Primordial Black Holes

a mini review

Vincent Vennin

Action Dark Energy - National colloquium 2020

14 October 2020

Primordial black holes

Carr, Hawking 1974

Form from the collapse of large primordial fluctuations as they re-enter the Hubble radius

Roles in cosmology

- Could constitute part or all of dark matter Chapline 1975

  $M = 10^{16} - 10^{17}\text{g},\ 10^{20} - 10^{24}\text{g},\ 10 - 10^{3}M_{\odot}$

- Could provide seeds for supermassive black holes in galactic nuclei

  $M > 10^{3}M_{\odot}$ Carr, Rees 1984
  Bean, Magueijo 2002

- Could provide seeds for cosmological structures

  $M > 10^{3}M_{\odot}$ Mészáros 1975
  Afshordi, McDonald, Spergel, 2003

- Could provide progenitors for the LIGO/VIRGO events

  $M = 10 - 100\ M_{\odot}$

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Properties and astrophysical implications of the $150\,M_\odot$ binary black hole merger GW190521

LIGO Scientific Collaboration and Virgo Collaboration

ABSTRACT

The gravitational-wave signal GW190521 is consistent with a binary black hole merger source at redshift 0.8 with unusually high component masses, $85^{+21}_{-14}\,M_\odot$ and $66^{+17}_{-18}\,M_\odot$, compared to previously reported events, and shows mild evidence for spin-induced orbital precession. The primary falls in the mass gap predicted by (pulsational) pair-instability supernova theory, in the approximate range $65-120\,M_\odot$. The probability that at least one of the black holes in GW190521 is in that range is 99.0%. The final mass of the merger ($142^{+28}_{-16}\,M_\odot$) classifies it as an intermediate-mass black hole. Under the assumption of a quasi-circular binary black hole coalescence, we detail the physical properties of GW190521's source binary and its post-merger remnant, including component masses and spin vectors. Three different waveform models, as well as direct comparison to numerical solutions of general relativity, yield consistent estimates of these properties. Tests of strong-field general relativity targeting the merger-ringdown stages of the coalescence indicate consistency of the observed signal with theoretical predictions. We estimate the merger rate of similar systems to be $0.13^{+0.30}_{-0.11}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. We discuss the astrophysical implications of GW190521 for stellar collapse, and for the possible formation of black holes in the pair-instability mass gap through various channels: via (multiple) stellar coalescences, or via hierarchical mergers of lower-mass black holes in star clusters or in active galactic nuclei. We find it to be unlikely that GW190521 is a strongly lensed signal of a lower-mass black hole binary merger. We also discuss more exotic possible sources for GW190521, including a highly eccentric black hole binary, or a primordial black hole binary.

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Properties and astrophysical implications of the $150\,M_\odot$ binary black hole merger GW190521

LIGO ...

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6.3. *Primordial BH Mergers*

Primordial BHs (PBHs; Carr & Hawking 1974; Khlopov 2010) are thought to be formed from collapse of dark matter overdensities in the very early Universe (at redshifts $z > 20$, i.e. before the formation of the first stars), and may account for a nontrivial fraction of the density of the Universe (Carr et al. 2016; Clesse & García-Bellido 2017). Since the binary components of GW190521 are unlikely both to have formed directly from stellar collapse, it is possible that they may be of PBH origin (Bird et al. 2016); however, theoretical expectations of the mass distribution and merger rate of PBH binaries have large uncertainties (e.g., Byrnes et al. 2018), so we do not attempt to quantify such scenarios. Some theories of PBH formation predict predominantly small component spins $\chi \ll 1$ (Chiba &

