Probing Primordial Black Holes with Gravitational Waves

Sumedha Biswas







Structure of the Talk

What are Primordial Black Holes (PBHs)?

PBHs and Gravitational Waves

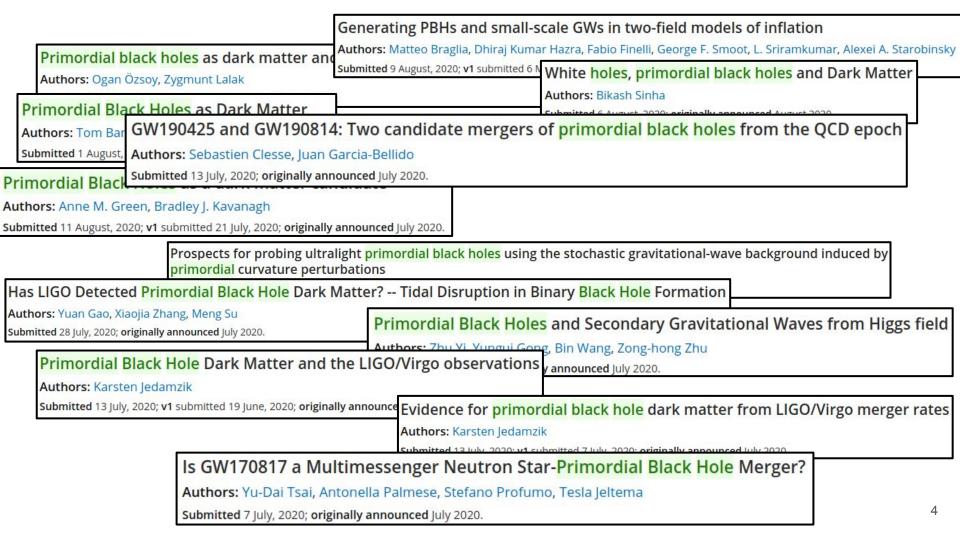
PBH Formation Mechanism Theories Detecting PBHs

PBHs as Dark Matter

What are Primordial Black Holes (PBHs)?

- Black holes from the Early Universe
- Formed seconds after the Big Bang
- Non-Stellar Evolution
- Exist over all mass ranges (Carr 2005)

Still **hypothetical** as no detections have been made so far!



Is Planet 9 a PBH?

(arXiv:1909.11090)

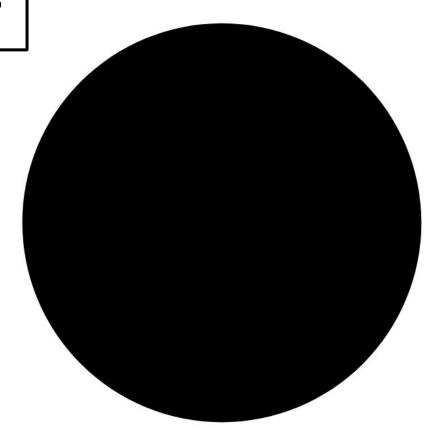


FIG. 1. Exact scale (1:1) illustration of a $5M_{\oplus}$ PBH. Note that a $10M_{\oplus}$ PBH is roughly the size of a ten pin bowling ball.

