PRIMORDIAL BLACK HOLES (PBH)

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GENERAL OUTLINE

- General introduction
- Formation of PBH
- Properties of PBH
- Experimental methods
- PBH as Dark Matter

BRIEF HISTORY OF PBH

- First hypothesized by Zel’dovich & Novikov 1967
- Concrete models proposed early 1970s by Hawking & Carr
  - Constraints due to Hawking radiation
  - Carr: thresholds for formation
- Proposed as a dark matter MACHO candidate (late 90s)
- Experimental searches
  - Resurgence due to grav wave detections

FORMATION OF PBH

- No definite explanation or whether they even exist
- Completely dependent on (cosmological) models
- Originate from inhomogeneities in density
- Can be much smaller than current day BHs
- Can span a big mass range (10^{-8} kg to 10^{5} M_{Sun})

SOURCE OF INITIAL INHOMOGENEITIES

- Depends on inflationary models of quantum fluctuations
  - Shortly after reheating
  - Specific peaks in power spectrum (designer inflation)
  - Other types of fluctuation spectra
  - Parametric resonance
  - Spontaneous formation due to phase transition
  - Many more
- Conclusion: origin still unknown

FROM INHOMOGENEITY TO PBH

- 1974: Carr's condition: $R_J \leq R_{max} \leq R_{PH}$

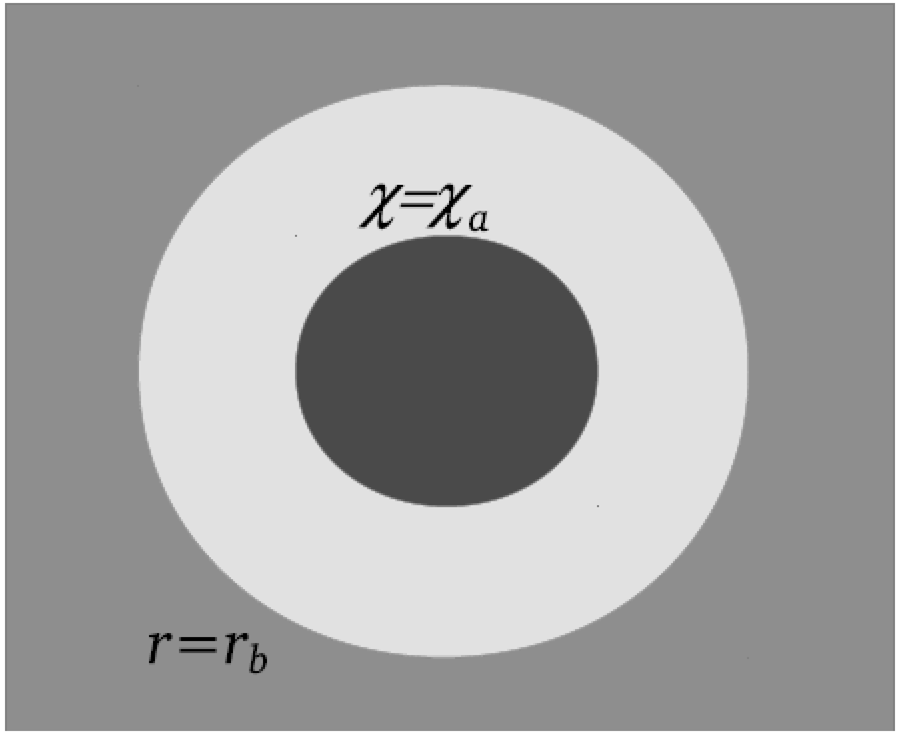
- Deeper analytic approach: add perturbation to Friedmann metric

$$ds^2 = -c^2 dt^2 + a^2(t)\left(\frac{dr^2}{1 - Kr^2} + r^2 d\Omega^2\right) \Rightarrow \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{c^2}{a^2}$$

