Probing Primordial Black Holes with Gravitational Waves

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UNIVERSITY OF AMSTERDAM

Structure of the Talk

What are Primordial Black Holes (PBHs)?

PBH Formation Mechanism Theories

PBHs as Dark Matter

PBHs and Gravitational Waves

Detecting PBHs

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!

Generating PBHs and small-scale GWs in two-field models of inflation

Authors: Matteo Braglia, Dhiraj Kumar Hazra, Fabio Finelli, George F. Smoot, L. Sriramkumar, Alexei A. Starobinsky

Submitted 9 August, 2020; **v1** submitted 6 M

Primordial black holes as dark matter and

Authors: Ogan Özsoy, Zygmunt Lalak

White holes, primordial black holes and Dark Matter

Authors: Bikash Sinha

Submitted 6 August, 2020; **originally announced** August 2020.

Primordial Black Holes as Dark Matter

Authors: Tom Bar

Submitted 1 August,

GW190425 and GW190814: Two candidate mergers of primordial black holes from the QCD epoch

Authors: Sebastien Clesse, Juan Garcia-Bellido

Submitted 13 July, 2020; **originally announced** July 2020.

Primordial Black

Authors: Anne M. Green, Bradley J. Kavanagh

Submitted 11 August, 2020; **v1** submitted 21 July, 2020; **originally announced** July 2020.

Prospects for probing ultralight primordial black holes using the stochastic gravitational-wave background induced by primordial curvature perturbations

Has LIGO Detected Primordial Black Hole Dark Matter? -- Tidal Disruption in Binary Black Hole Formation

Authors: Yuan Gao, Xiaojia Zhang, Meng Su

Submitted 28 July, 2020; **originally announced** July 2020.

Primordial Black Holes and Secondary Gravitational Waves from Higgs field

Authors: Zhu Yi, Yungui Gong, Bin Wang, Zong-hong Zhu

announced July 2020.

Primordial Black Hole Dark Matter and the LIGO/Virgo observations

Authors: Karsten Jedamzik

Submitted 13 July, 2020; **v1** submitted 19 June, 2020; **originally announce**

Evidence for primordial black hole dark matter from LIGO/Virgo merger rates

Authors: Karsten Jedamzik

Submitted 13 July, 2020; **v1** submitted 7 July, 2020; **originally announced** July 2020.

Is GW170817 a Multimessenger Neutron Star-Primordial Black Hole Merger?

Authors: Yu-Dai Tsai, Antonella Palmese, Stefano Profumo, Tesla Jeltema

Submitted 7 July, 2020; **originally announced** July 2020.

Is Planet 9 a PBH?

(arXiv:1909.11090)

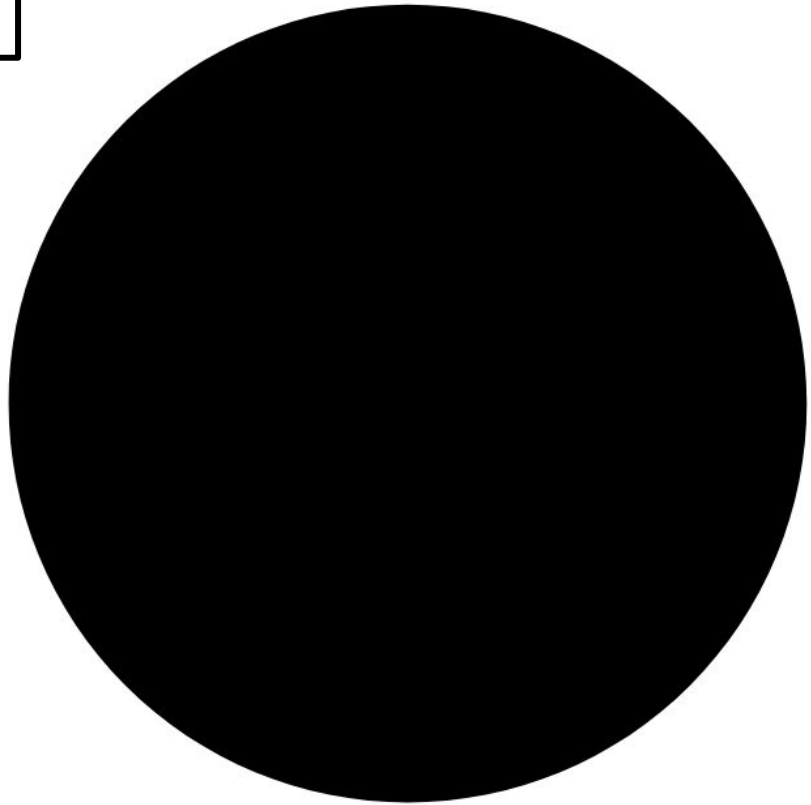
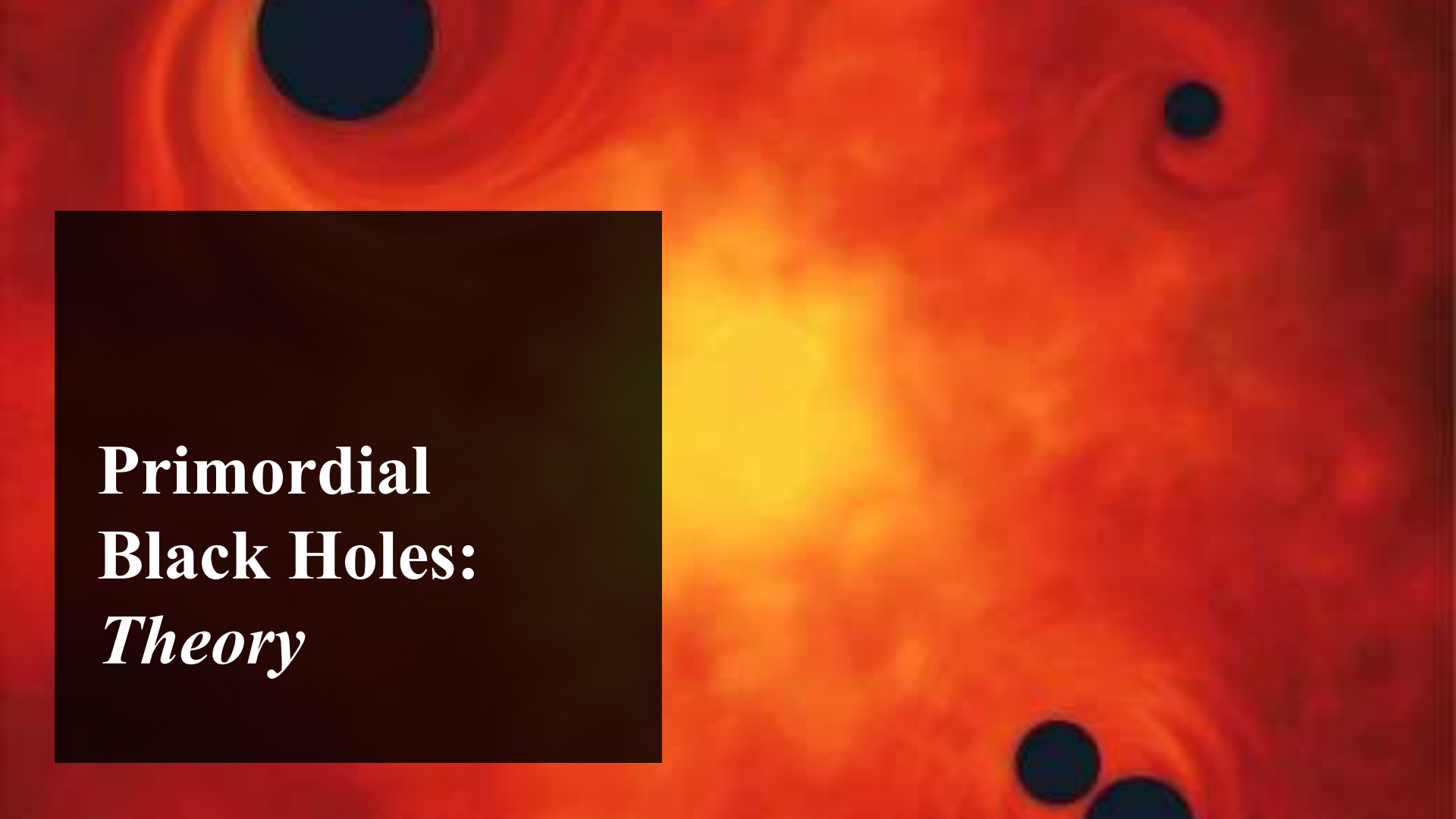


FIG. 1. Exact scale (1:1) illustration of a $5M_\oplus$ PBH. Note that a $10M_\oplus$ PBH is roughly the size of a ten pin bowling ball.