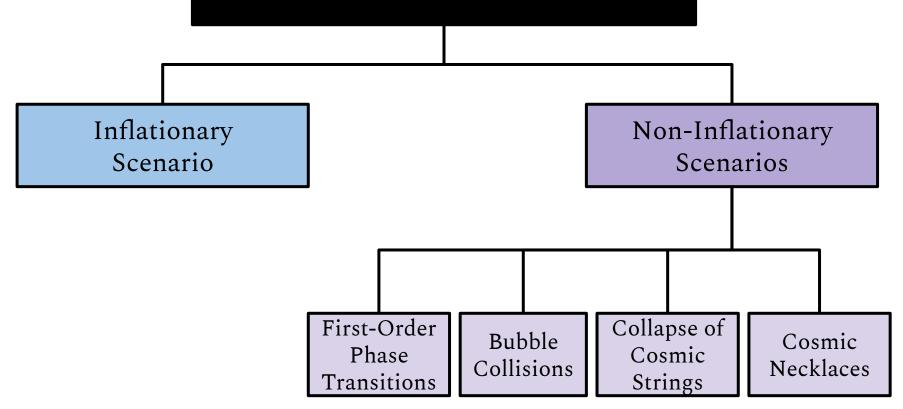


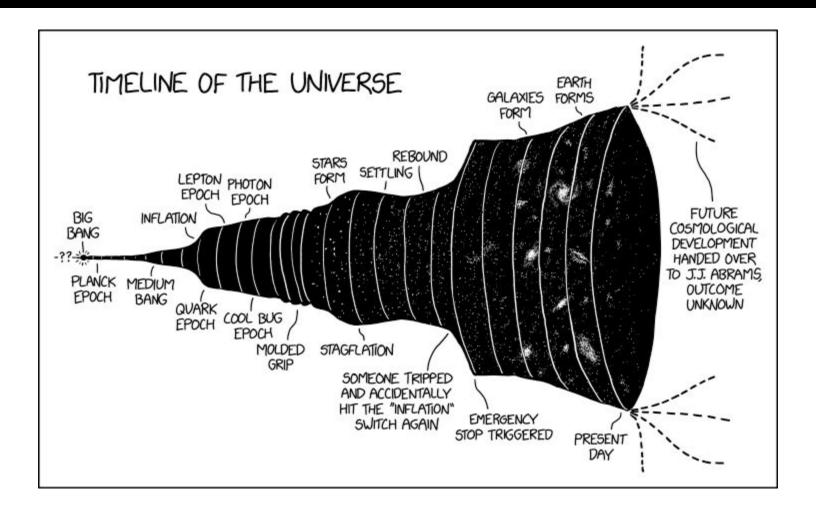
Basis of Primordial Black Hole Formation

- ★ Density inhomogeneities in certain parts of the Universe
- ★ Leads to gravitational collapse
- ★ Subsequent birth of a PBH

But how and why did these inhomogeneities arise?

PBH Formation Mechanisms



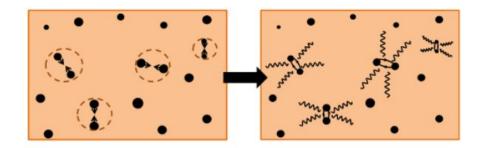


Inflationary Scenario

★ Inflation led to a homogenous Universe

★ Amplitude of density fluctuations in a perturbed region

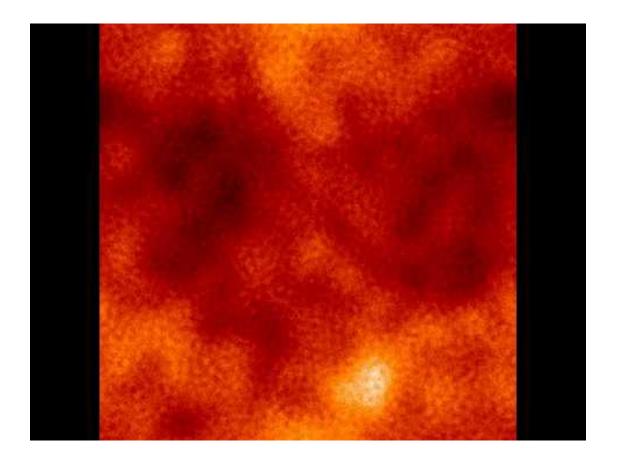
★ If greater than a critical amplitude, PBHs formed

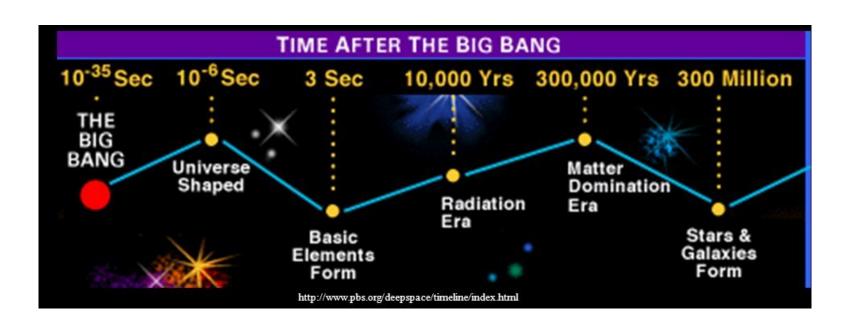


Schematic representation of the formation of PBH binaries in the **radiation-dominated Universe**; (Sasaki et al 2018)

100 years after the Big Bang

(Wilkinson Microwave Anisotropy Probe team, Princeton 2000)