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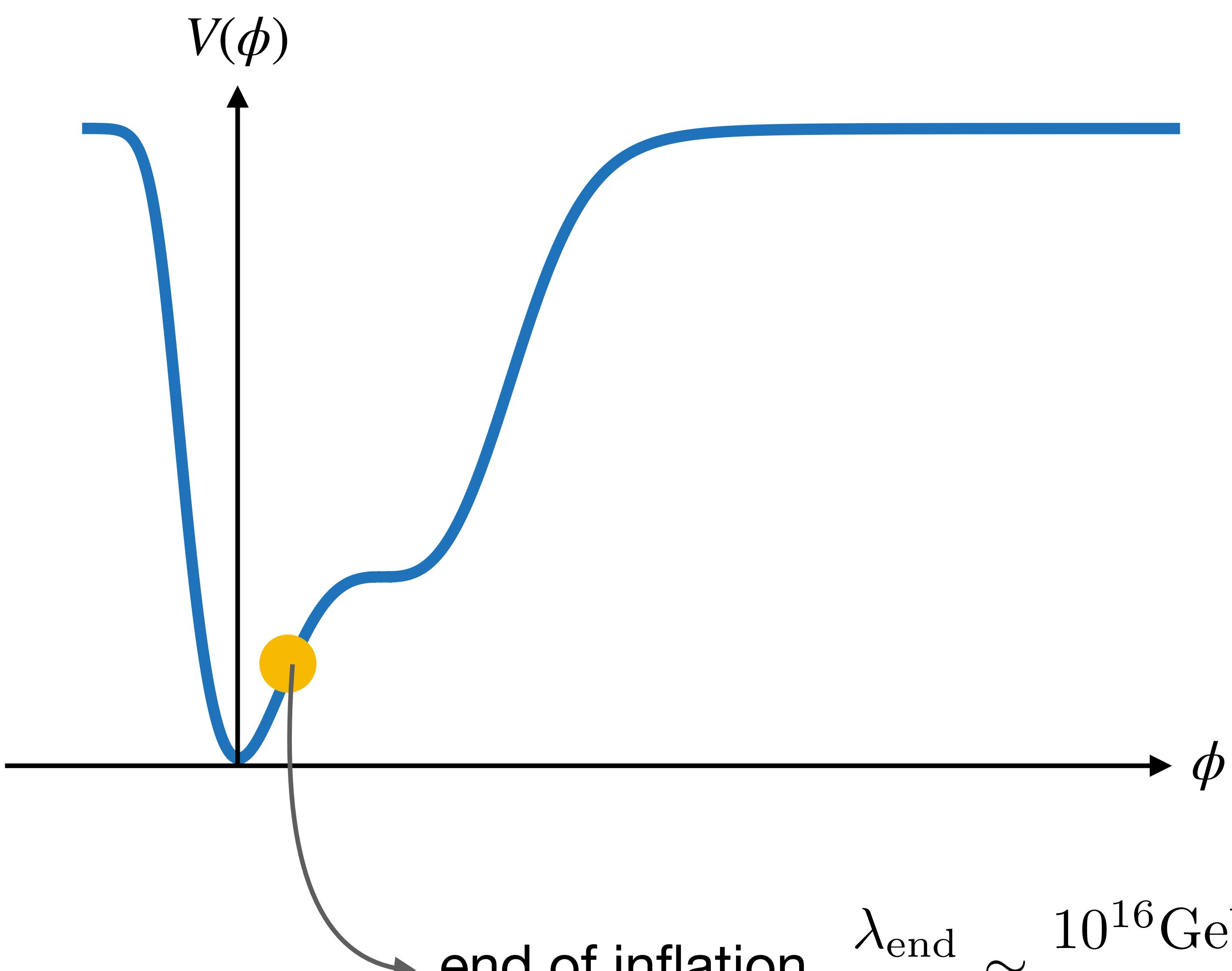
For hints in favour of PBH existence, see *e.g.* García-Bellido and Clesse (1711.10458)

- How can those large primordial fluctuations can be seeded?
- Under what conditions do PBHs form? (How to compute their abundance?)
- How do they evolve?
- How can they be constrained?