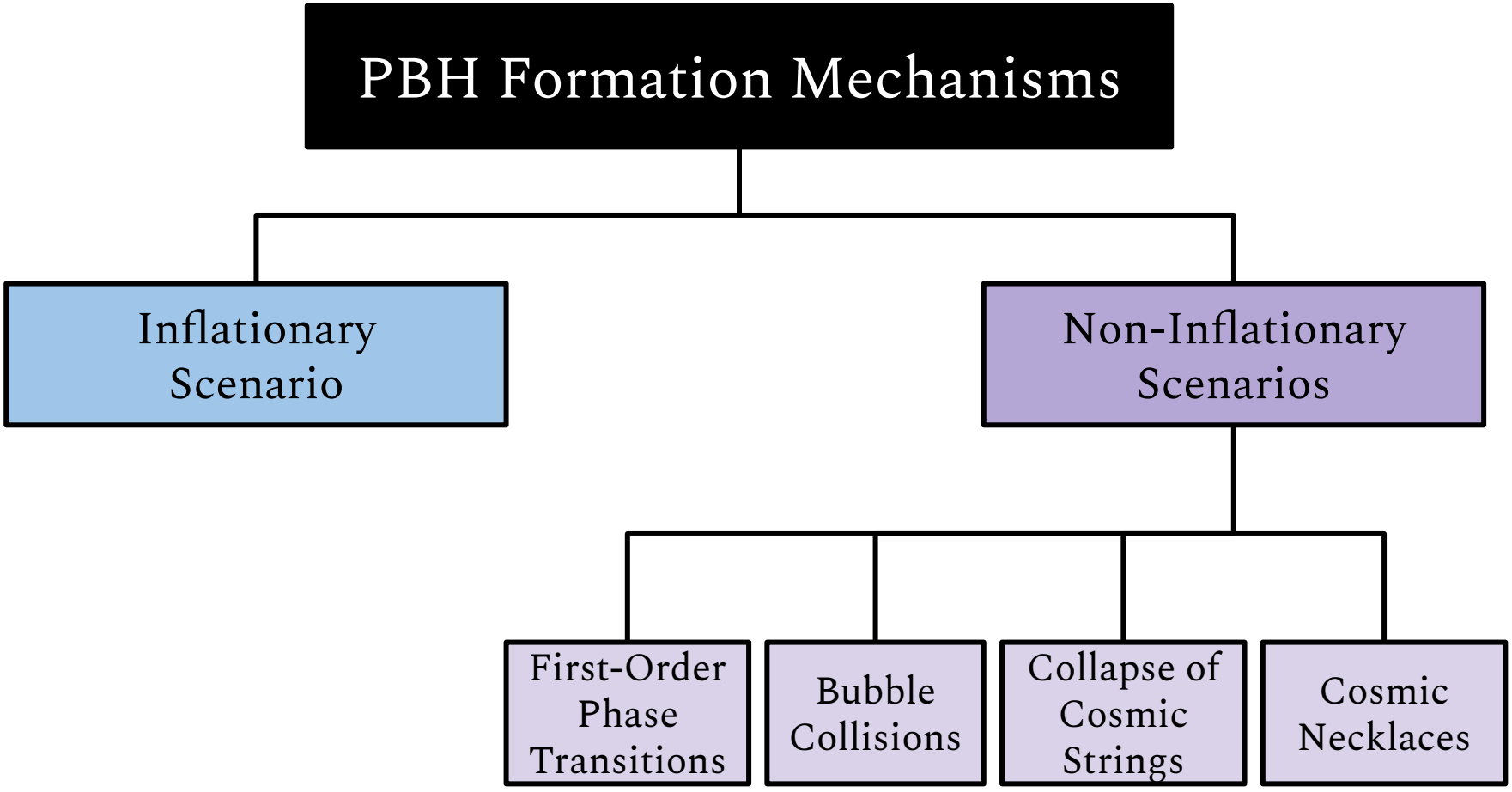


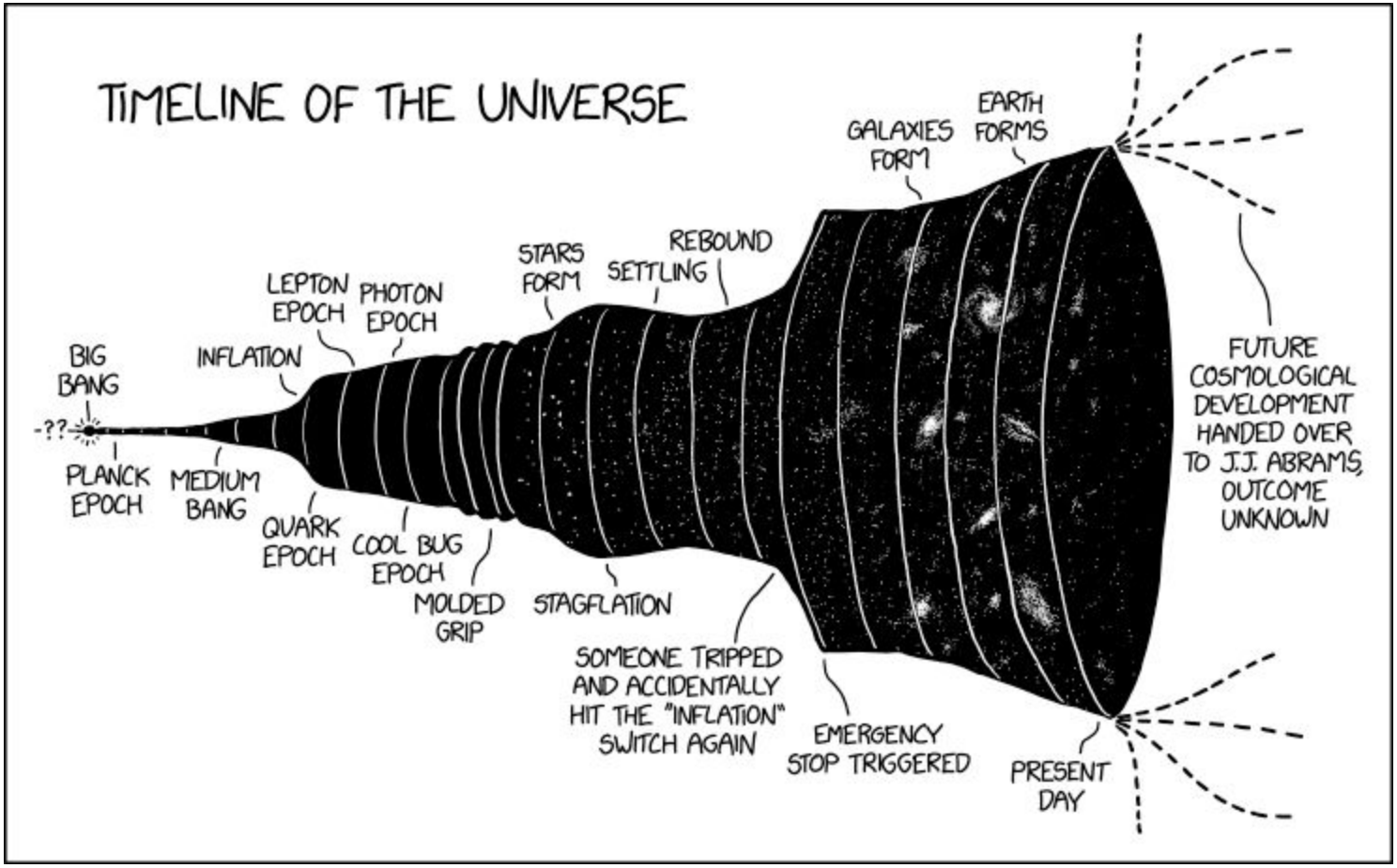
Primordial Black Holes: *Theory*

Basis of Primordial Black Hole Formation

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

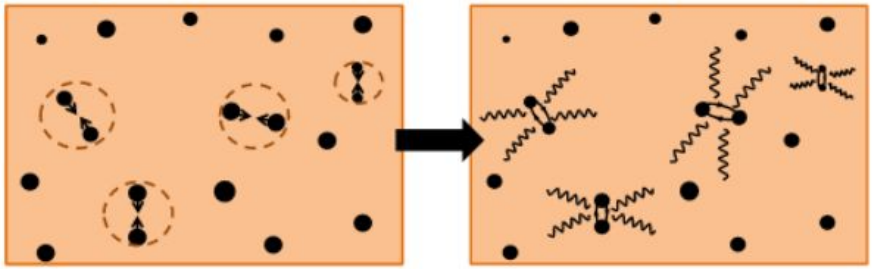
But how and why did these inhomogeneities arise?


PBH Formation Mechanisms
Inflationary Scenario
Non-Inflationary Scenarios
First-Order Phase Transitions
Bubble Collisions
Collapse of Cosmic Strings
Cosmic Necklaces


TIMELINE OF THE UNIVERSE
BIG BANG
-??-
PLANCK EPOCH
MEDIUM BANG
INFLATION
LEPTON EPOCH
PHOTON EPOCH
QUARK EPOCH
COOL BUG EPOCH
MOLDED GRIP
STARS FORM
STAGFLATION
REBOUND
SETTLING
SOMEONE TRIPPED AND ACCIDENTALLY HIT THE "INFLATION" SWITCH AGAIN
GALAXIES FORM
EARTH FORMS
EMERGENCY STOP TRIGGERED
PRESENT DAY
FUTURE COSMOLOGICAL DEVELOPMENT HANDED OVER TO J.J. ABRAMS, OUTCOME UNKNOWN

Inflationary Scenario

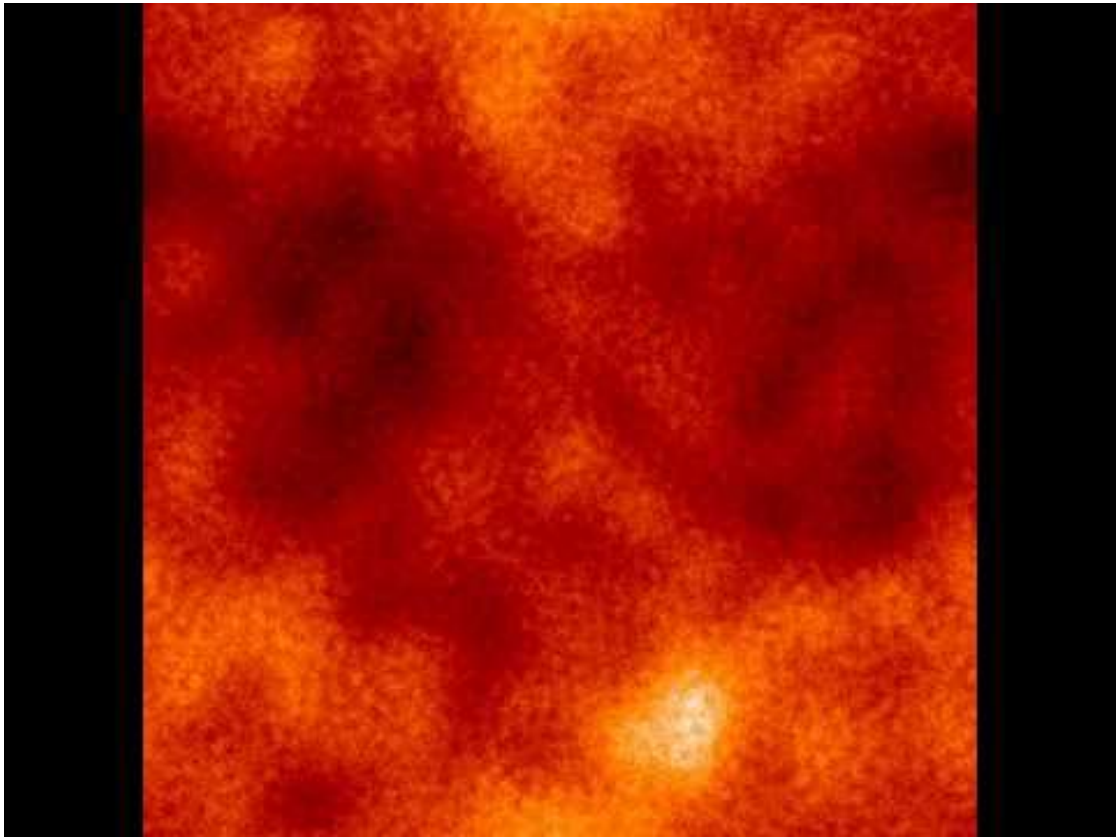
- ★ Inflation led to a homogenous Universe
- ★ Amplitude of density fluctuations in a perturbed region
- ★ If greater than a critical amplitude, PBHs formed