- Harada 2013: three-zone model

FROM INHOMOGENEITY TO PBH

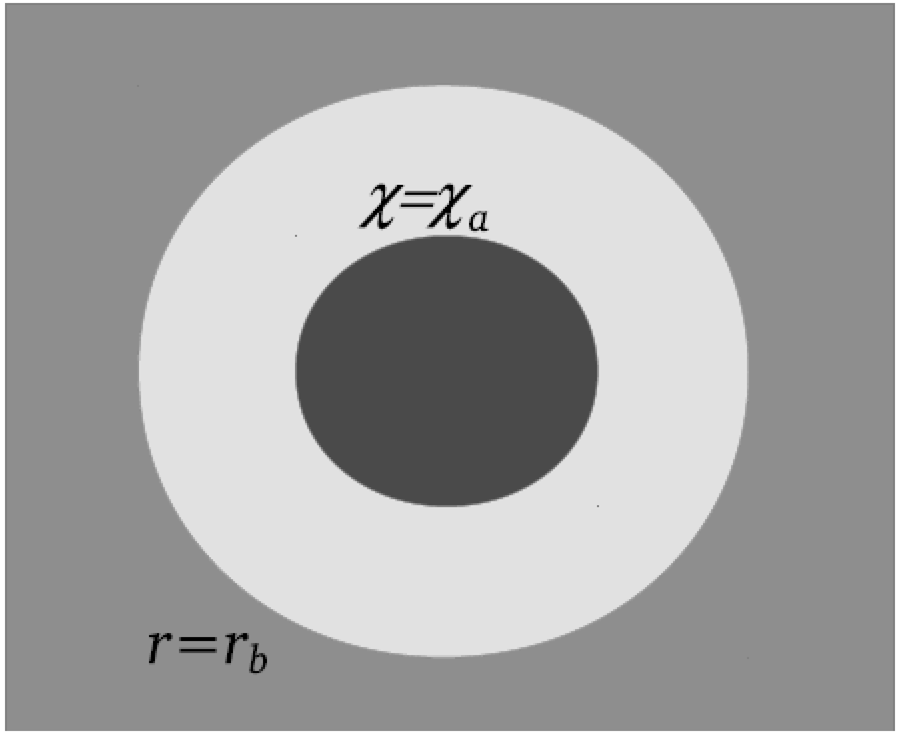
- Three zone model
- Aligns nicely with numerical results
- Same starting point as Carr
- Dependent on spherical symmetry and dust/perfect fluid



Harada, 2013

FROM INHOMOGENEITY TO PBH

- Three zone model
- Gives threshold for overdense region $\delta = \frac{\Delta\rho}{\rho}$
- Result: $\delta_{Hc}^{UH} < \delta_{H}^{UH} \leq 1$
- Where $\delta_{Hc}^{UH} = \sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right)$



Harada, 2013

FROM INHOMOGENEITY TO PBH

- We can also use these models to get an estimate of the mass at formation

$$M \sim t\left[1+\frac{t}{\mathrm{t}_1}\left(\frac{t_1}{M_1}-1\right)\right]^{-1}$$

Carr 1975

$$M \sim \frac{c^3 t}{G} \sim 10^{12}\left(\frac{t}{10^{-23} s}\right) kg$$

Carr 2019

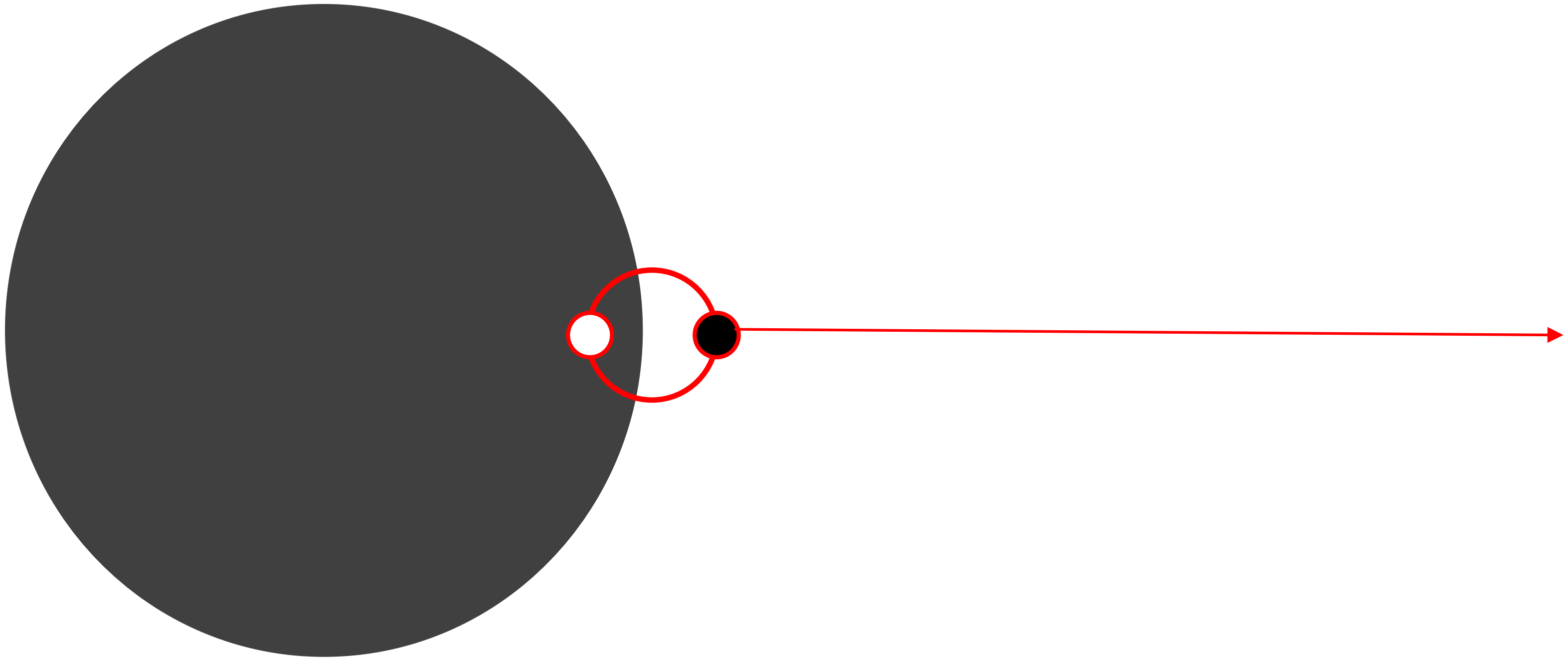
NO HAIR THEOREM

- An isolated black hole is completely determined by its mass, electric charge and angular momentum.

