Primordial black hole Dark matter: Part-2

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arXiv: 2109.01678

The Dark Side of the Universe: How Black Holes Became Supermassive

We will look at two types of supermassive black holes here:

- Galaxies' centers
- Quasars' centers

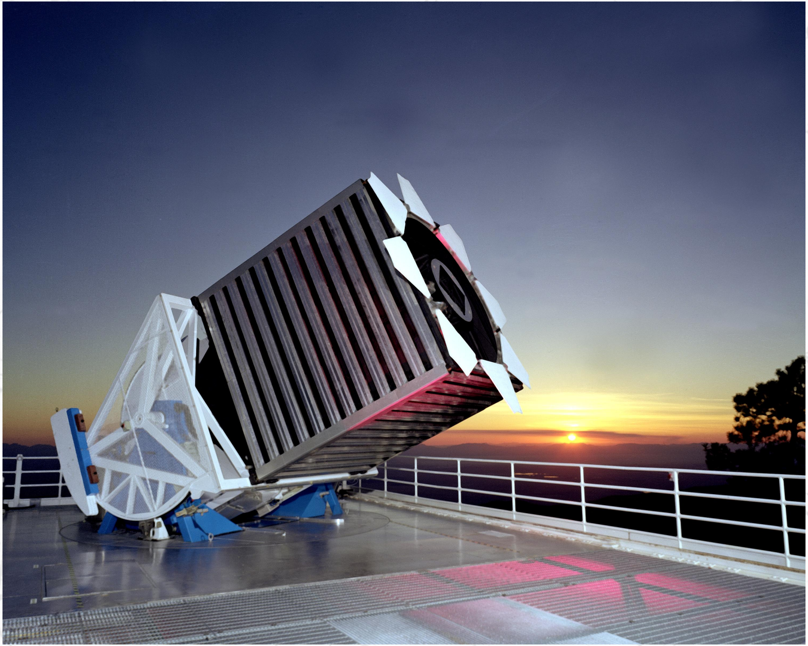
Center of galaxies

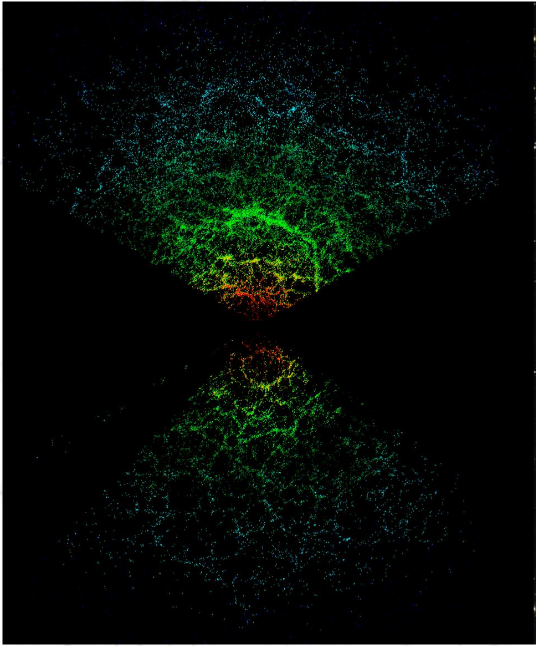
- Tiny Galaxies Reveal Supermassive Black Holes' Secrets.
- Dwarf galaxies weren't supposed to have big black holes.
- Their surprise discovery has revealed clues about how the universe's biggest black holes could have formed.

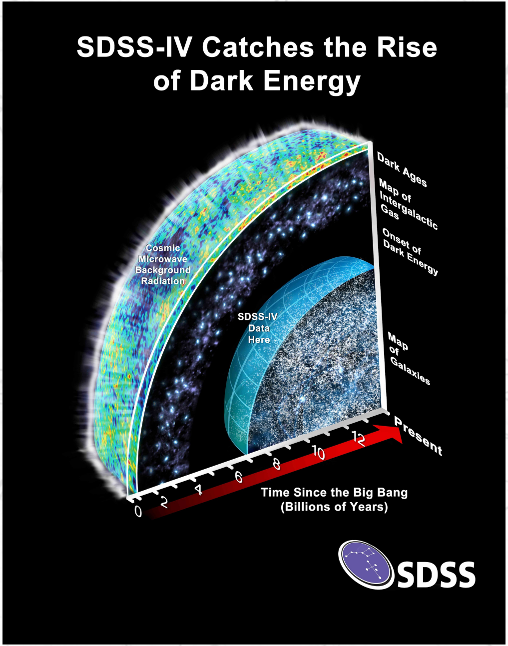
- The Sloan Digital Sky Survey has seen billion-solar-mass black holes dating back to the universe's first billion years.
- Astronomers couldn't figure out how they had gotten so heavy so quickly.

