Summary without Summary

Random Thoughts on PBHs

Focus Week on Primordial Black Holes

November 13-17, 2023

Misao Sasaki

21 fantastic talks!

1. Anne Green: Stellar microlensing constraints on PBH dark matter
2. Florian Kühnel: Positive Evidence for PBHs
3. Sergey V. Ketov: Production of PBHs as a probe of high-scale inflation and SUSY (SUGRA)
4. Jason Kristiano: One-loop correction in PBH formation from single-field inflation
5. Xinpeng Wang: PBHs from R^2 gravity theory with a nonminimally coupled scalar field

6. Marcos M. Flores: Early structure formation and PBHs
7. Guillem Domenech: Early universe cosmology of Yukawa interactions and PBHs
8. Michael Zantedeschi: PBHs from confinement
9. Albert Escrivà: Formation of trapped vacuum bubbles during inflation, and consequences for PBH
10. Yuber Perez-Gonzalez: Spin Properties of Evaporating PBHs from a Neutrino Perspective
11. Elenna Capote: Advanced LIGO and LIGO Detector Commissioning for O4 (Special seminar)

12. Kazunori Kohri: Importance of Subsolar-Mass PBHs
13. Tomohiro Harada: Revisiting compaction functions
14. Alexsander Kusenko: Newest ideas regarding the oldest black holes (APEC seminar)
15. Joe Silk: Black Holes in the Cosmos (Colloquium)

16. Sachiko Kuroyanagi: Searching for planetary-mass PBHs
17. Ravi Sheth: Predicting the abundance of PBHs
18. Ryodai Kawaguchi: Highly asymmetric PDF from a finite-width upward step during
19. Mitsunari Takahashi: PBH evaporation searches with very-high-energy gamma-ray telescopes

20. Jessica Turner: PBHs and the matter-antimatter asymmetry
21. Volodymyr Takhistov: PBHs: new signatures and new dark matter

what we have discussed

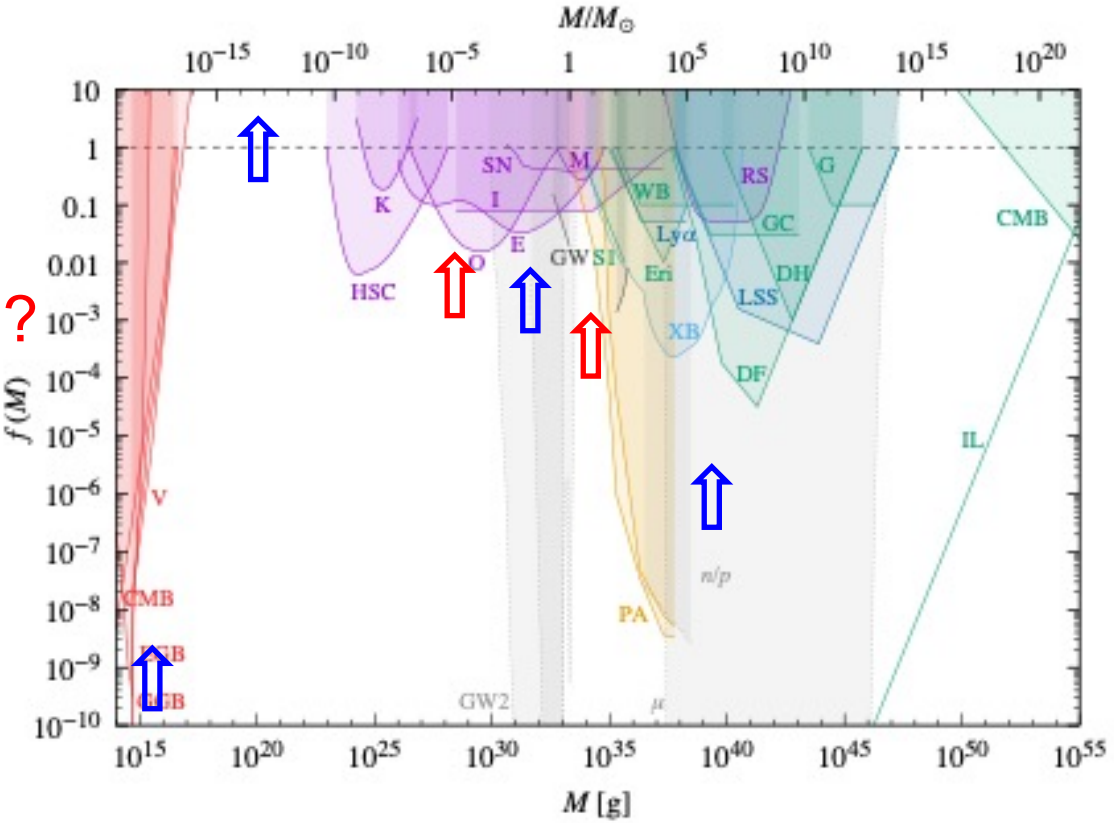
- PBH as DM, or part of DM
- probe for early universe physics
- GWs associated with PBHs
- formation mechanism: during or after inflation
- formation criterion
- …