How can large fluctuations be seeded?



end of inflation $\frac{\lambda_{\rm end}}{\rm m} \simeq \frac{10^{16}{\rm GeV}}{\rho_{\rm end}^{1/4}} R_{\rm rad}^{-1}$

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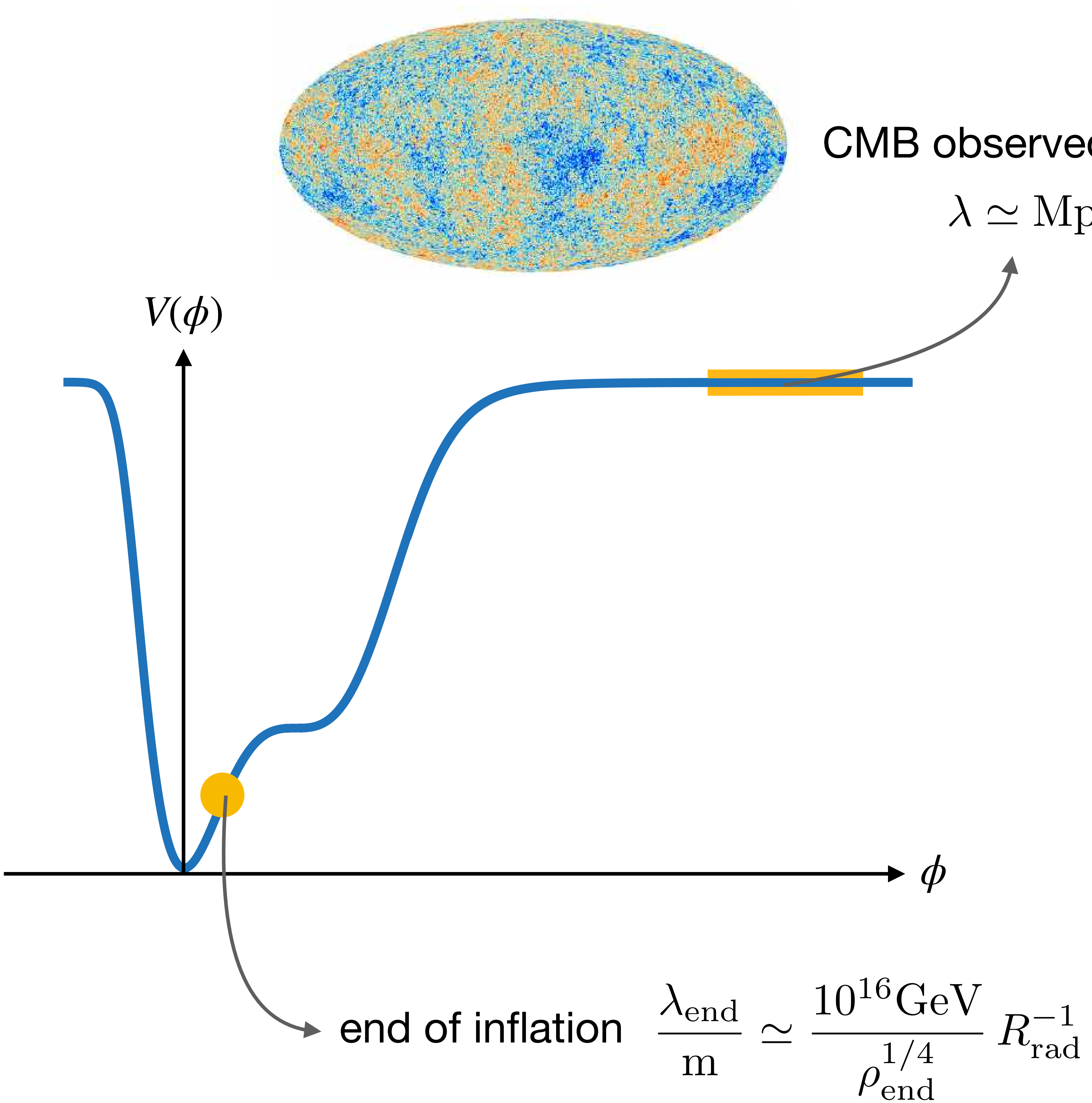