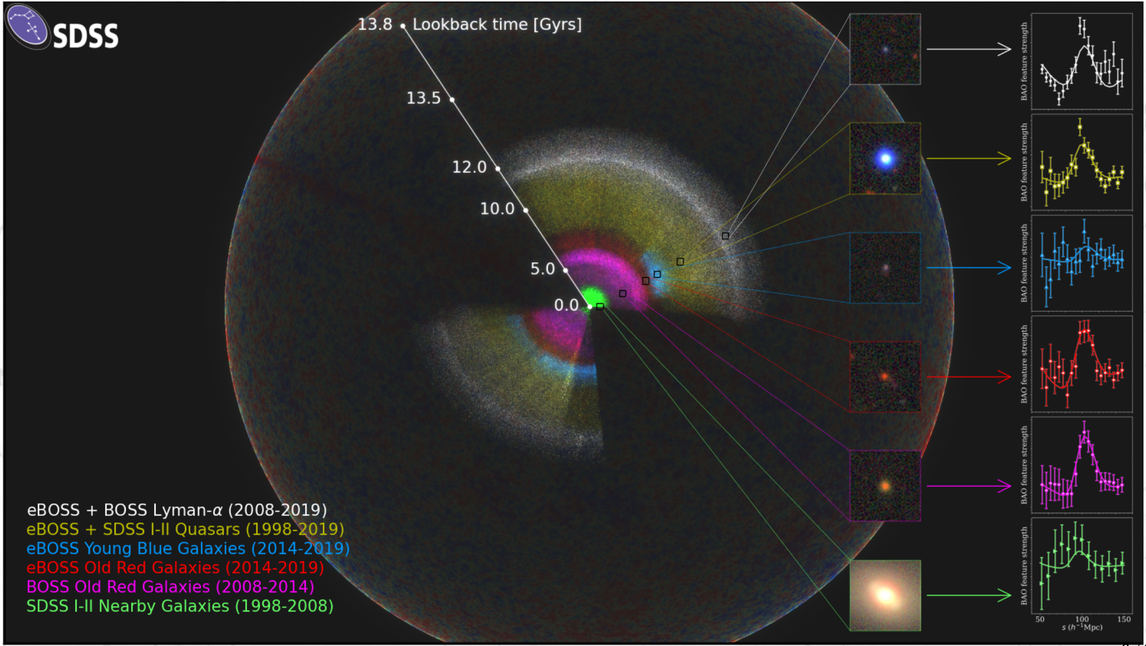
Sloan Digital Sky Survey

- The Sloan Digital Sky Survey, or SDSS, is a major multi-spectral imaging and spectroscopic redshift survey using a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico, United States.
- The project was named after the Alfred P. Sloan Foundation, which contributed significant funding.







SDSS-IV Catches the Rise of Dark Energy
Dark Ages
Map of Intergalactic Gas
Onset of Dark Energy
Cosmic Microwave Background Radiation
SDSS-IV Data Here
Map of Galaxies
Present
0
2
4
6
8
10
12
Time Since the Big Bang (Billions of Years)
SDSS


SDSS
13.8 Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
BAO feature strength
50
100
150
$s\ (h^{-1}\mathrm{Mpc})$
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)

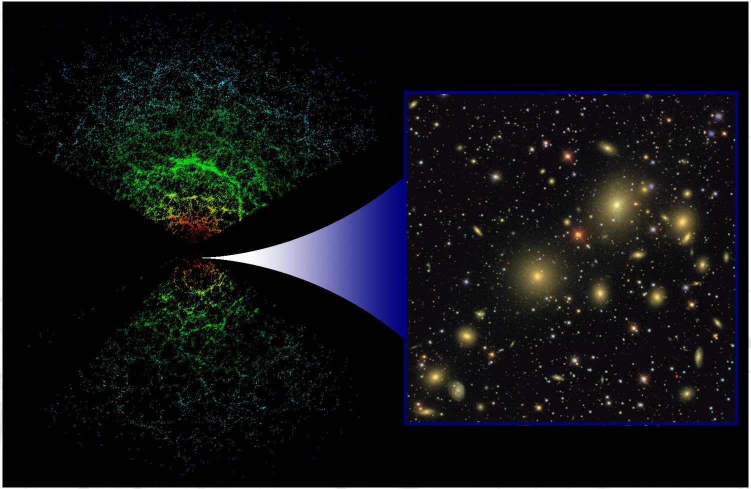


Figure: The SDSS is two separate surveys in one: galaxies are identified in 2D images (right), then have their distance determined from their spectrum to create a 2 billion light years deep 3D map (left) where each galaxy is shown as a single point, the color representing the luminosity - this shows only those 66,976 out of 205,443 galaxies on the map that lie near the plane of Earth's equator.