EVOLVING BH'S

- Growth: accretion
- Shrinkage: Hawking radiation

HAWKING RADIATION (1/3)



HAWKING RADIATION (2/3)

- Unruh principle + equivalence principle
- Accelerating observer sees thermal bath of particles
  - Different description of states and operators
- Equivalence: gravity = acceleration

HAWKING RADIATION (3/3)

- BH-lifetime (assuming no accretion):
- $\tau \approx 10^{65} yr \left(\frac{M}{M_{sun}}\right)^3 \approx 10^{10}\ yr \left(\frac{M}{10^{12}\ kg}\right)^3$
- Resulting luminosity
- $L \approx 10^{-28} W\ \left(\frac{M_{sun}}{M}\right)^2 \approx 4 \cdot 10^8 W \left(\frac{10^{12} kg}{M}\right)^2$

INFORMATION PARADOX

- No hair theorem $\rightarrow$ information loss upon accretion?
- Solution: black hole is maximum entropy state
- Hawking radiation $\rightarrow$ information loss upon evaporation
- Solution: ???

INFORMATION PARADOX

- No hair theorem → information loss upon accretion?
- Solution: black hole is maximum entropy state
- Hawking radiation → information loss upon evaporation
- Solution: ???

Waveform collapses upon accretion?

In Hawking radiation?

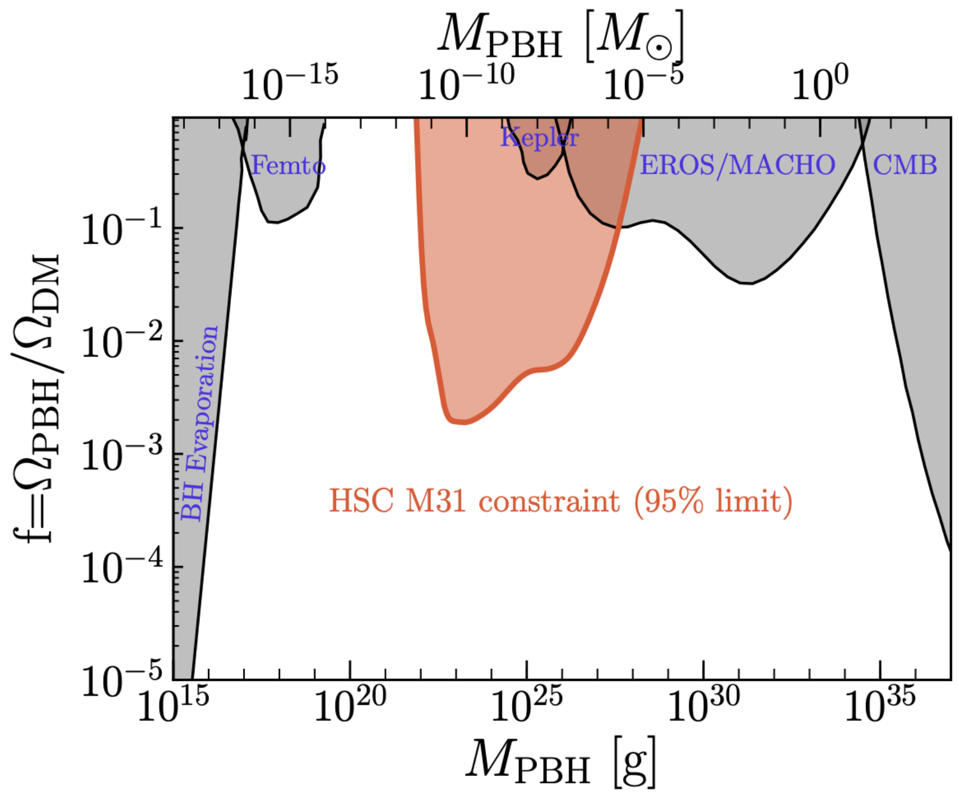
White hole?

In small remnant?

Holographic principle?