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)



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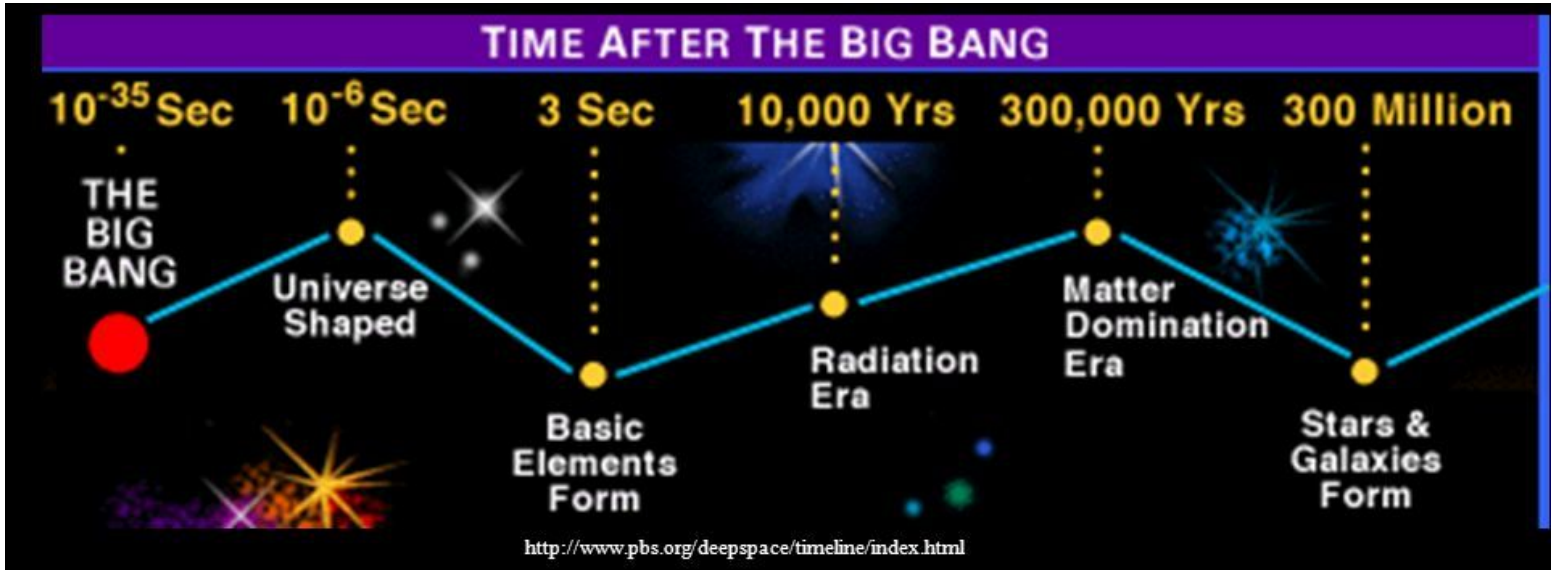

TIME AFTER THE BIG BANG
10-35 Sec
10-6 Sec
3 Sec
10,000 Yrs
300,000 Yrs
300 Million
THE BIG BANG
Universe Shaped
Basic Elements Form
Radiation Era
Matter Domination Era
Stars & Galaxies Form
http://www.pbs.org/deepspace/timeline/index.html

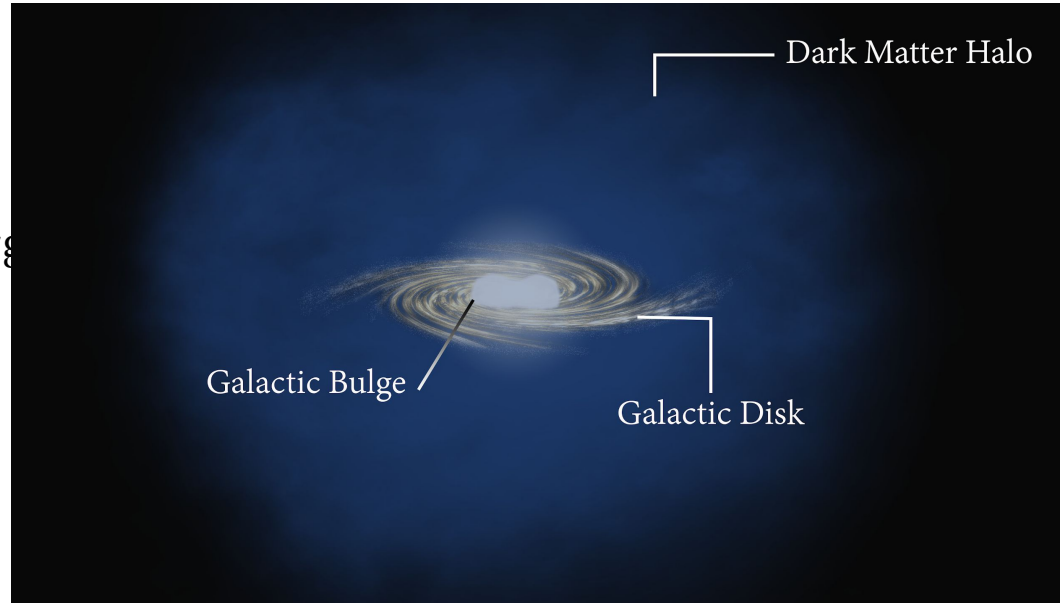
Open Problem

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 larg dark matter halos
- ★ Interacts with another PBH and forms a binary

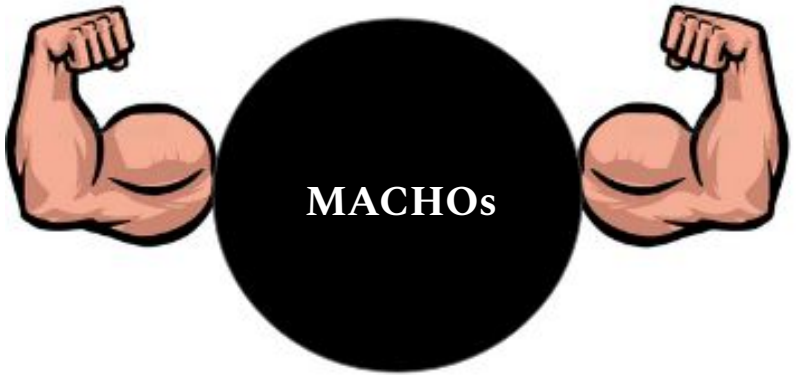


Open Problem

How did Primordial Black Holes really form?

Primordial Black Holes as Dark Matter

Weakly **I**nteracting **M**assive **P**articles

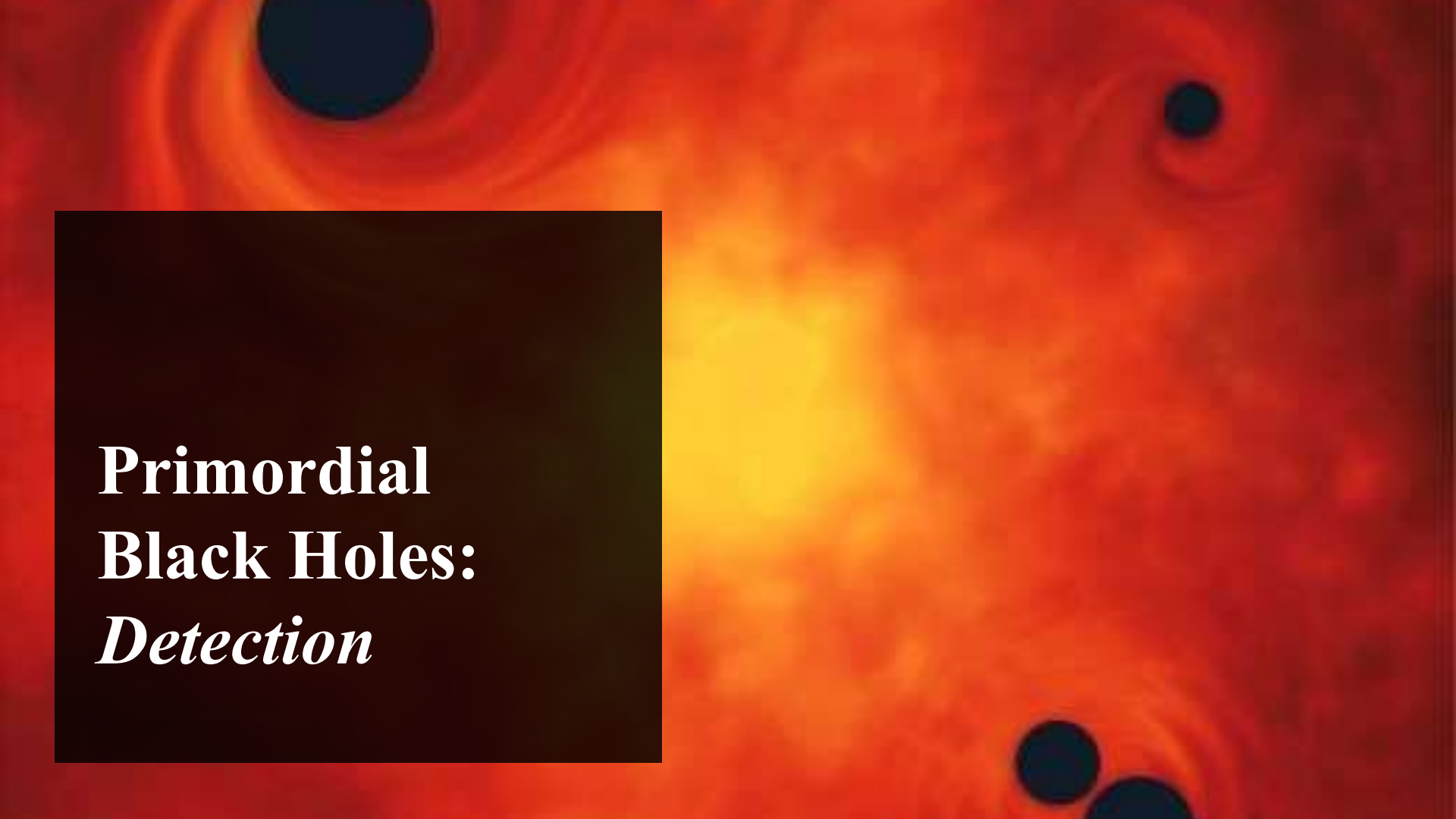


Massive **A**strophysical **C**ompact **H**alo **O**bject

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. Riess[1]