and

observational evidence!

PBH as (part of) DM

- evaporating PBHs: $M \lesssim 10^{15}$g, $f_{PBH} \ll 1$
- tiny PBHs:
  $M \sim 10^{22}$g, $f_{PBH} = 1$?
- planetary mass:
  $M \sim 10^{-5} M_\odot$, $f_{PBH} \sim 10^{-2}$?
- subsolar mass:
  $M \sim 0.1 M_\odot$, $f_{PBH} \sim 10^{-2}$?
- massive PBHs:
  $M \sim 10 M_\odot$, $f_{PBH} \sim 10^{-3}$?
- supermassive PBHs:
  $M \sim 10^{5} M_\odot$, $f_{PBH} \sim 10^{-6}$?



Carr, Kohri, Sendouda, Yokoyama, 2002.12278

probe for early universe physics

- inflation

  spectrum & non-Gaussianity

  ⇔ potential features, multiverse, confinement?

- phase transitions, EOS, Yukawa force

  oscillons, PBH formation + GWs?

- matter-antimatter asymmetry from PBH

  PBH jets/evaporation: non-equil + C & CP violation

  modified gravity?

GWs associated with PBHs

- GWs from PBH formation
  strong force collapse, string-induced, bubble collision, early MD, …
- GWs from PBH binaries
  LVK binaries, subsolar mass binaries, SMBH,…
- scalar-induced GWs
  curvature and/or isocurvature, non-Gaussianity?
- GWs from evaporating PBHs
  poltergeist GWs, isocurvature, …
- parity violation signatures?

Formation Mechanisms

-during or after inflation-

- enhanced curvature perturbation
  formation during RD, MD, wD, …
- type I (normal) vs type II (wormhole-like?)
  small mass PBHs for >O(1) amplitude perturbations?
- trapped during inflation/quantum tunneling
  proving multiverse, need more quantitative studies
- strong force collapse
  heating/cooling, fermion stars?

$$M_{ch} \sim m_\psi y^{-3} \quad (y \ll 1)$$

- PBH clustering
  non-Gaussian curvature/isocurvature perturbation, …

Formation Criterion

- Press-Schechter formalism
  perhaps not reliable any more…
- Window Function dependence?
  observables shouldn't depend on WF

- Peaks theory
  inclusion of non-sphericity
- Critical behavior
  small mass tail wouldn't reflect reality

$$M = kM_{\rm H}(\delta - \delta_{\rm c})^{\gamma}$$

- Compaction Function
  legitimate C_{CMC} vs universal C_{ss}

$F(\partial^2\psi, \partial\psi)$ $\quad$ $F(\partial\psi)$

$R^{(3)} \ni \partial^2\psi, \partial\psi$

✓ why doesn't the criterion contain 2nd derivatives?

