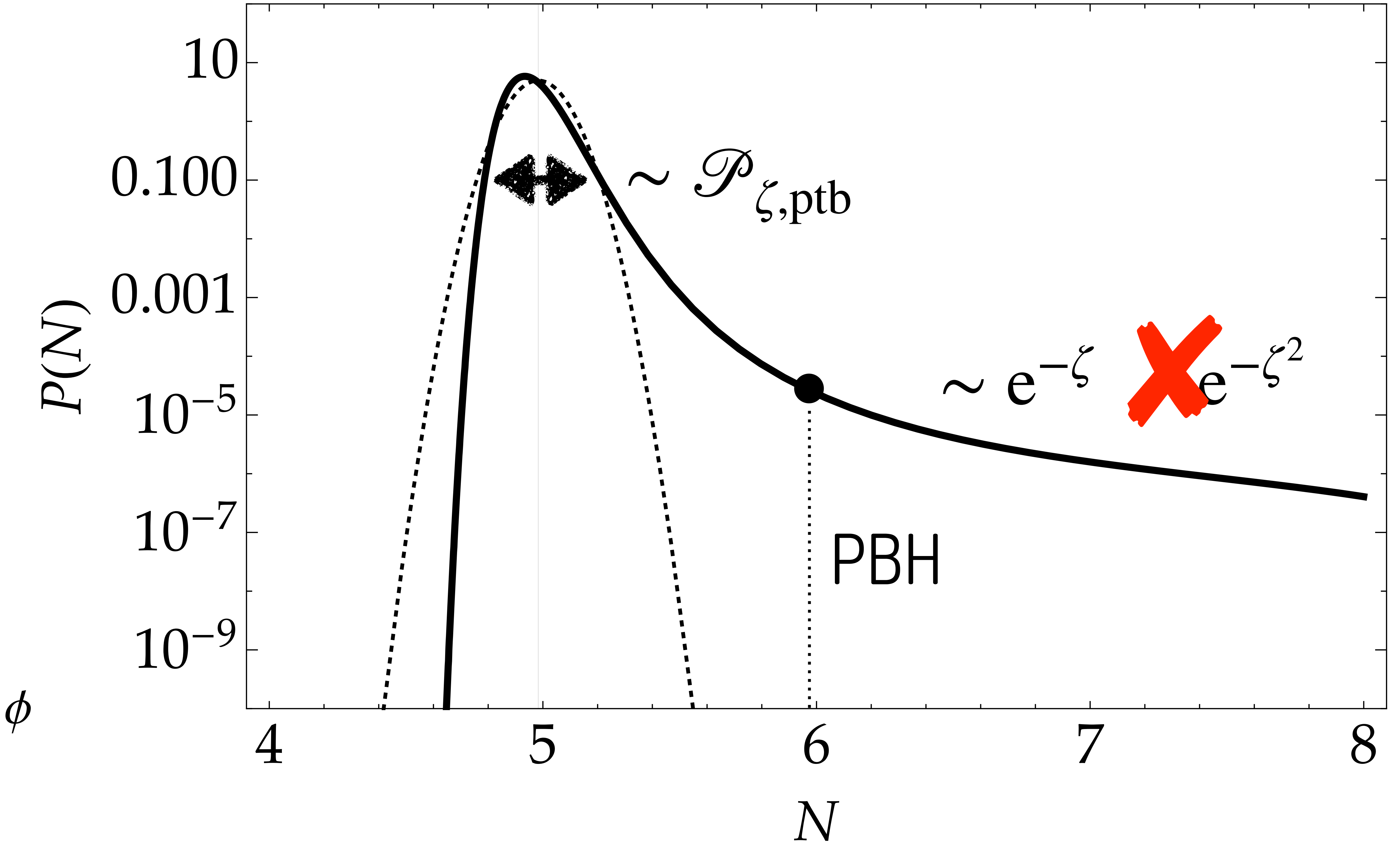
c.f. stock price in finance

When are you expected to achieve the goal?

Finance in (Cosmic) Inflation!

Flat Inflection





c.f. Ezquiaga, Garcia-Bellido, Vennin '20

Conclusions

- Self-introduction
- Gravity is metric-affine?
- Multistage inflation?
- Stochastic approach to inflationary ptb.

Appendices

Higgs inf.

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}(M_{\mathrm{Pl}}^2 + \xi\phi^2)R - \frac{1}{2}(\partial_\mu\phi)^2 - \frac{\lambda}{4}\phi^4\right]$$

- Metric

$$V(\chi) \sim \frac{\lambda M_{\mathrm{Pl}}^4}{\xi^2}\left(1 - \exp\left(-2\sqrt{\frac{\xi}{1+6\xi}}\frac{\chi}{M_{\mathrm{Pl}}}\right)\right)$$

$\xi \to \infty$: R^2 inflation

- Metric-Affine

$$V(\chi) \sim \frac{\lambda M_{\mathrm{Pl}}^4}{\xi^2}\left(1 - 8\exp\left(-2\sqrt{\xi}\frac{\chi}{M_{\mathrm{Pl}}}\right)\right)$$