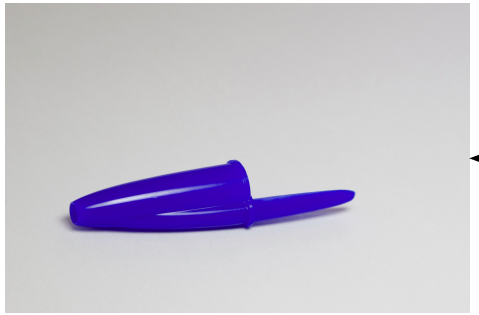
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

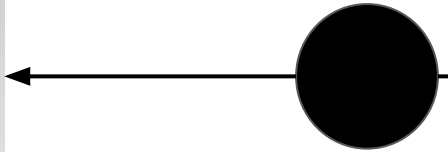


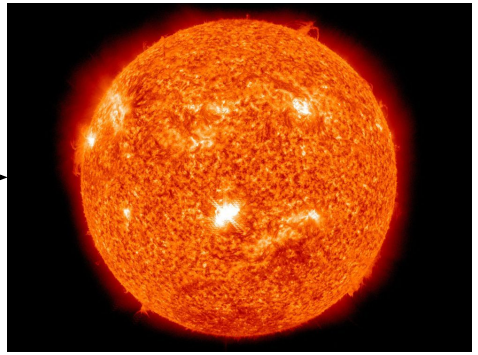
Primordial Black Holes: *Detection*

Primordial Black Holes are predicted to exist over all masses.

(Carr 2005)