EXPERIMENTAL METHODS

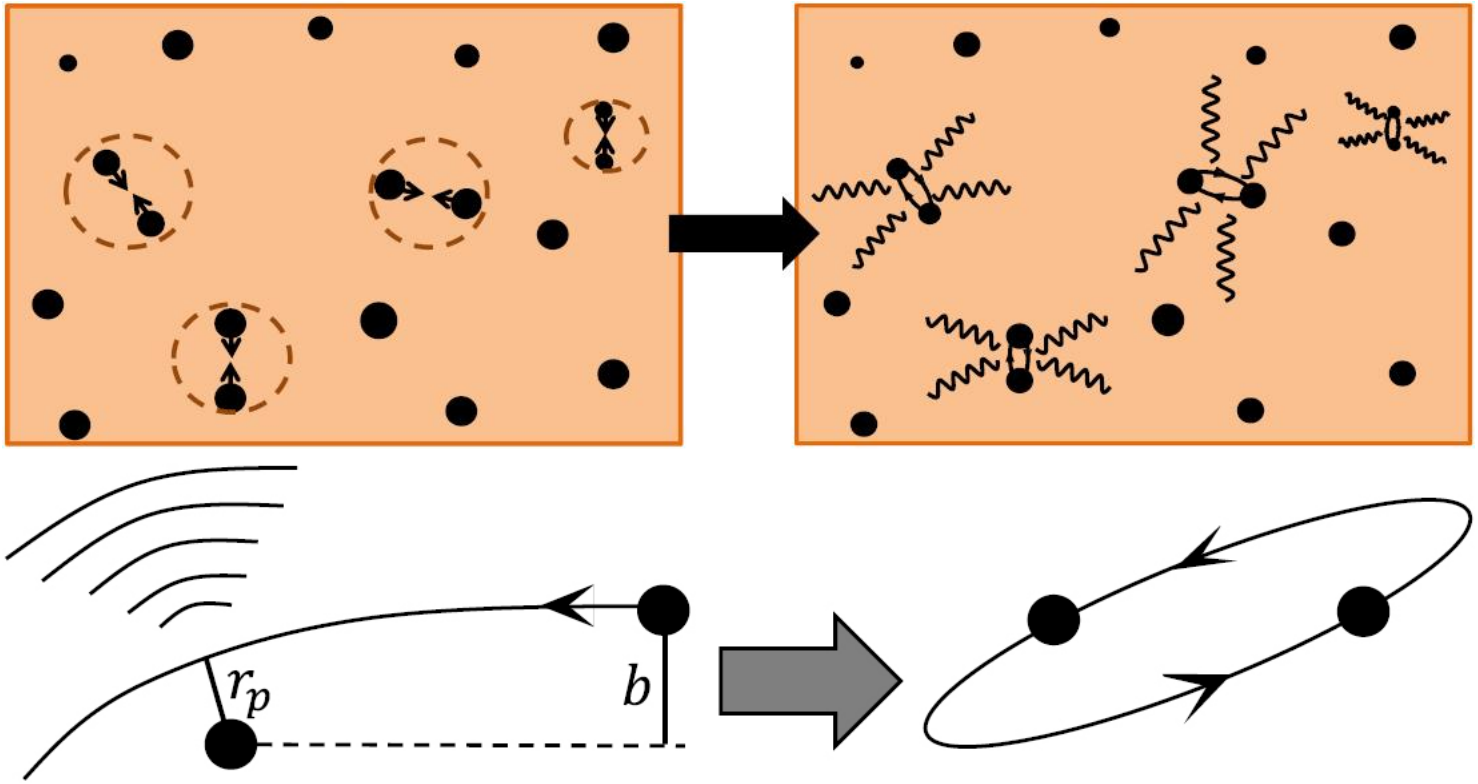
- Gravitational waves (GW), Microlensing and Gravitational slingshot
- Most experimental for other research
- Subaru → Microlensing



Niikura, 2018

GRAVITATIONAL WAVES (1/2)

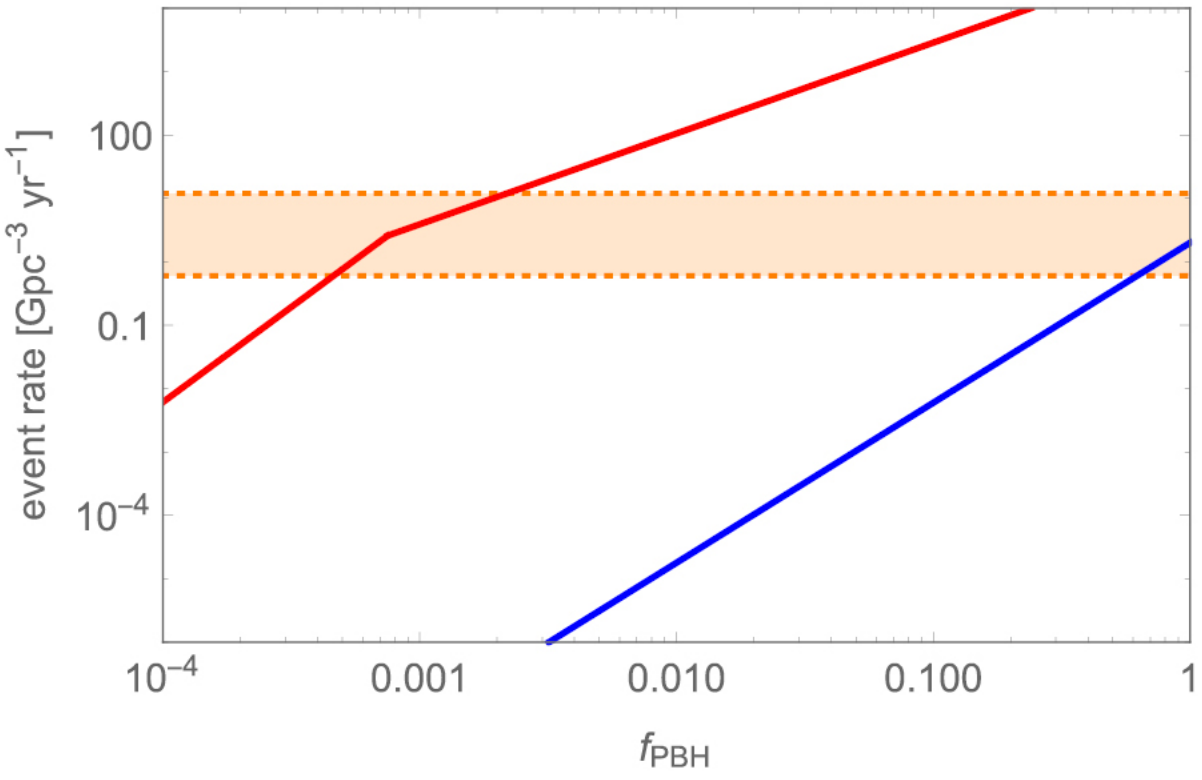
- Effects on expected rate
- Origin of binary's
  - Radiation dominated
  - Present Universe