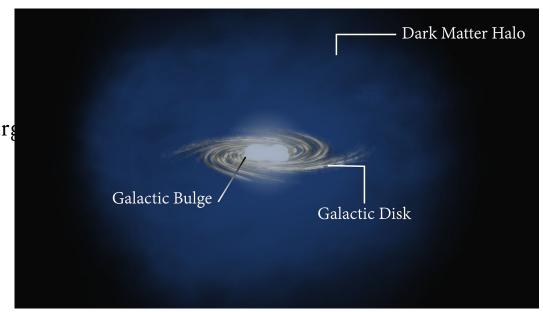
Open Problem

Simulating the early Universe - a few seconds after the Big Bang;

Might shed light on the formation of PBHs!

Can PBH Binaries form in the Present Universe?

- ★ PBHs may be freely moving through the Universe
- ★ Might also be concentrated in larged dark matter halos
- ★ Interacts with another PBH and forms a binary



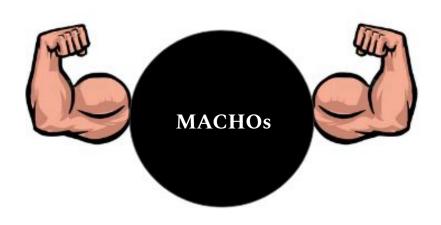
Open Problem

How did Primordial Black Holes really form?

Primordial Black Holes as Dark Matter



Weakly Interacting Massive Particles



Massive Astrophysical Compact Halo Object

Did LIGO detect dark matter?

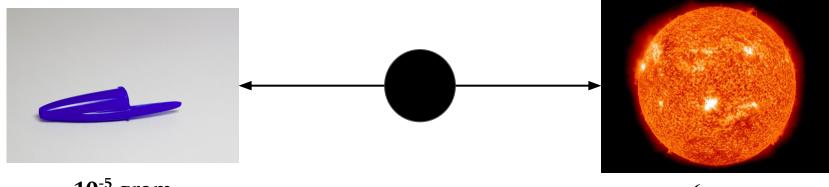
Simeon Bird Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess¹

¹Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA



Primordial Black Holes are predicted to exist over all masses.

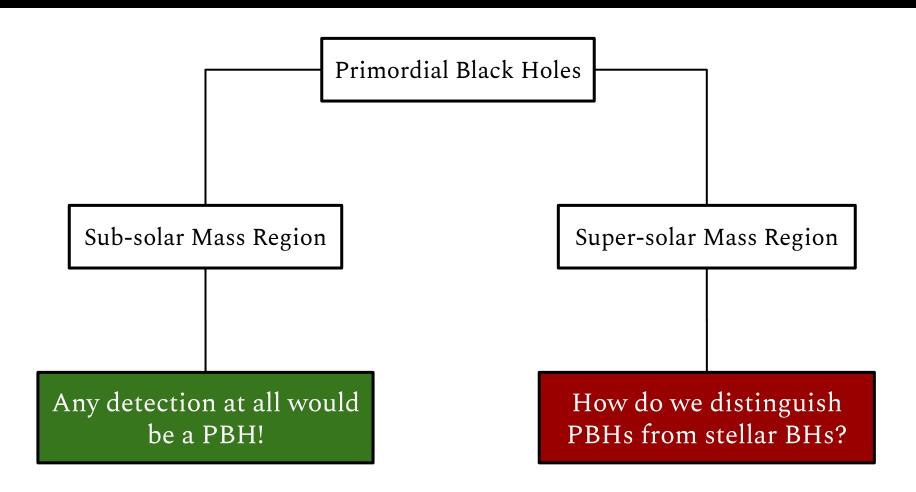
(Carr 2005)