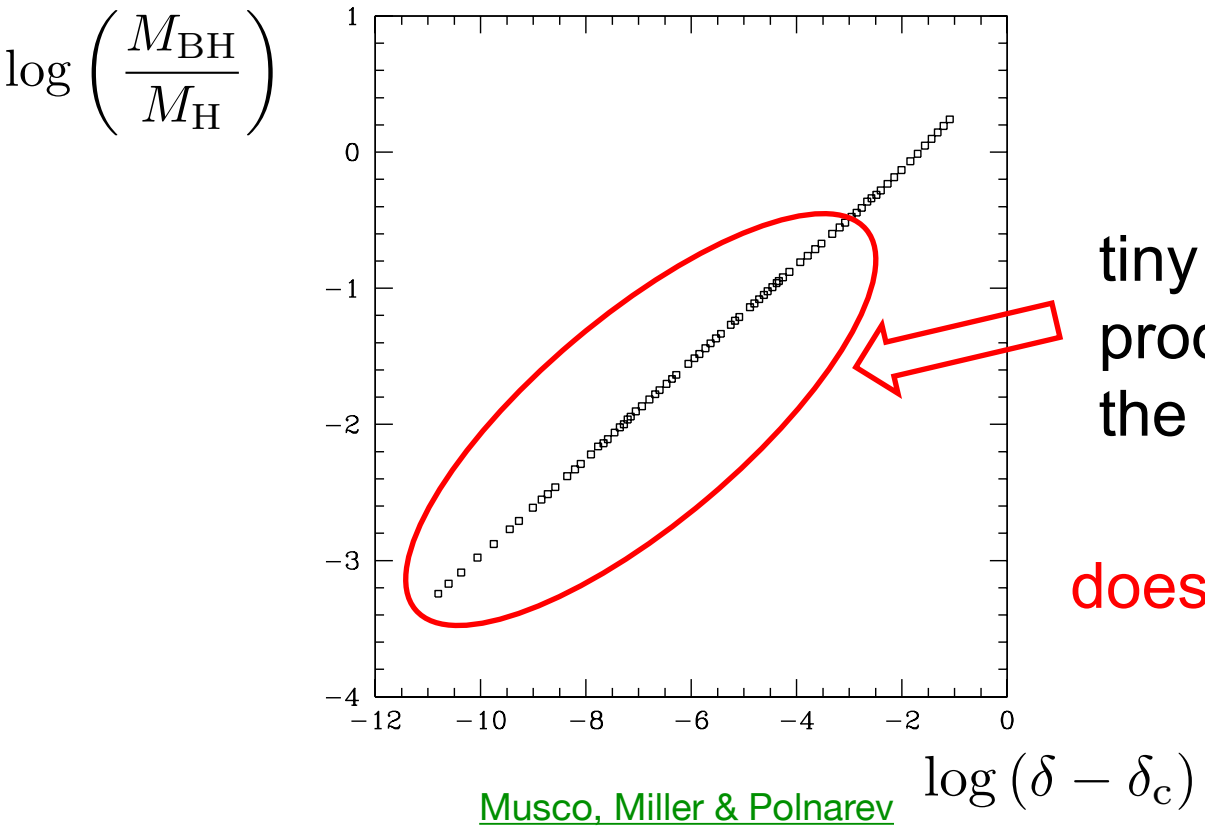
✓ spherical symmetry artifact?

Critical behavior

(borrowed from Anne's slides)

$$M = kM_{\rm H}(\delta - \delta_{\rm c})^{\gamma}$$

$\gamma \simeq 0.36$



tiny mass BHs are produced just above the threshold δ_c

does this really happen?

Musco, Miller & Polnarev

non-sphericity will kill critical behavior

温故知新 = learning from the past

THE ASTROPHYSICAL JOURNAL, **304**:15–61, 1986 May 1

BBKS

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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BBKS Sec. 7

a) The Triaxial Ellipsoid Approximation

In the immediate neighborhood of a peak, the density profile is given by the Taylor expansion

$$F(r) = F(0) - \sum \lambda_i r_i^2/2 \ .$$

eigen values of $F_{,ij}$

$$\Rightarrow \quad F(r) \approx \nu\sigma_0 - x\sigma_2 \frac{r^2}{2}\,[1 + A(e, p)]$$

$$x = -\nabla^2 F/\sigma_2 \qquad e = \frac{\lambda_1 - \lambda_3}{2\sum \lambda_i}, \qquad p = \frac{\lambda_1 - 2\lambda_2 + \lambda_3}{2\sum \lambda_i} \ .$$

$$A(e, p) = 3e[1 - \sin^2\theta(1 + \sin^2\phi)] + p(1 - 3\sin^2\theta\cos^2\phi) \ .$$

$\lambda_2 = \lambda_3$: oblate spheroid $\Leftrightarrow e = p$

$\lambda_1 = \lambda_2$: prolate spheroid $\Leftrightarrow e = -p$

but the probability to be axi-symmetric is very low

High ν peaks are neither oblate nor prolate, but they are definitely triaxially asymmetric,

$$P_{ep}(e, p) \approx P_{ep}(e_m, p_m) \exp\left[-\frac{(e-e_m)^2}{2\sigma_e^2} - \frac{(p-p_m)^2}{2\sigma_p^2}\right],$$

$$e_m = \frac{1}{\sqrt{5}x[1+6/(5x^2)]^{1/2}}, \qquad \sigma_e = \frac{e_m}{\sqrt{6}}, \qquad p_m = \frac{6}{5x^4[1+6/(5x^2)]^2}, \qquad \sigma_p = \frac{e_m}{\sqrt{3}}.$$

$p \sim 0$, but

$e \to e_m \sim \nu^{-1}$

(typically $\gtrsim 0.1$)

conjecture!

critical behavior is killed for

$(\delta - \delta_c) \lesssim e_m \delta_c \sim 0.1\delta_c$

non-Gaussianity!?