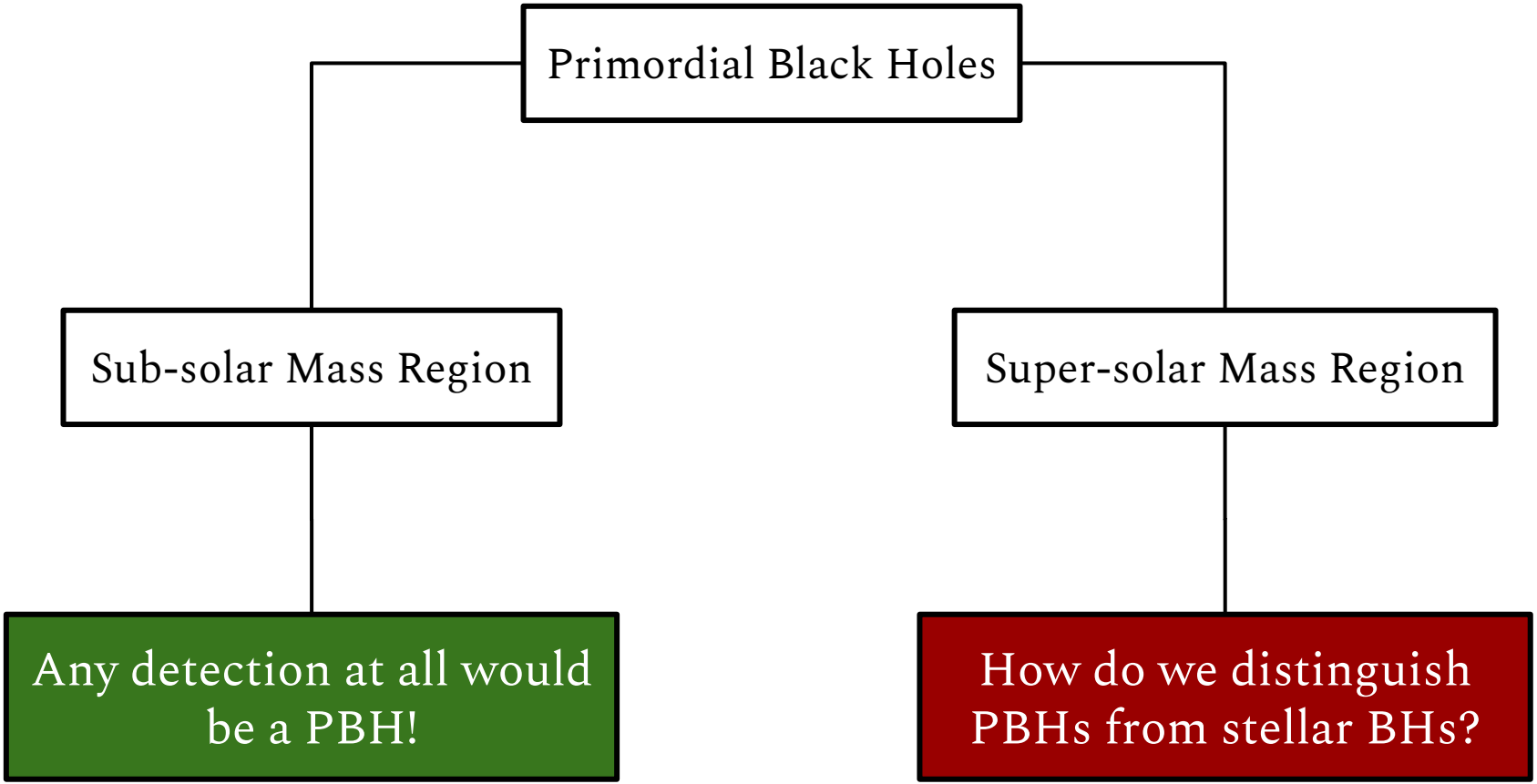


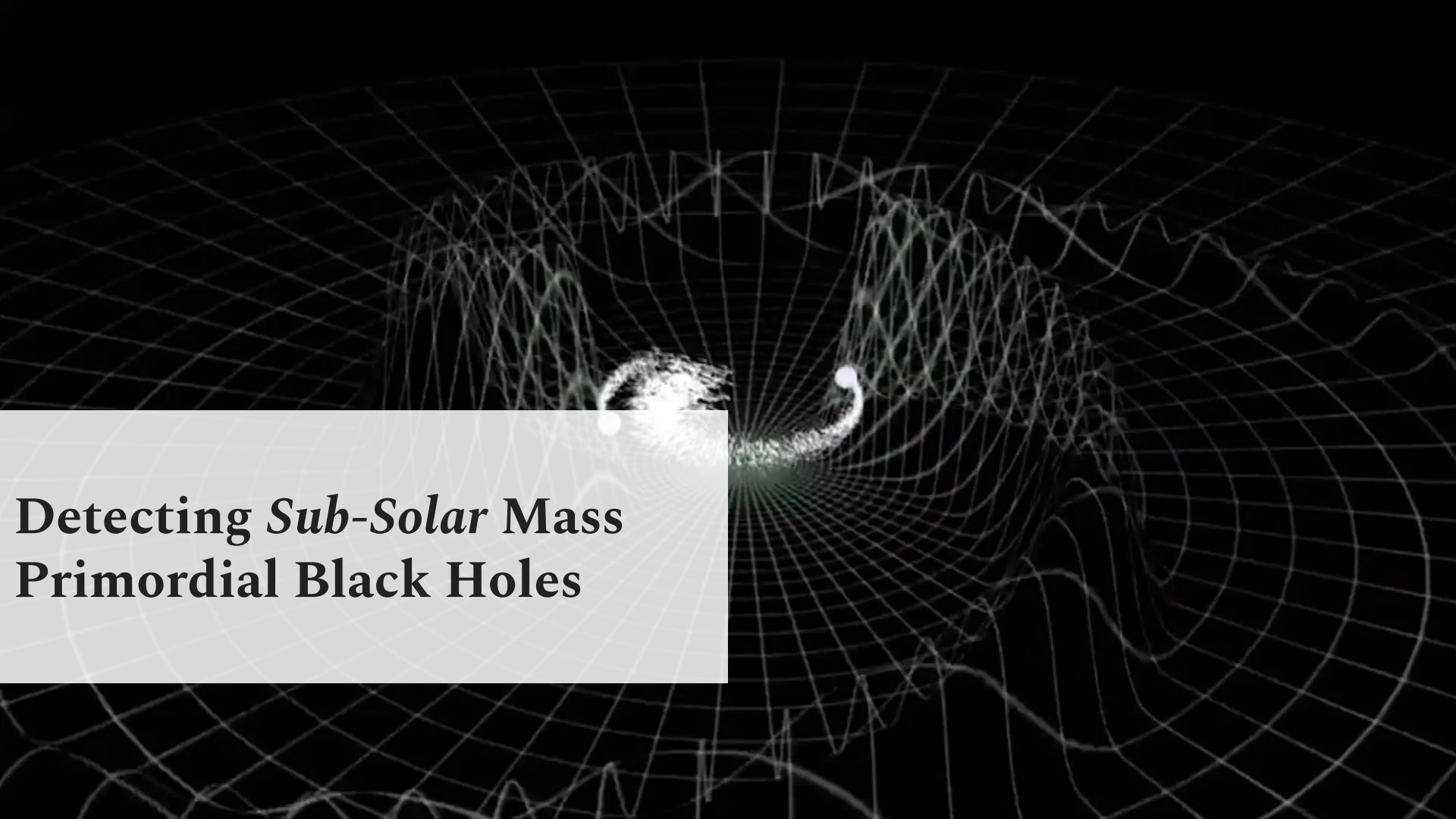


10^{-5} gram
or
10,000 times less
than the mass of a
pen cap

10^{6} Msun
or
100,000 times the
mass of the Sun

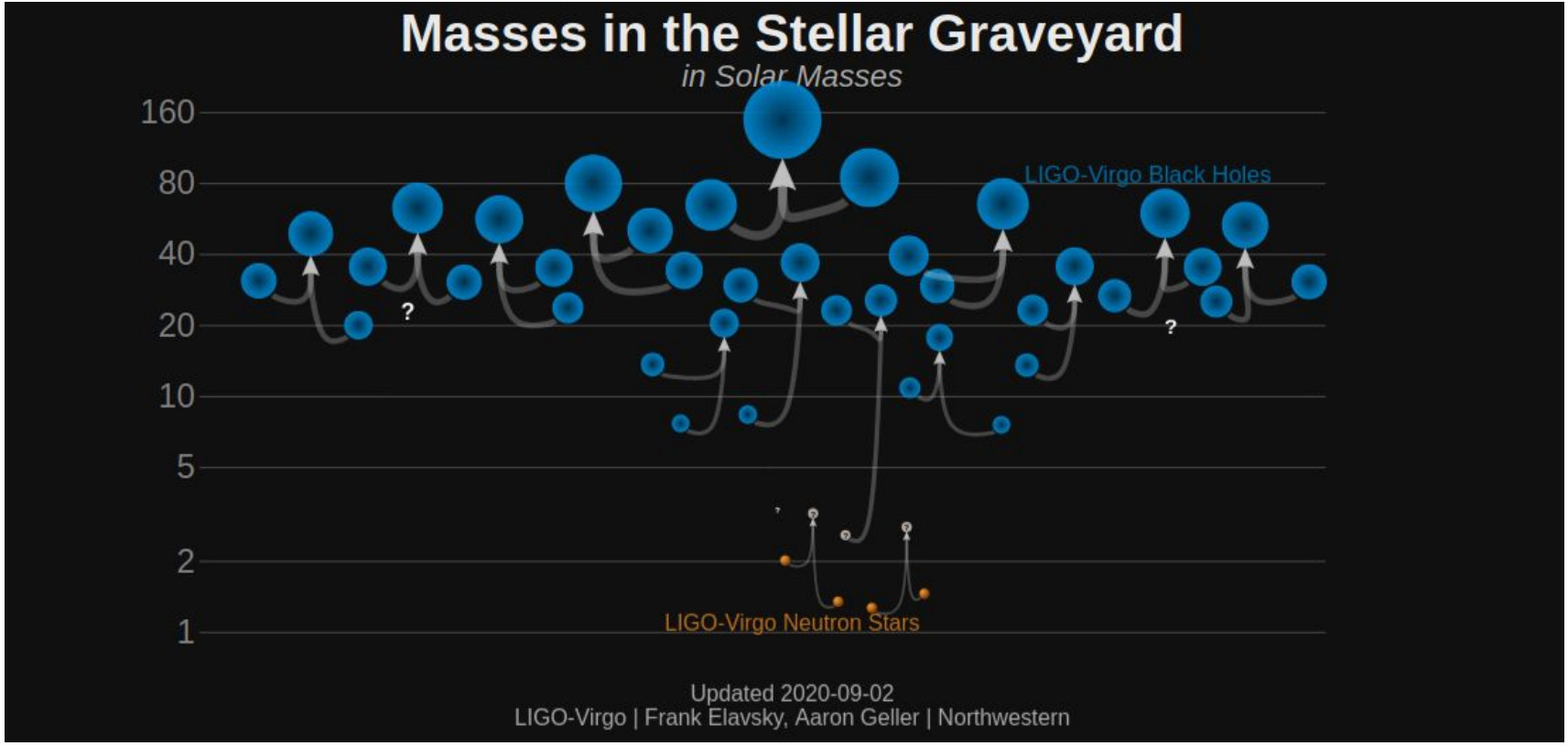
Mass of a pen cap ~ 1 gram
Mass of the Sun (Msun) ~ 10^{33} gram


Primordial Black Holes
Sub-solar Mass Region
Super-solar Mass Region
Any detection at all would be a PBH!
How do we distinguish PBHs from stellar BHs?



Detecting *Sub-Solar* Mass Primordial Black Holes

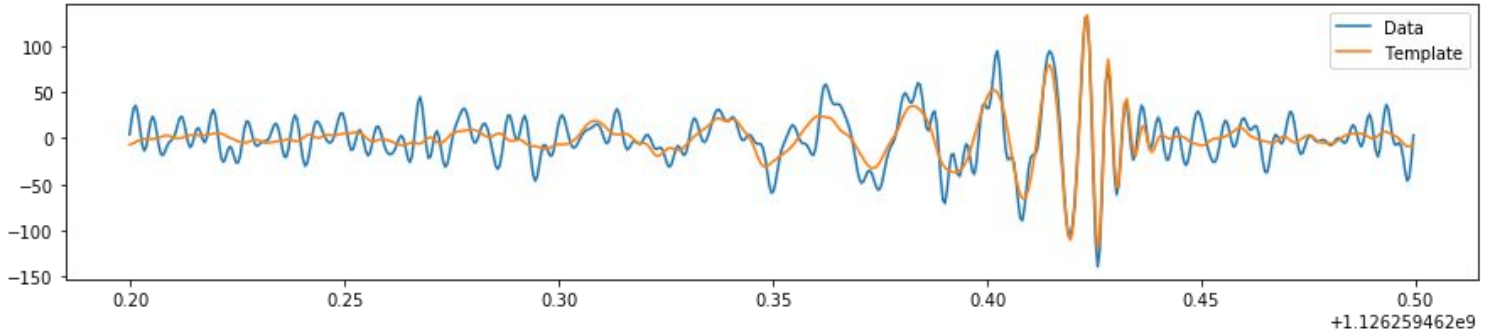
Why consider the Sub-Solar Mass Region?



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

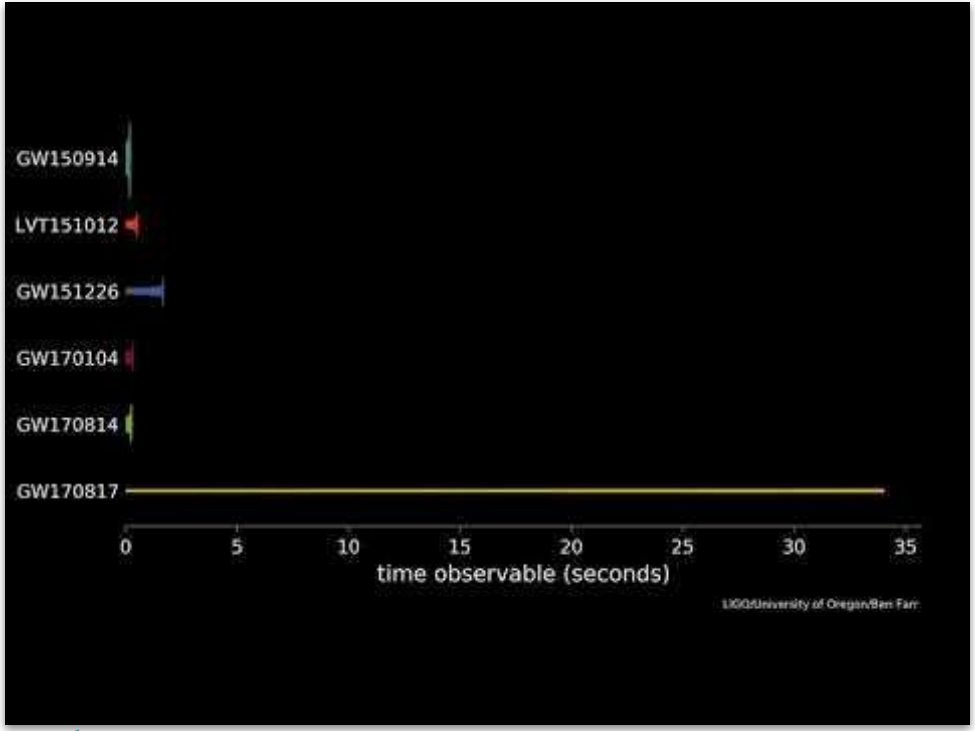
★ Very long waveforms

★ 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?



Link

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

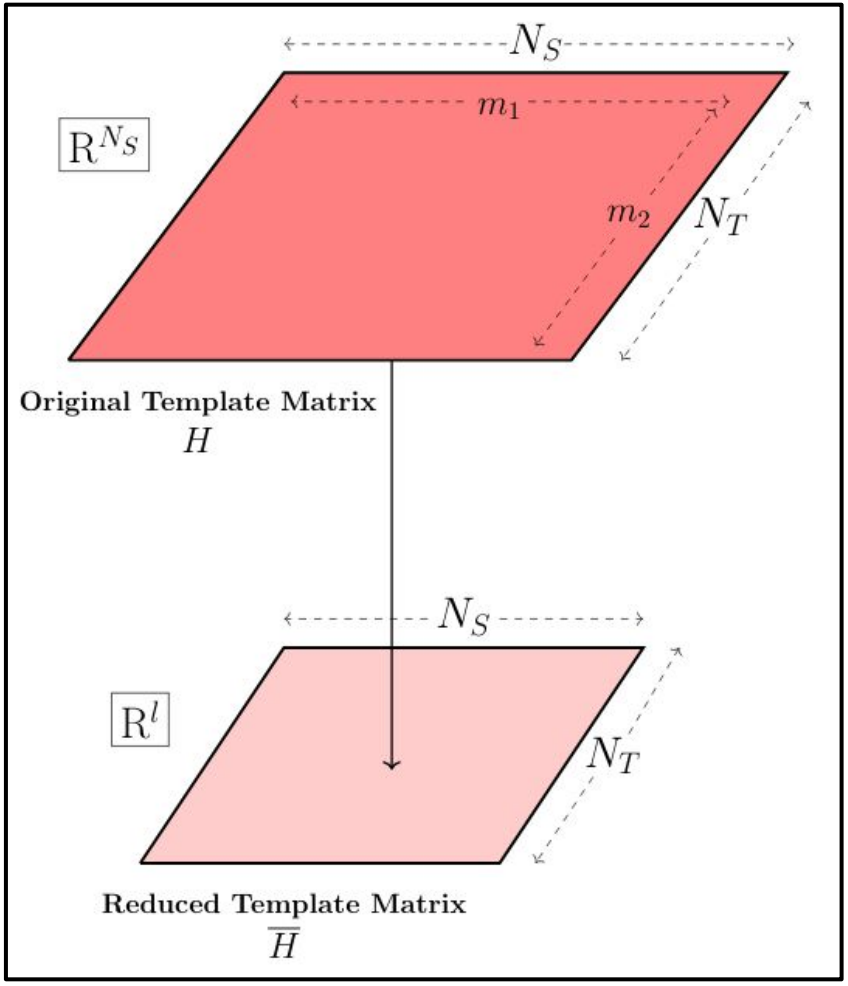
Search for sub-solar mass ultracompact binaries in Advanced LIGO's first observing run