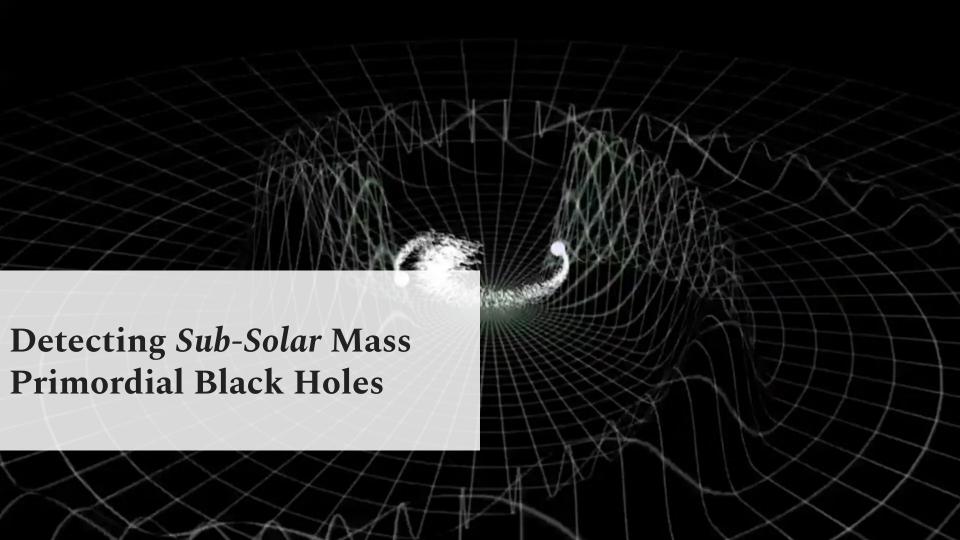


or 10,000 times less than the mass of a pen cap

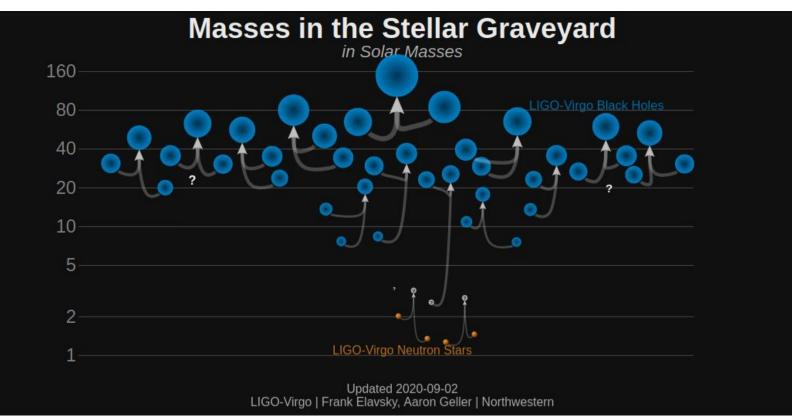
10⁶ Msun or 100,000 times the mass of the Sun

Mass of a pen cap ~ 1 gram Mass of the Sun (Msun) ~ 10³³ gram





Why consider the Sub-Solar Mass Region?

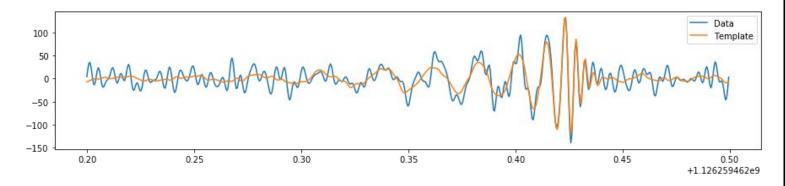


Basic Steps of a Gravitational Wave Detection

- 1. Generate template banks
- 2. Singular Value Decomposition (SVD)

(only used in the GstLAL pipeline)

3. Matched Filtering



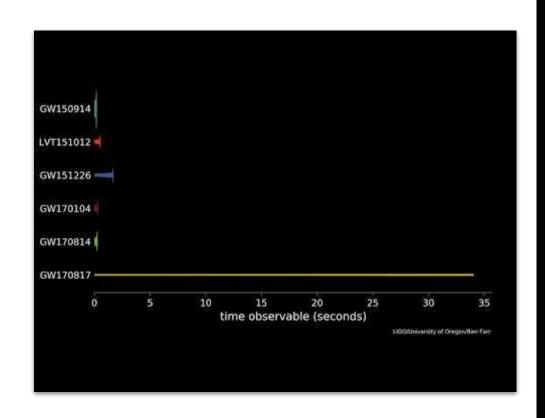
The Problem

- ★ Very long waveforms
- ★ High computational costs

$$N \sim m_{min}^{-8/3}$$

(BJ Owen and B.S. Sathyaprakash 1999)

So how do we use LIGO/Virgo to detect subsolar mass PBHs?