Sasaki, 2018

GRAVITATIONAL WAVES (2/2)

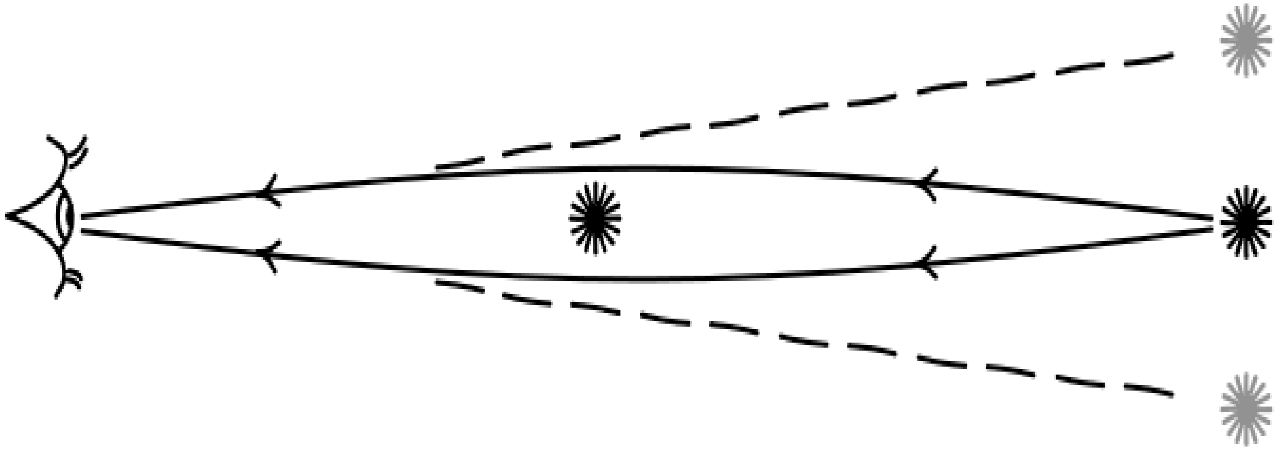
- Radiation dominated rate to high
- Present universe only a fraction



Sasaki, 2018

MICROLENSING

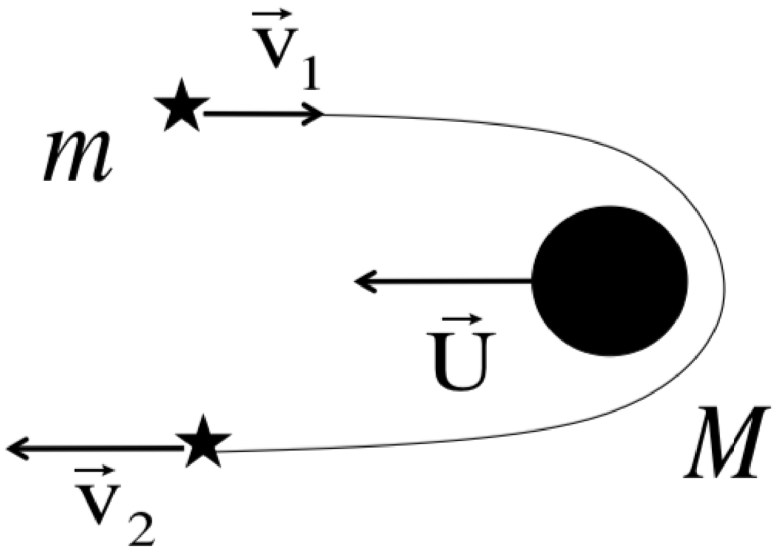
- Bending of the light
- Characteristic Schwarzschild radius
- $10^{-11} M_{Sun} \rightarrow 300\ nm$
- Wave effect
- Oscillations in the light curve