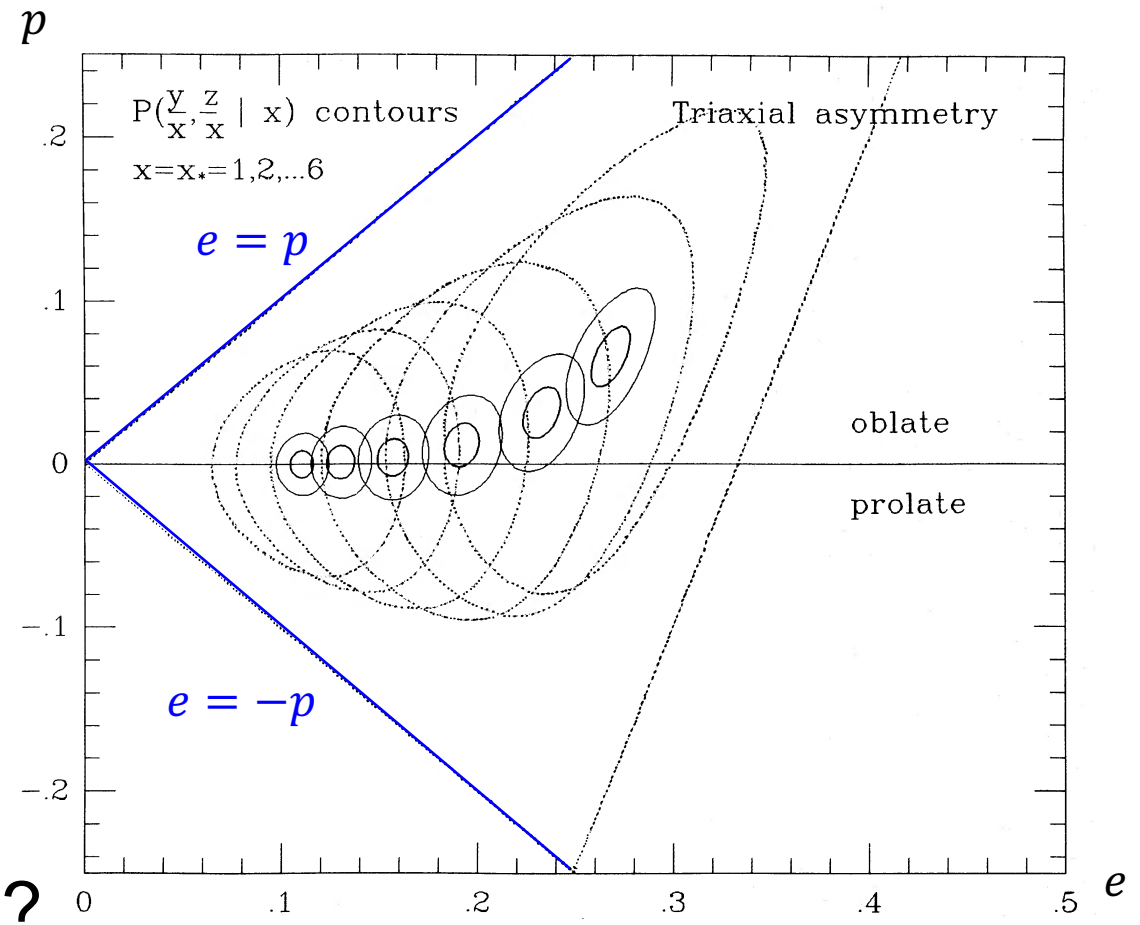

FIG. 7.—The 95%, 90%, and 50% contours

Summary of Summary without Summary

- PBHs have started to play an important role in astrophysics/cosmology/gravity/particle physics or in fundamental physics
- They may (have already?) become a leading character.
- There are a lot of fascinating issues associated with/related to PBHs waiting for us to be solved.

So, whether Florian wins the bet or not,

bottoms up! Kanpai! 乾杯！