[Submitted on 14 Aug 2018 (v1), last revised 15 Aug 2018 (this version, v2)]

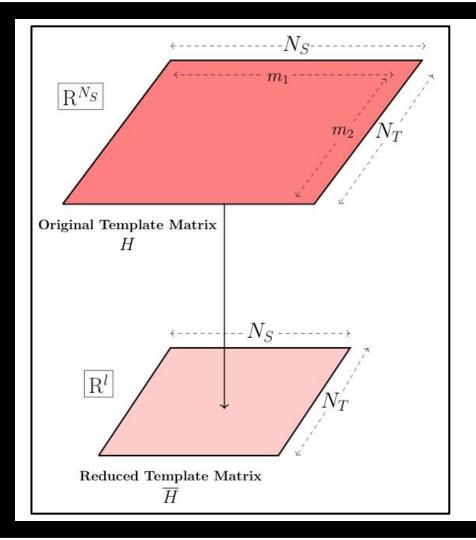
Search for sub-solar mass ultracompact binaries in Advanced LIGO's first observing run

B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, C. Affeldt, B. Agarwal, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, B. Allen, G. Allen, A. Allocca, M. A. Aloy, P. A. Altin, A. Amato, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Ar'ene, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, M. Ast, S. M. Aston, P. Astone, D. V. Atallah, F. Aubin, P. Aufmuth, C. Aulbert, K. AultONeal, C. Austin, A. Avila-Alvarez, S. Babak, P. Bacon, F. Badaracco, M. K. M. Bader, S. Bae, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, S. Banagiri, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, K. Barkett, S. Barnum, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, J. C. Batch, M. Bawaj, J. C. Bayley, M. Bazzan, B. B'ecsy, C. Beer, M. Bejger, I. Belahcene, A. S. Bell, D. Beniwal, M. Bensch, B. K. Berger, G. Bergmann, S. Bernuzzi, J. J. Bero, C. P. L. Berry, D. Bersanetti, A. Bertolini, J. Betzwieser, R. Bhandare, I. A. Bilenko, S. A. Bilgili, G. Billingsley, C. R. Billman, J. Birch, R. Birney et al. (1038 additional authors not shown)

[Submitted on 18 Apr 2019 (v1), last revised 25 May 2019 (this version, v3)]

Search for sub-solar mass ultracompact binaries in Advanced LIGO's second observing run

The LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, G. Allen, A. Allocca, M. A. Aloy, P. A. Altin, A. Amato, S. Anand, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Arène, N. Arnaud, S. M. Aronson, K. G. Arun, S. Ascenzi, G. Ashton, S. M. Aston, P. Astone, F. Aubin, P. Aufmuth, K. AultONeal, C. Austin, V. Avendano, A. Avila-Alvarez, S. Babak, P. Bacon, F. Badaracco, M. K. M. Bader, S. Bae, J. Baird, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, A. Bals, S. Banagiri, J. C. Barayoga, C. Barbieri, S. E. Barclay, B. C. Barish, D. Barker, K. Barkett, S. Barnum, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, M. Bawaj, J. C. Bayley, M. Bazzan, B. Bécsy, M. Bejger, I. Belahcene, A. S. Bell, D. Beniwal, M. G. Benjamin, B. K. Berger, G. Bergmann, S. Bernuzzi, C. P. L. Berry, D. Bersanetti, A. Bertolini, J. Betzwieser, R. Bhandare, J. Bidler, E. Biggs, I. A. Bilenko, S. A. Bilgili, G. Billingsley, R. Birney, O. Birnholtz et al. (1090 additional authors not shown)



A Solution

Random-Projection Based Singular Value Decomposition (RSVD)

Kulkarni et al. (2019)

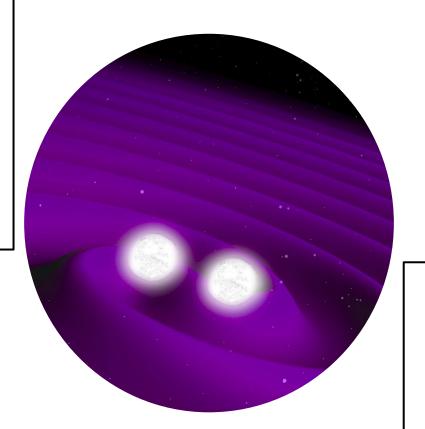
RSVD performed better in terms of:

★ Time

★ Computational

Costs

★ Overall Efficiency

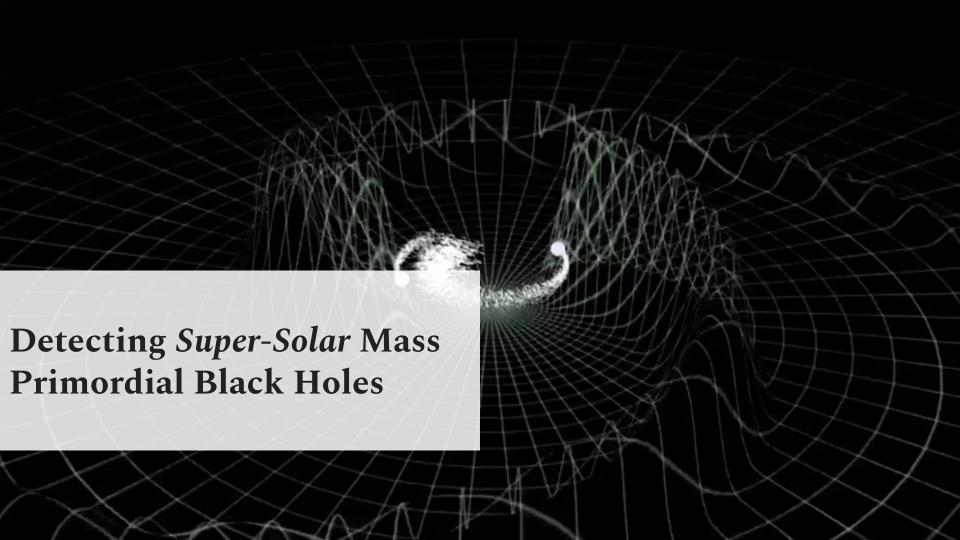


CONCLUSION

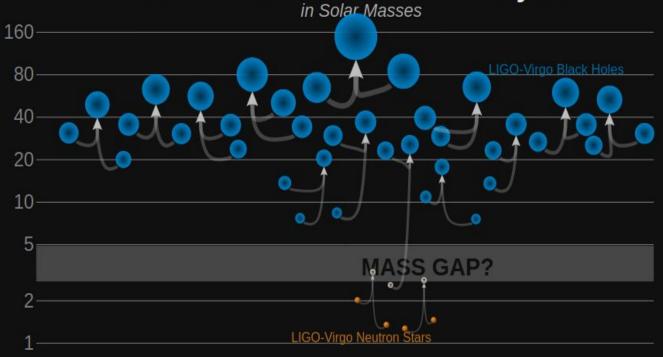
RSVD IS A BETTER METHOD THAN SVD

Open Problem

How do we develop more computationally-efficient search methods, such that we can probe the Universe better?



Masses in the Stellar Graveyard



Updated 2020-09-02 LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Open Problem

How do we distinguish between astrophysical/stellar black holes and primordial black holes?