Norton, 2015

GRAVITATIONAL SLINGSHOT

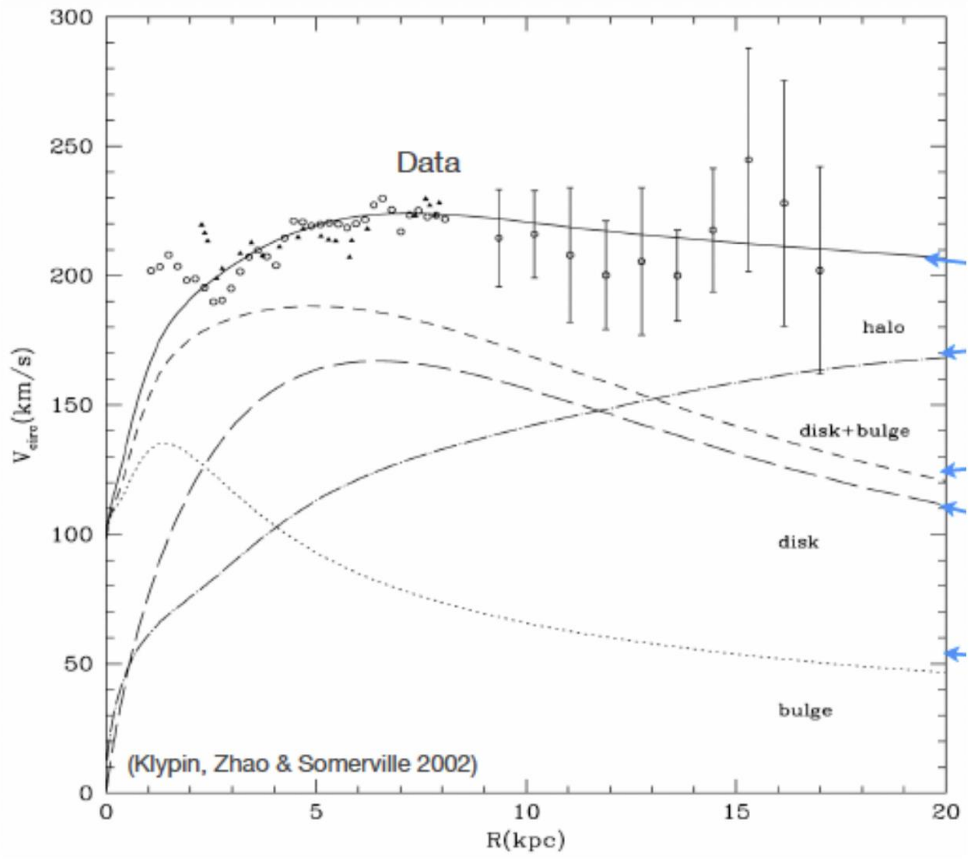
- GAIA
- Few in 10^5 interact with PBH
- 1 in 10^5 right feature



García-Bellido, 2017

PROPERTIES OF DARK MATTER (1/4)

- DM should have a mass
- PBHs do!
  - $10^{-8}kg < M_{PBH} < 10^{5}M_{Sun}$

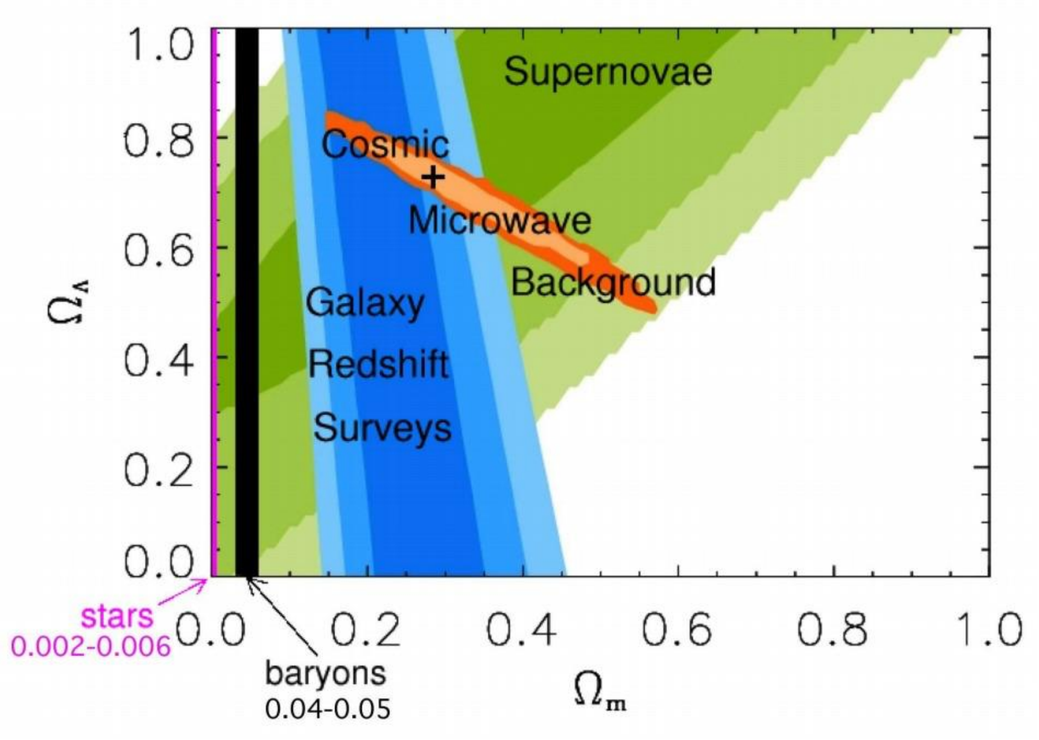


Colijn, 2015

PROPERTIES OF DARK MATTER (2/4)