α attractor

Unitarity?

$$S \supset \frac{\xi^2}{M_{\mathrm{Pl}}^2}\phi^2\Box\phi^2 \to \Lambda_{\mathrm{cut}} \sim \frac{M_{\mathrm{Pl}}}{\xi} \ll \Lambda_{\mathrm{inf}} \sim \frac{M_{\mathrm{Pl}}}{\sqrt{\xi}}$$

ξ^2R^2 will inevitably appear

& scalaron $m_\sigma \sim M_{\mathrm{Pl}}/\xi$ regularizes theory Ema+ '20

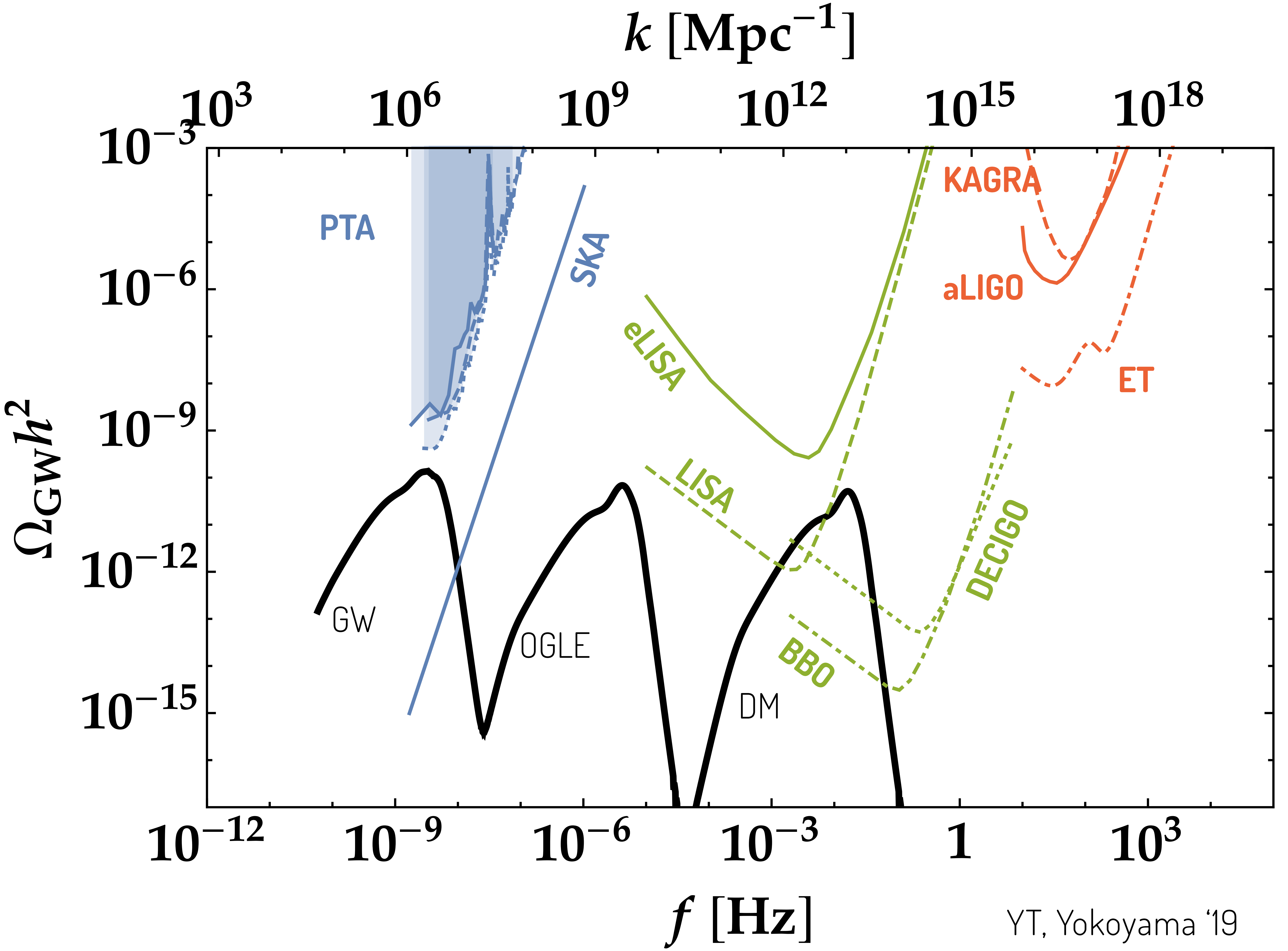
$$\Lambda_{\mathrm{cut}} \sim \Lambda_{\mathrm{inf}} \sim \frac{M_{\mathrm{Pl}}}{\sqrt{\xi}}$$

Testability

large scalar PTB.

2ndary tensor PTB.
(stochastic GWs)

$$\Omega_{\mathrm{GW}} h^2 \sim 10^{-9} \left(\frac{\mathcal{P}_{\mathcal{R}}}{10^{-2}} \right)^2$$



YT, Yokoyama '19