Choose astrophysical and primordial BH models to describe the lower mass gap



Generate "fake GW signals" or injections and inject them into the detectors



Run a parameter estimation analysis using BILBY

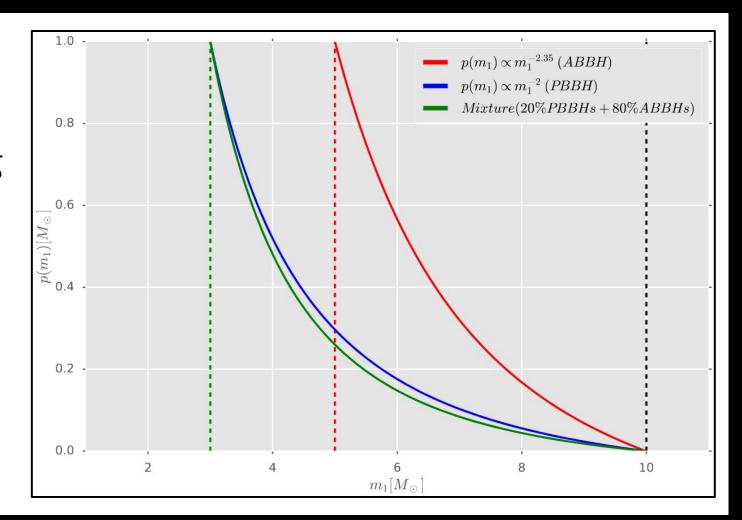


Determine which model is more likely for our given conditions

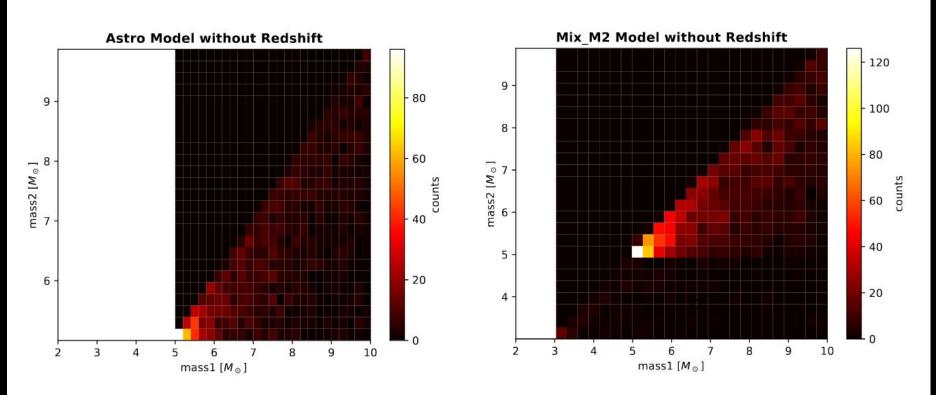
The Framework

Choosing Models ("Priors")

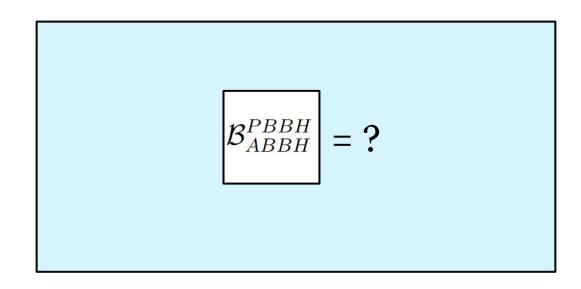
(test run)



Simulating GW Populations

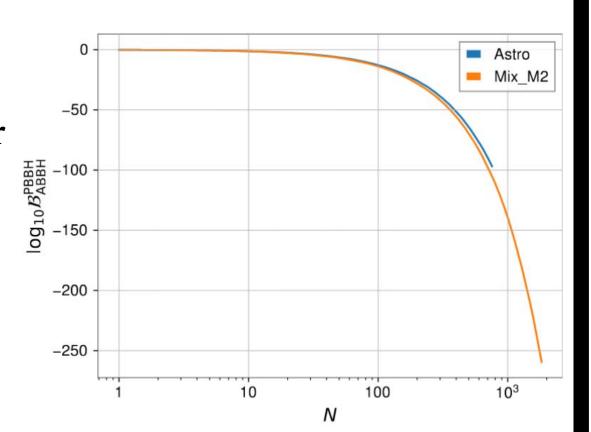


Calculating the Bayes Factor

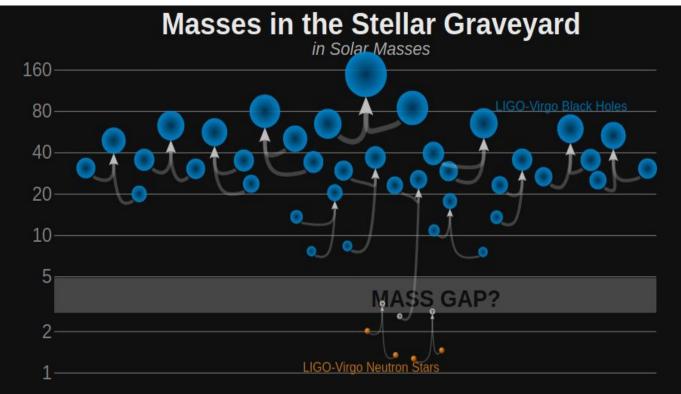


PBBH Bayes Factor in the Lower Mass Gap

(test run)



Recent Detections in the Lower Mass Gap



Updated 2020-09-02 LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Comparison between GW190425 and GW190814		
Parameter	GW190425	GW190814
Primary Mass (m ₁)	1.61 - 2.52 M_{\odot}	22.2 - 24.3 M_{\odot}
Secondary Mass (m ₂)	1.12 - 1.68 M_{\odot}	2.5 - $2.67~M_{\odot}$
Mass Ratio (q)	0.4 - 1.0	0.1 - 0.12
Effective Spin ($\chi_{ m eff}$)	0.01 - 0.17	0.059 - 0.062
Redshift (z)	0.01 - 0.04	0.04 - 0.06

Open Problem

Can the lower mass gap be explained by Primordial Black Holes?