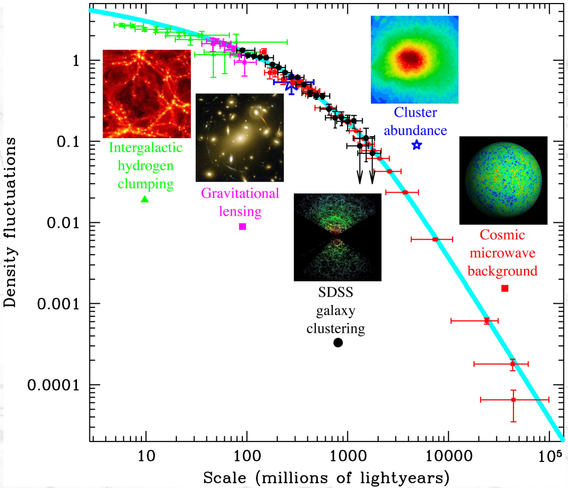


Figure: The new SDSS results (black dots) are the most accurate measurements to date of how the density of the Universe fluctuates from place to place on scales of millions of light years. These and other cosmological measurements agree with the theoretical prediction (blue curve) for a Universe composed of 5% atoms, 25% dark matter, and 70% dark energy. The larger the scales we average over, the more uniform the Universe appears.

Center of galaxies

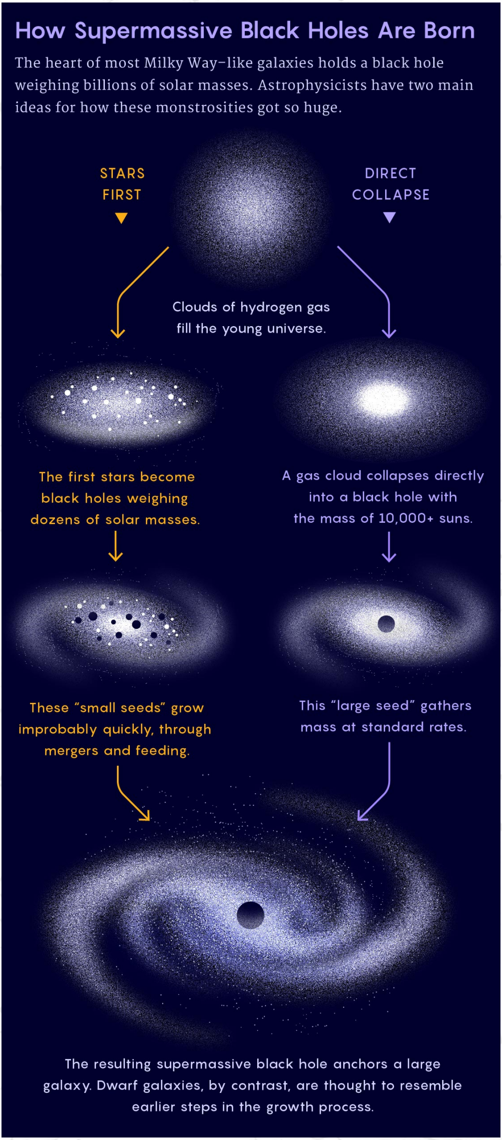
- About 46,000 dwarf galaxies were observed by the Sloan Digital Sky Survey, which found that 81 galaxies glimmered with the faint orange of damaged iron.
- In these dwarf galaxies, a giant black hole is heating the gas around it enough to blast electrons from their atoms.

Mallory Molina, Amy E. Reines, Colin J. Latimer, Vivienne Baldassare, and Sheyda Salehirad,
A Sample of Massive Black Holes in Dwarf Galaxies Detected via [Fe x] Coronal Line Emission:
Active Galactic Nuclei and/or Tidal Disruption Events,
2021 ApJ **922** *155*

Center of galaxies

- Astronomers should search the smallest of galaxies for colossal black holes – hulking behemoths weighing many thousands of solar masses.
- If they could find them, the objects could teach us how the universe's very first black holes formed.

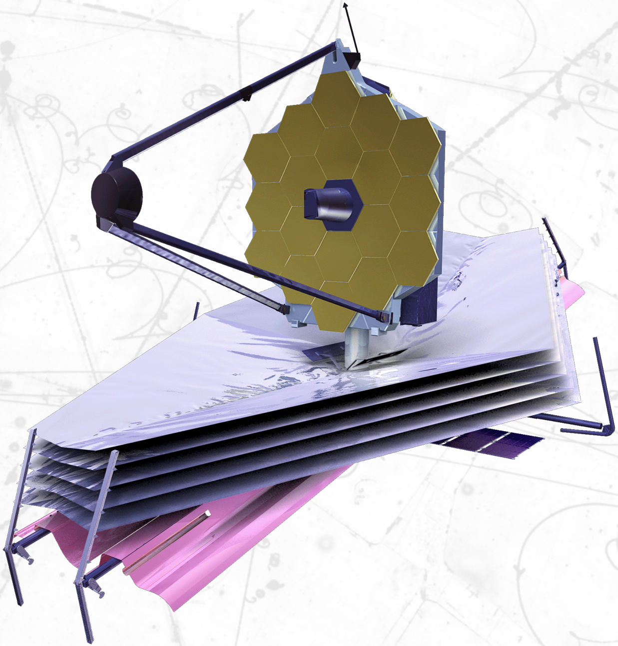
Marta Volonteri, Giuseppe Lodato, and Priyamvada Natarajan,
The evolution of massive black hole seeds,
Monthly Notices of the Royal Astronomical Society,
Volume 383, Issue 3, 21 January 2008, Pages 1079–1088