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)



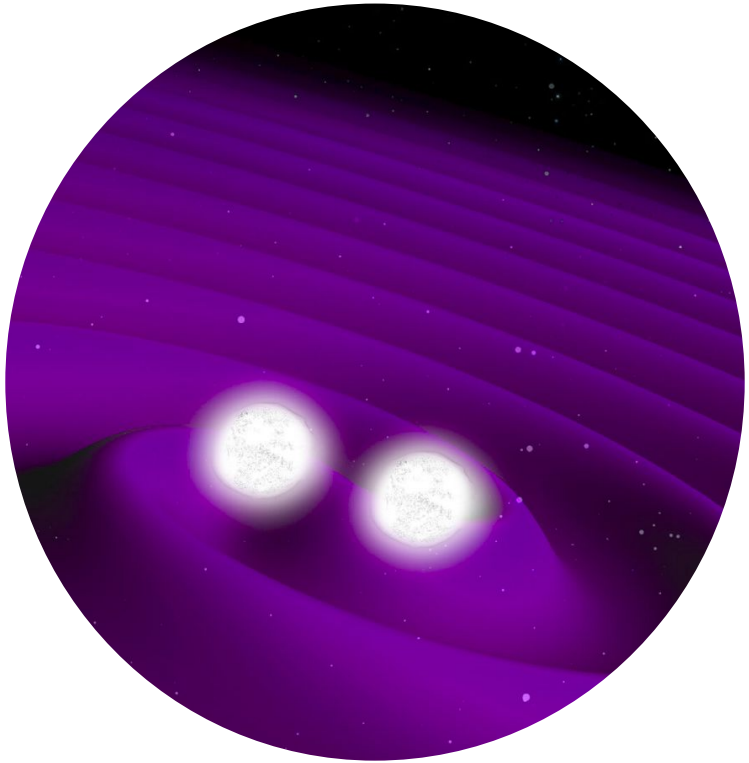
A Solution

Random-Projection Based Singular Value Decomposition (RSVD)

Kulkarni et al. (2019)

RSVD performed better in terms of:

- ★ Time
- ★ Computational Costs
- ★ Overall Efficiency

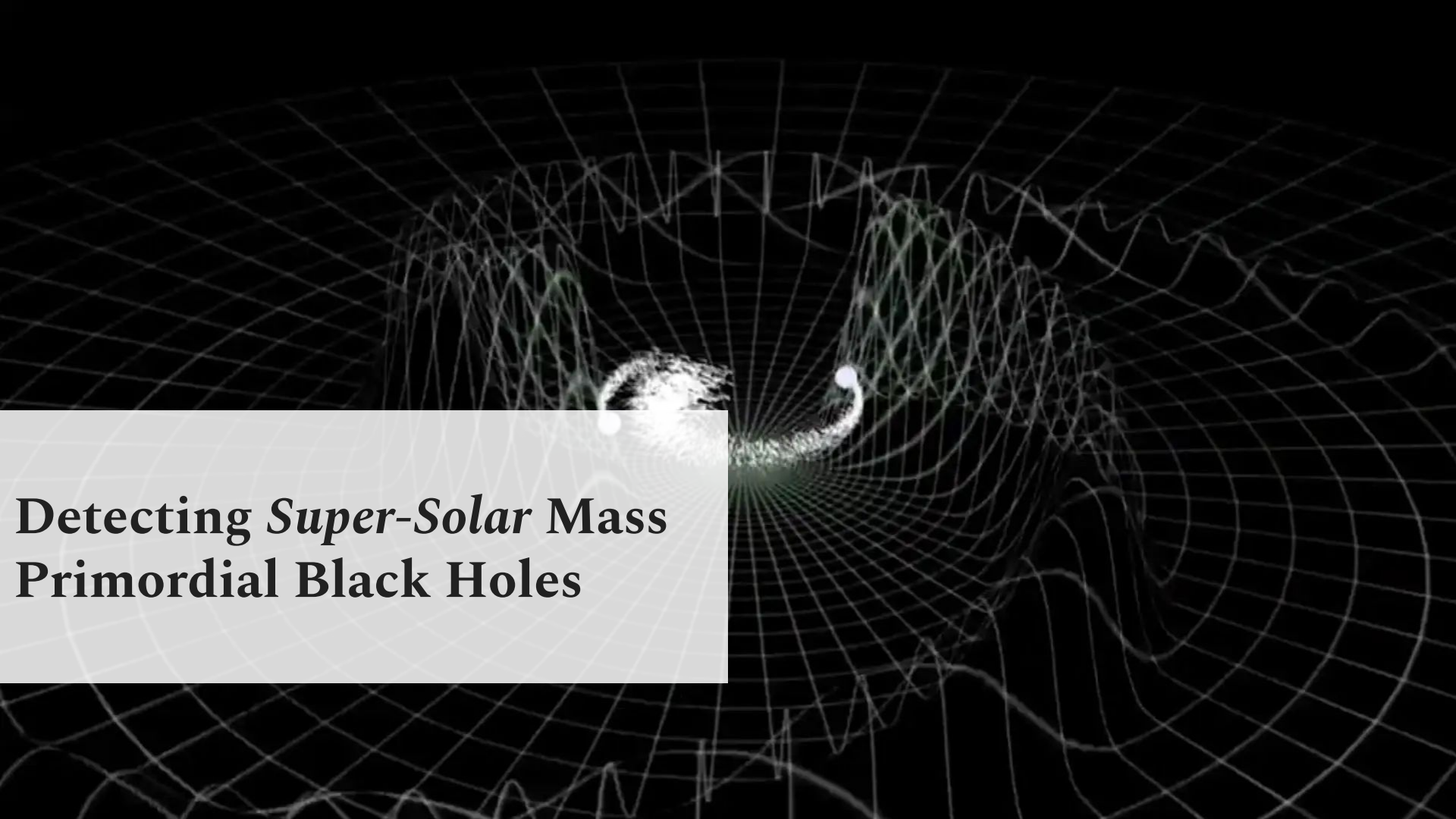


CONCLUSION

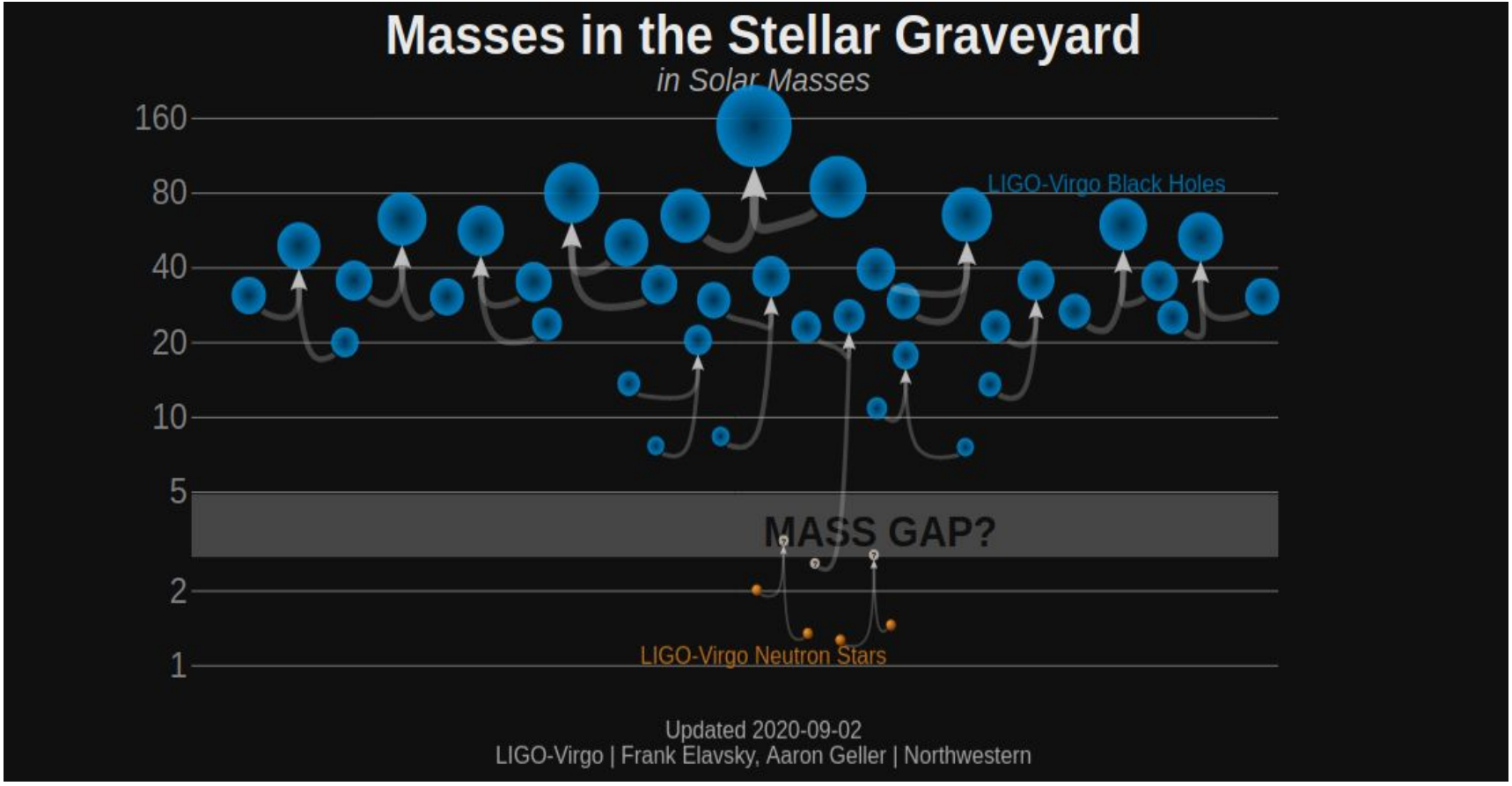
RSVD IS A BETTER METHOD THAN SVD

Open Problem

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



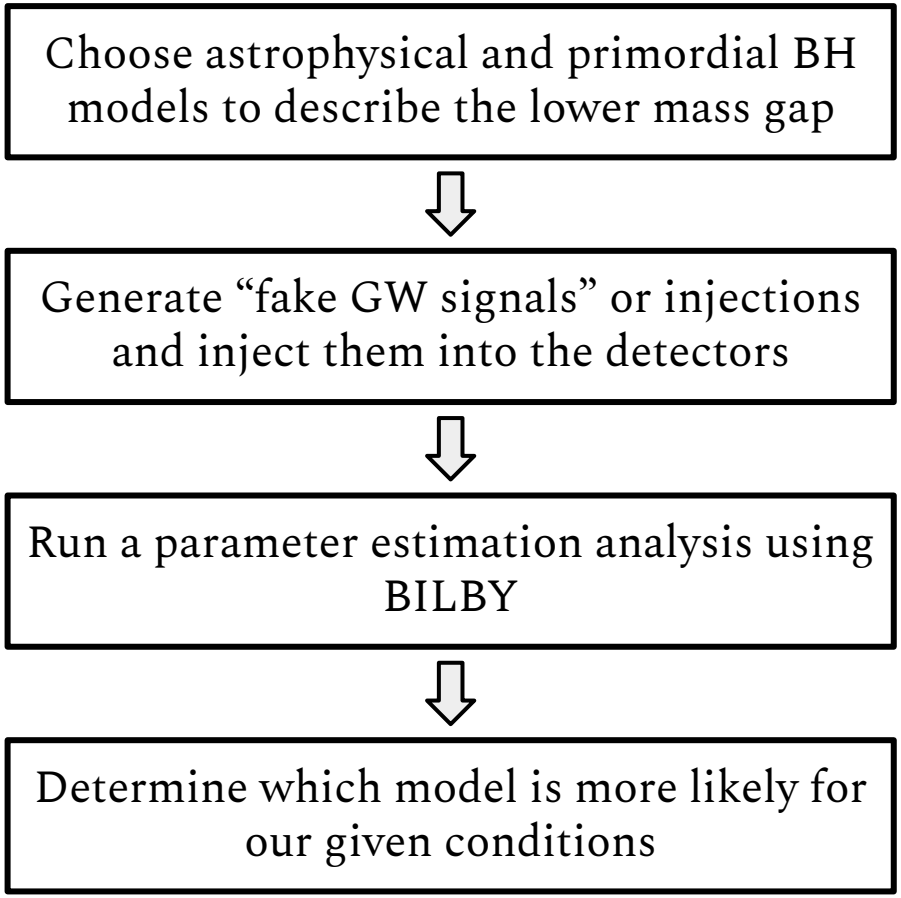
Detecting *Super-Solar* Mass Primordial Black Holes


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
MASS GAP?
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Open Problem

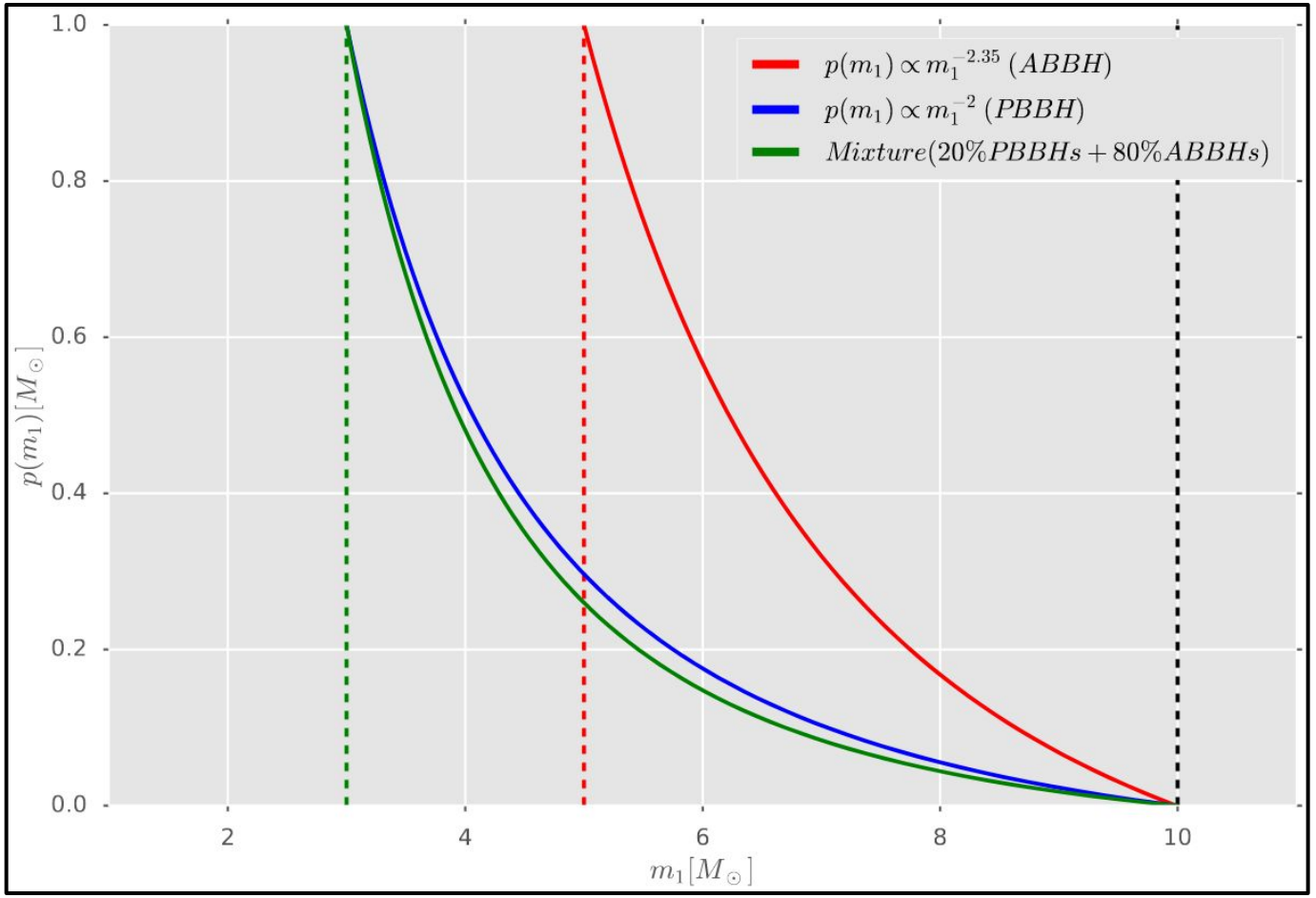
How do we distinguish between astrophysical/stellar black holes and primordial black holes?

The Framework

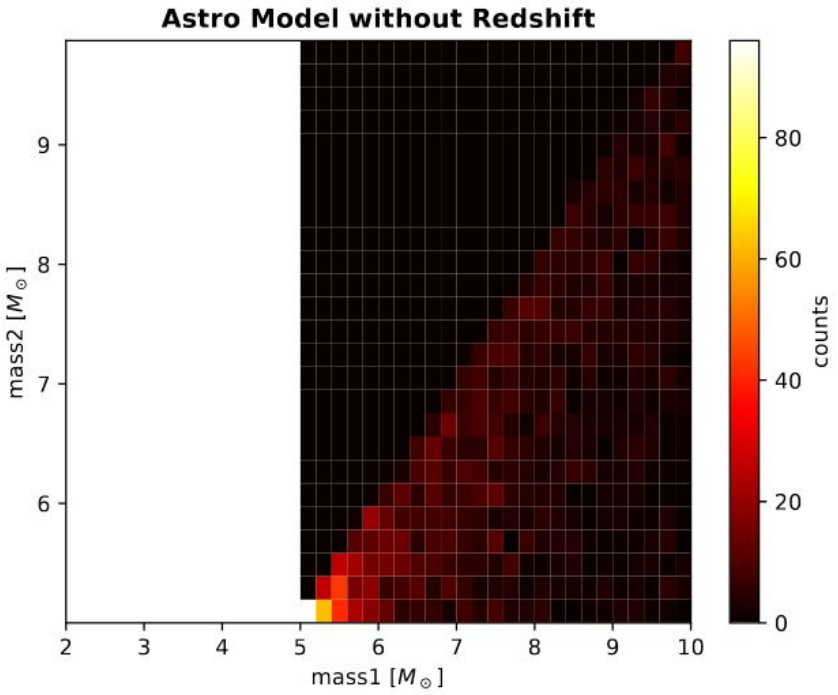


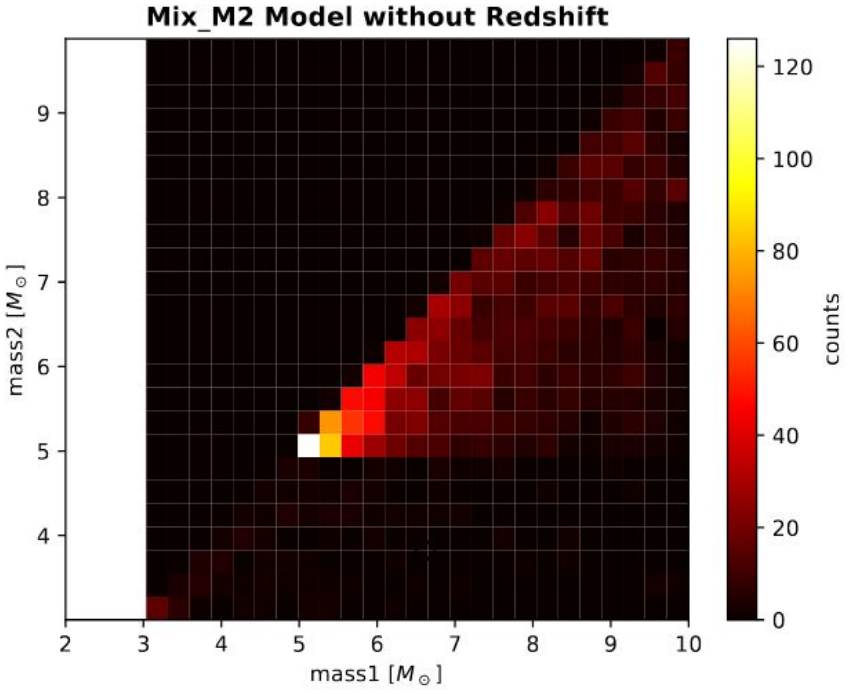
Choosing Models ("Priors")

(test run)