Next Step:

Develop better PBH models!

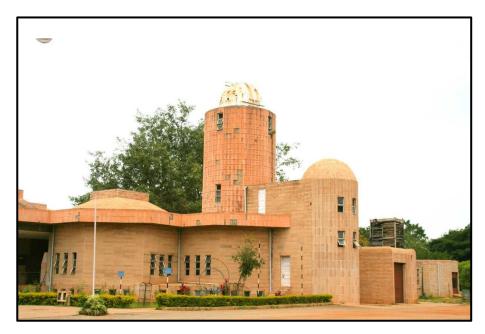
Open Problem

Do Primordial Black Holes even exist?



Bangalore Association for Science Education (BASE)

Jawaharlal Nehru Planetarium (JNP), Bangalore





Founded by Prof. C V Vishveshwara

(also called the 'Black Hole Man of India')



Research Education **A**dvancement Programme (REAP)

REAP rich dividends as a scientific researcher

A unique course—REAP—offered in Bangalore encourages students to undertake research programmes by exposing them to scientists and their studies. It comes with a nominal fee and can be pursued concurrently along with your BSc course, during the weekends

Aishhwariya Subramanian

Interested in research? Your search for the right route to become a researcher should end at the planetarium in Bangalore.

Bangalore Association for Science Education (BASE) collaborates with the fndian Institute of Science (IISc), Indian Institute of Astrophysics (IIA) and Raman Research Institute to offer a unique three-year course-called REAP-that brings some of the top scientists in contact with aspiring students.

"The idea behind the Research Education Advancement Programme (REAP) is to promote the small percentage of students who want to pursue research as a career," said BS Shylaia, director of the Jawaharlal Nehru Planetarium and one of the teachers of the course, REAP could be concurrently studied by students who are pursuing their Bachelor of Science (BSc) degree. Classes for the course is conduct-During the three years of the course, students will be lectured by scientists from IISc. IIA and RRI as well. The sciof the students," Shylaia said.



first year. "They will be taught the basies of astronomy, astrophysics and mathematics. They are also given homework and we are very strict about ed during the weekends. "We want to attendance. This is a course that should motivate students to pursue research. be taken seriously," Shylaia warned.

Students also get to visit research institutes as part of the programme. "Bangalore has many research instientists also evaluate the performance tutes. The second year will take things

Students get to learn the basics in the will be exposed to subjects like quanturn mechanics and electrodynamics. At that time, they will also be conducting experiments. This course is loaded with practicals. Some of the ex- small part of the project, they are inperiments go on for four to five valuable experiences," she offered. weeks," Shylaia said.

Students move out of the classrooms Not so popular during the final year, when practicals REAP however, has very few takers and completely take over. "In the third year, many students fail to sustain their instudents will be paired with local sci-terest in research. When the first year to a more advanced level and students entists, and be part of their ongoing, ends, our classroom strength size is of the programme is July 23.

research studies. We have students visiting IISc, the National Centre for Biological Sciences (NCBS) and other such institutes. Even though they are only a

usually around 25 and it becomes half the size by the end of the second year, But those who do complete the three years usually take up integrated Phd programmes offered here or even go abroad," she said. "The programme that was started 10 years ago is only recognised at an academic level. So, a certificate of having completed this programme would not register with importance at a workplace that is outside of the academic world but every year we have students who take up Phil and

that is an achievement," she says. While the course is structured to boost the academics of a BSc student, according to Shylaia, students pursuing engineering degrees also take up the course, "Engineering students have recently started approaching us to be part of the programme. But it is very hard for engineering students to focus after the first year because our structure works around the schedule of an average BSc student but we also have had such students who completed all three years," she added.

When the course was launched, it was offered free of cost. Now, the fees for REAP programmes start at ₹350. The last date for submission of applications 3 year program, mainly for UG students

★ Classes on advanced topics during the weekends

Field trip to the Vainu Bappu Observatory (IIA), Kavalur

★ Professors from IIA, RRI, ICTS, IISc

★ Experimental work

★ Exams at the end of each year

★ Final year students do a research project at one of the other related institutes

Successful students get a scholarship from the Government of India



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. Scholtz et al. (2019)