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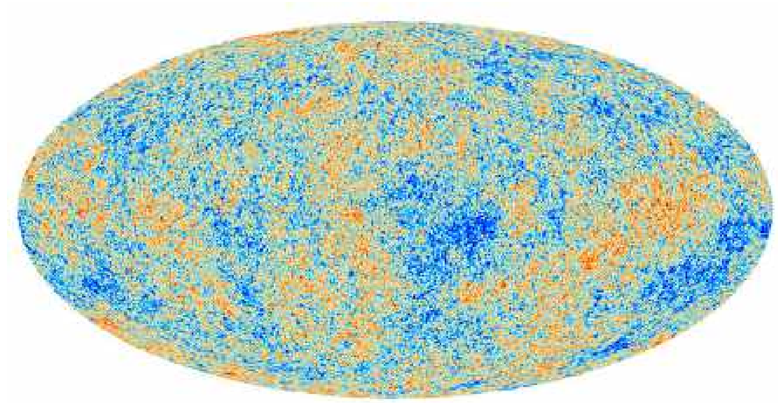
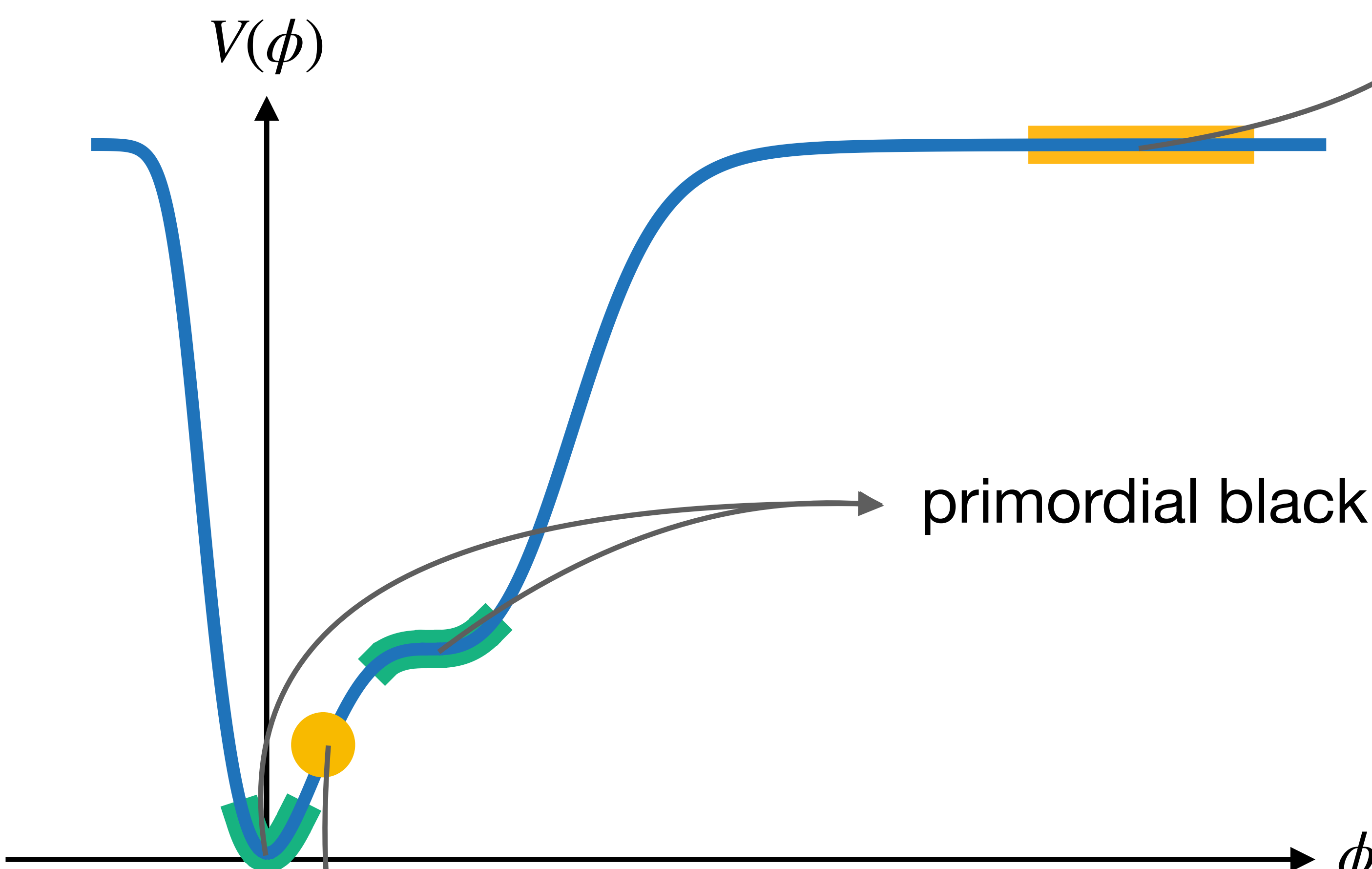
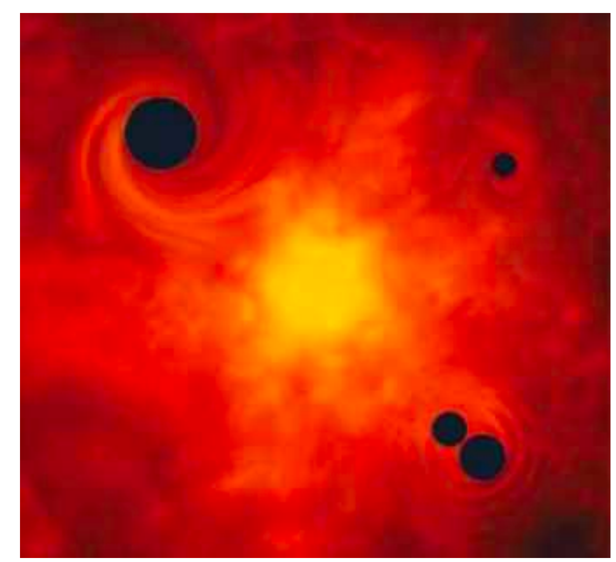