- Non baryonic
  - Microlensing experiments constrain mass
  - Baryonic mass in this unconstrained region should be observable

- PBHs formed during radiation dominated era



Gondolo, 2002

PROPERTIES OF DARK MATTER (3/4)

- Long lifetime
- $\tau \approx 10^{65} yr \left(\frac{M}{M_{sun}}\right)^3 \approx 10^{10}\ yr \left(\frac{M}{10^{12}\ kg}\right)^3$
- So $M > 10^{12} kg$ is sufficient

PROPERTIES OF DARK MATTER (4/4)

- 'Dark'
- The event horizon does not allow emission of light

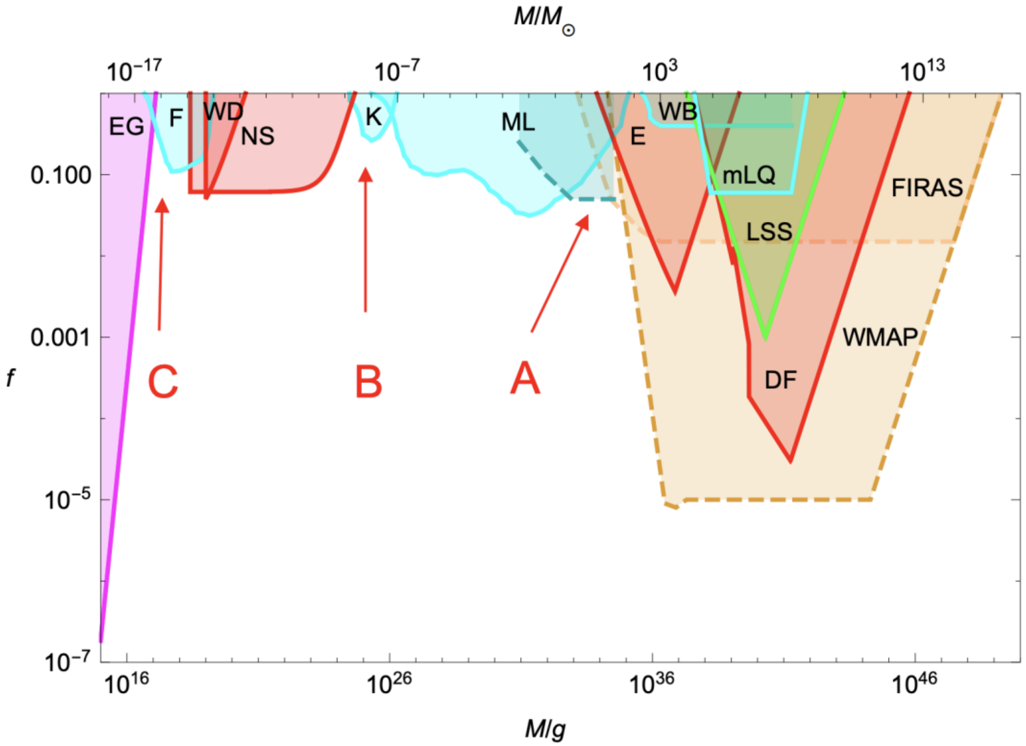
MOTIVATION FOR PBHS AS DARK MATTER

- PBHs seem to meet the requirements
- Could be probed via gravitational lensing, Hawking radiation and gravitational waves

- Bonus feature: no introduction of new particles
  - WIMPS, sterile neutrinos, QCD axions, SUSY particles, ...

CONSTRAINTS

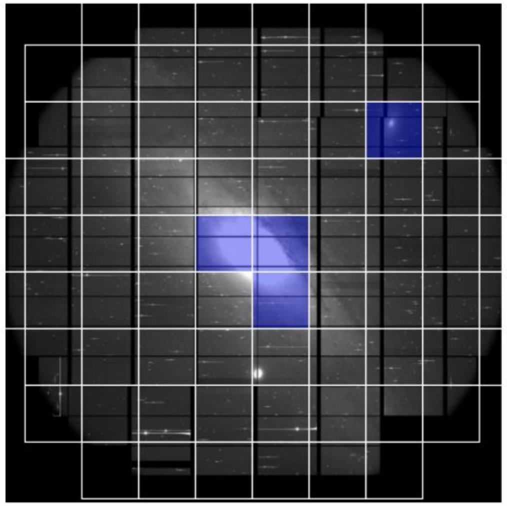
- Extragalactic gamma-rays from evaporation (EG), white-dwarf explosions (WD), Micro-lensing (ML), etc…
- Permitted mass windows for f ~ 1 are:
  - A) intermediate $(10-10^{3})M_{Sun}$
  - B) sublunar mass range $(10^{-5}-10^{-7})M_{Sun}$
  - C) asteroid mass range $(10^{-15}-10^{-19})M_{Sun}$