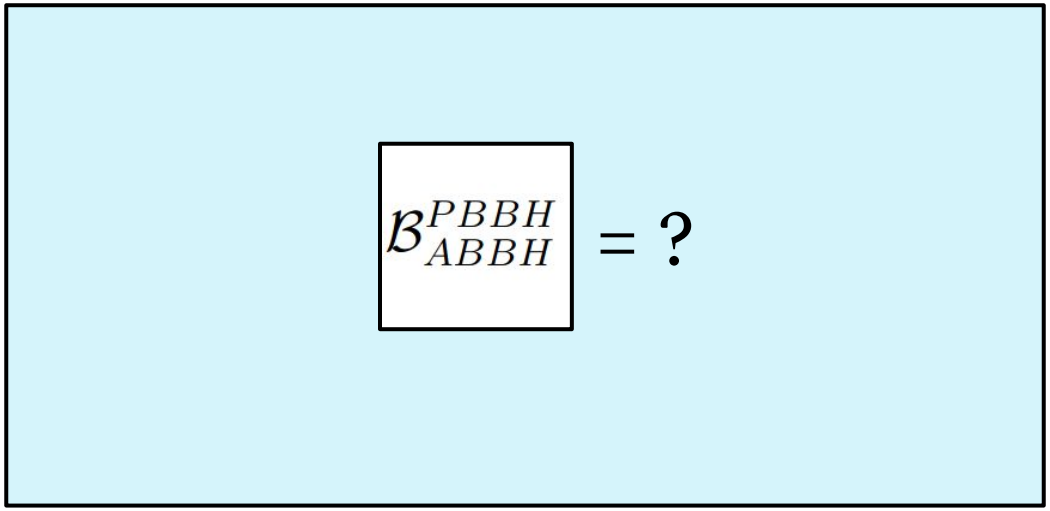


Simulating GW Populations



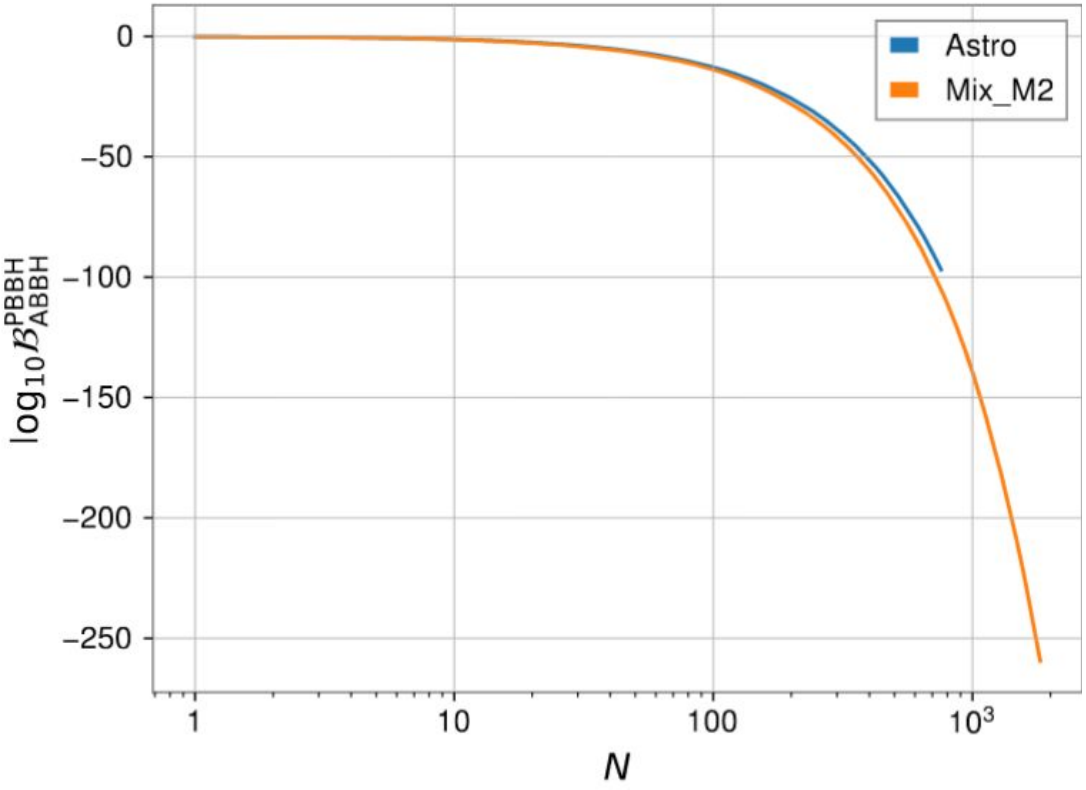


Calculating the Bayes Factor

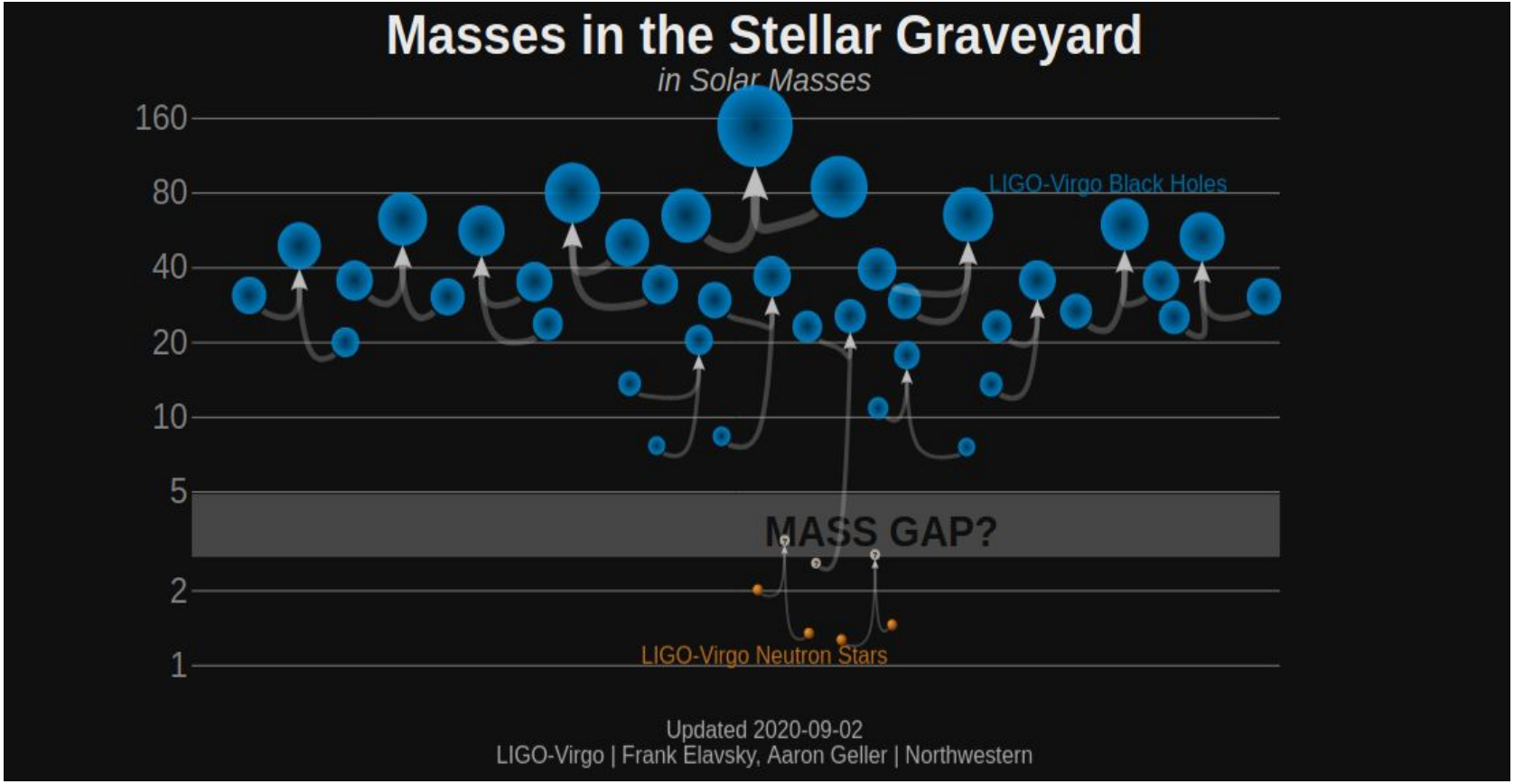


PBBH Bayes Factor in the Lower Mass Gap

(test run)



Recent Detections in the Lower Mass Gap



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 (χ_{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?

BASE & REAP

Bangalore **A**ssociation for **S**cience **E**ducation (**BASE**)

Jawaharlal Nehru Planetarium (JNP), Bangalore

Founded by **Prof. C V Vishveshwara**

(also called the ‘Black Hole Man of India’)

Research
Education
Advancement
Programme
[(REAP)]

BANGALORE
DNA
DAILY NEWS AND ANALYSIS

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 Indian 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 Shylaja, 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 conducted during the weekends. "We want to motivate students to pursue research. During the three years of the course, students will be lectured by scientists from IISc, IIA and RRI as well. The scientists also evaluate the performance of the students," Shylaja said.

Students get to learn the basics in the first year. "They will be taught the basics of astronomy, astrophysics and mathematics. They are also given homework and we are very strict about attendance. This is a course that should be taken seriously," Shylaja warned.

Students also get to visit research institutes as part of the programme. "Bangalore has many research institutes. The second year will take things to a more advanced level and students will be exposed to subjects like quantum mechanics and electrodynamics. At that time, they will also be conducting experiments. This course is loaded with practicals. Some of the experiments go on for four to five weeks," Shylaja said.

Students move out of the classrooms during the final year, when practicals completely take over. "In the third year, students will be paired with local scientists and be part of their ongoing research studies. We have students visiting IISc, the National Centre for Biological Sciences (NCBS) and other such institutes. Even though they are only a small part of the project, they are invaluable experiences," she offered.

Not so popular

REAP, however, has very few takers and many students fail to sustain their interest in research. "When the first year ends, our classroom strength size is 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 that 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 Phd and that is an achievement," she says.

While the course is structured to boost the academics of a BSc student, according to Shylaja, 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 stat at ₹350. The last date for submission of applications of the programme is July 23.

- ★ 3 year program, mainly for UG students
- ★ Classes on advanced topics during the weekends
- ★ Professors from IIA, RRI, ICTS, IISc
- ★ Experimental work
- ★ Field trip to the Vainu Bappu Observatory (IIA), Kavalur
- ★ Exams at the end of each year
- ★ Successful students get a scholarship from the Government of India
- ★ Final year students do a research project at one of the other related institutes

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)

Extra Slides