CMB observed scales

$\lambda \simeq \mathrm{Mpc}$





primordial black holes?

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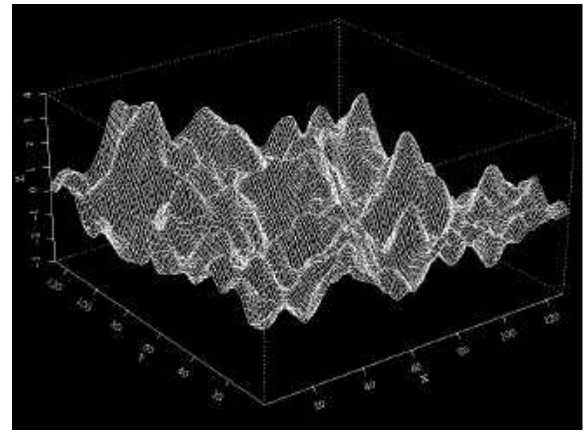
When do PBHs form?



$$(aH)^3 \int_{a|\vec{y}-\vec{x}|<H^{-1}} \delta(\vec{y}) < \delta_\mathrm{c}$$

Inferred from numerical simulations

e.g. Musco and Miller 2012

Inferred from analytical arguments

$$\delta_\mathrm{c} = \frac{3w+3}{3w+5}\sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right)$$

Harada, Yoo, Nakama, Koga
2013 & 2015

- Press-Schecter
- Excursion set
- Peak theory

Further refinements:

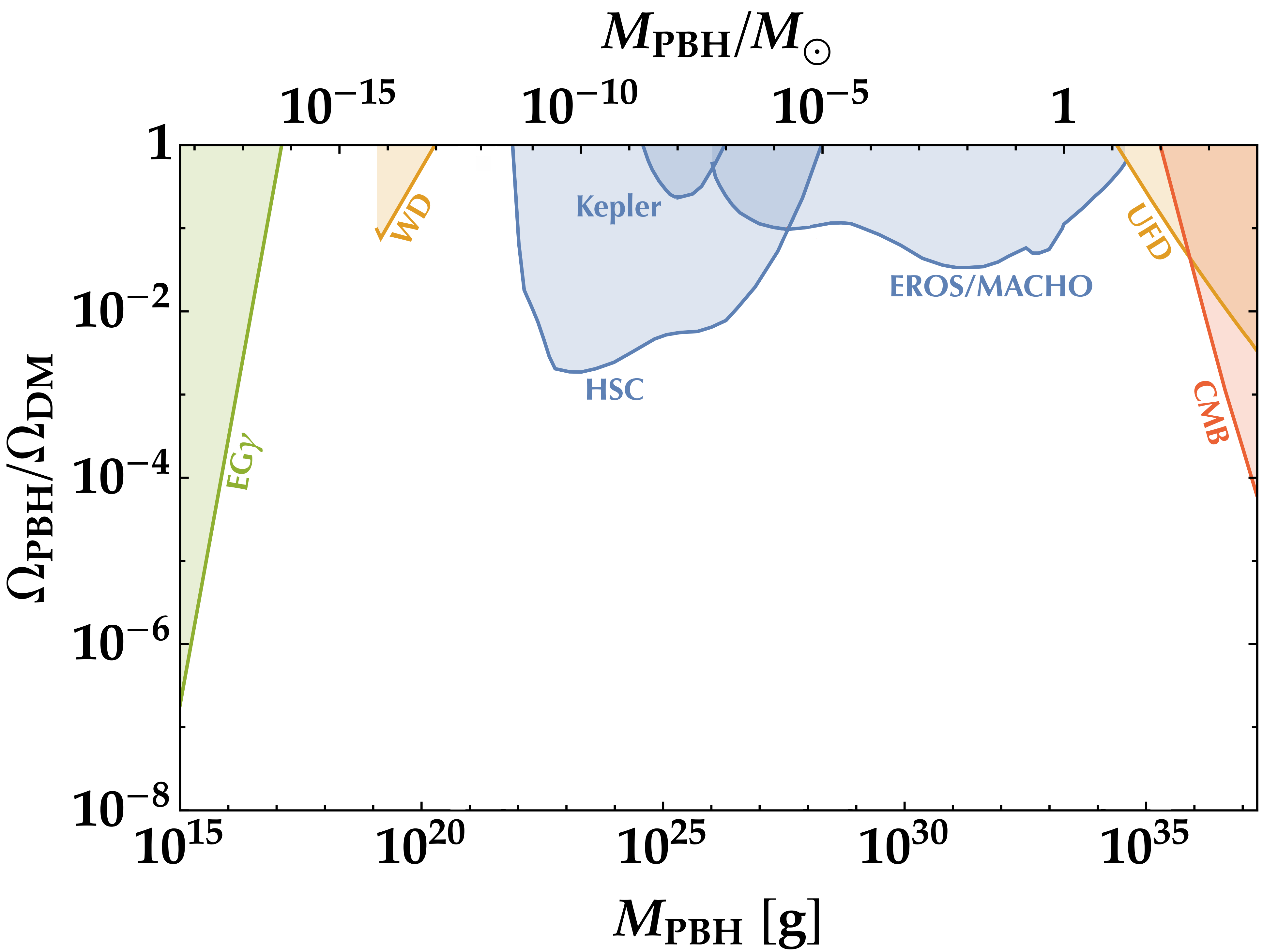
Critical scaling $m_\mathrm{PBH} = K m_H (\delta - \delta_\mathrm{c})^{0.37}$ Choptuik 1993, e.g. Niemeyer & Jedamzik 1998

Compaction function $C(r) = 2\frac{m(r,t) - \bar{m}(r,t)}{R(r,t)}$ Musco 2019

How do PBHs evolve?

- Clustering
- Merging
- Accretion
- Hawking evaporation

How can PBHs be constrained/detected?



adapted from Tada and Yokoyama (1904.10298)
for a recent review of constraints, see *e.g.* Carr, Kohri, Sendouda, Yokoyama (2002.12778)

Thank you for your attention!

One possible connection to dark energy:

Evaporating primordial black holes as varying dark energy

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(Dated: November 11, 2019)

If light enough primordial black holes (PBH) account for dark matter, then its density decreases with time as they lose mass via Hawking radiation. We show that this time-dependence of the matter density can be formulated as an equivalent $w(z)$ dark energy model and we study its implications on the expansion history. Using our approach and comparing with the latest cosmological data, including the supernovae type Ia, Baryon Acoustic Oscillations, Cosmic Microwave Background and the Hubble expansion H(z) data, we place observational constraints on the PBH model. We find that it is statistically consistent with ΛCDM according to the AIC statistical tool. Furthermore, we entertain the idea of having a population of ultra-light PBHs, decaying around neutrino decoupling, on top of the dark matter fluid and show how this offers a natural dark matter-radiation coupling altering the expansion history of the Universe and alleviating the H_0 tension.