Carr, 2019

SUBARU/HSC CAMERA

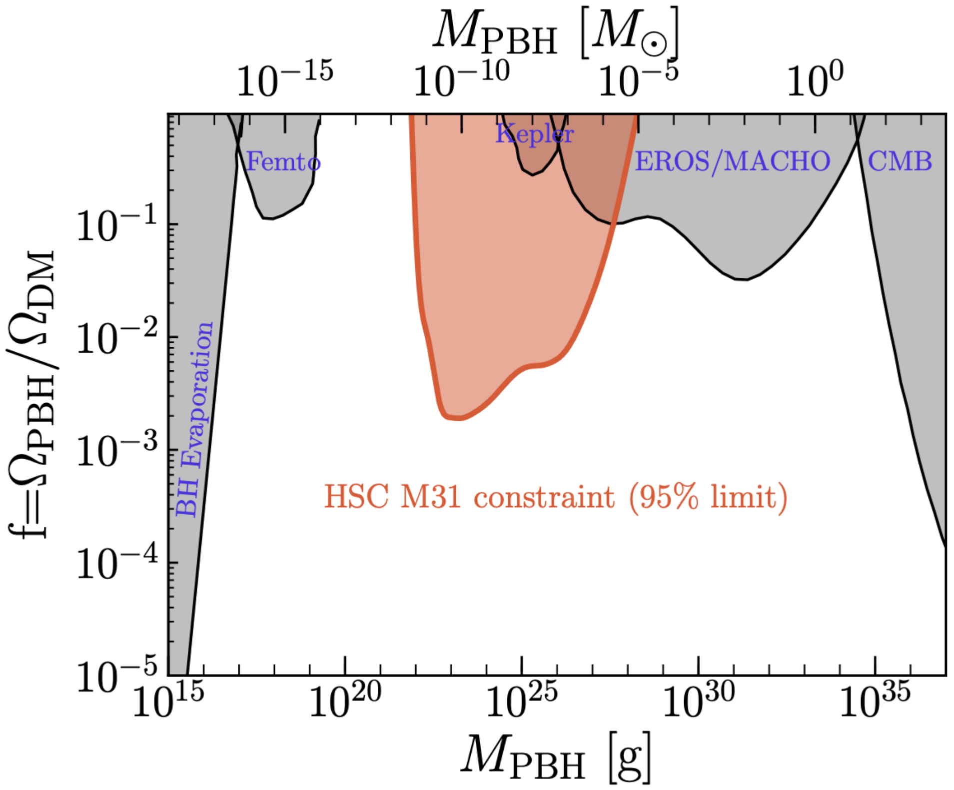
- Look at Andromeda Galaxy (M31) stars
- Several advantages
- Expect many microlensing effects, but...



Niikura, 2018

FURTHER CONSTRAINTS...

- New constraints from 2019 in mass-range of $10^{-11} - 10^{-4} M_{Sun}$
- **Excludes sublunar range (B)**
- Gravitational microlensing



Niikura, 2018

CONCLUSION

- Formation is still largely unknown, but several models exist
- Hawking radiation
- Difficult to measure experimentally
- PBHs are not expected to make up a dominant fraction of DM

- http://inspirehep.net/record/107085/, https://doi.org/10.1086/153853 Carr 1975
- https://arxiv.org/abs/1812.01930, Raidal et al 2019
- https://arxiv.org/abs/0912.5297, Carr et al 2010
- http://adsabs.harvard.edu/abs/1974MNRAS.168..399C, Hawking and Carr 1974, Mon. Not. R. astr. Soc. (1974), 168, 399-415.
- http://adsabs.harvard.edu/abs/1971MNRAS.152...75H, Hawking 1971, Mon. Not. R. astr. Soc. (1971) 152, 75-78.
- https://arxiv.org/abs/1805.04087, Germani and Musco 2019
- https://arxiv.org/abs/1309.4201v4, Harada et al 2013
- http://adsabs.harvard.edu/abs/1967SvA....10..602Z, Zel'dovich and Novikov 1967
- https://arxiv.org/abs/hep-ph/9812342v1, Taruya 1998
- https://arxiv.org/abs/1901.07803, Carr 2019

- https://arxiv.org/abs/1801.05235, Sasaki et al, 2019
- https://arxiv.org/abs/1702.08275, Garcia-Bellido, 2017
- https://arxiv.org/abs/1102.5564, Singleton, 2011
- https://arxiv.org/abs/hep-th/9508151v1, Giddings, 1995
- https://www.nature.com/articles/353807a0, Halzen et al, Nature 353, 807-815 (1991)
- https://www.nature.com/articles/248030a0, Hawking, Nature 248, 30-31 (1974)