How Supermassive Black Holes Are Born
The heart of most Milky Way–like galaxies holds a black hole weighing billions of solar masses. Astrophysicists have two main ideas for how these monstrosities got so huge.
STARS FIRST
DIRECT COLLAPSE
Clouds of hydrogen gas fill the young universe.
The first stars become black holes weighing dozens of solar masses.
A gas cloud collapses directly into a black hole with the mass of 10,000+ suns.
These “small seeds” grow improbably quickly, through mergers and feeding.
This “large seed” gathers mass at standard rates.
The resulting supermassive black hole anchors a large galaxy. Dwarf galaxies, by contrast, are thought to resemble earlier steps in the growth process.

Center of galaxies

- The James Webb Space Telescope (JWST) will soon be able to determine whether this theory is correct or incorrect.



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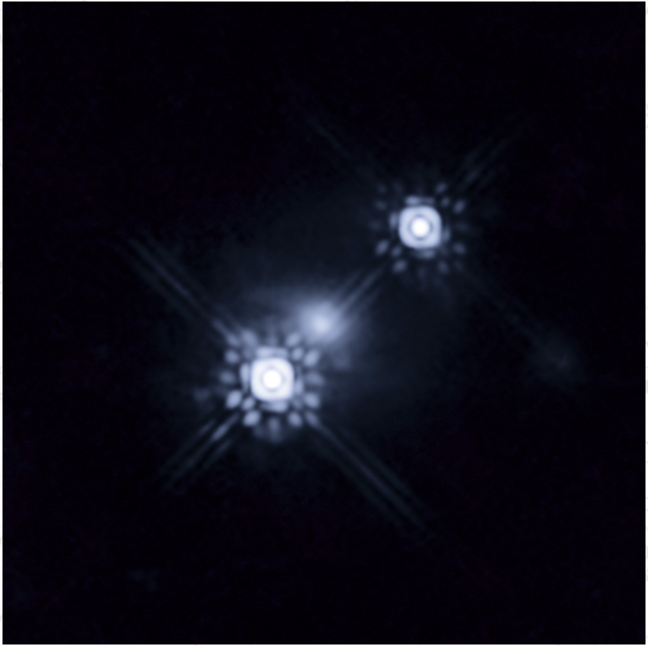
- The discovery of quasars, which are thought to be powered by supermassive black holes (SMBHs) at redshifts of $4 < z < 5$ and $z > 7$ begs the question, "How did the first SMBHs grow so large so fast?" It is possible that the formation of such SMBHs with masses of $\gtrsim \mathcal{O}(10^9 M_\odot)$ — is the result of long-term mergers and accretion of matter.
- However, in general, very efficient processes and special conditions are required to be maintained over several orders of magnitude of mass growth for the formation of these SMBHs in the early Universe.
- Whether or not these circumstances are feasible is not a settled issue.
- Hence, the appearance of such SMBHs at high redshifts poses an open question.
- One possible explanation is based on the primordial formation of black holes coming from large density fluctuations.

What is a Quasar?

- A quasar (also known as a quasi-stellar object, abbreviated QSO) is an extremely luminous active galactic nucleus (AGN), powered by a supermassive black hole, with a mass ranging from millions to tens of billions of solar masses, surrounded by a gaseous accretion disc. Gas in the disc falling towards the black hole heats up because of friction and releases energy in the form of electromagnetic radiation. The radiant energy of quasars is enormous; the most powerful quasars have luminosities thousands of times greater than those of a galaxy such as the Milky Way.
- Usually, quasars are categorized as a subclass of the more general category of AGN. The redshifts of quasars are of cosmological origin.

Quasars detections

- The quasar $J0313-1806$ with a 1.6 billion solar mass black hole was discovered at $z = 7.64$, 670 million years after the Big Bang, in early 2021.
- The nearest known being is about 600 million light-years away from Earth.
- More than a million quasars have been discovered until now.



Center of quasars

- A new model from Brookhaven Lab physicists suggests the early universe experienced a phase transition that formed supermassive black holes in a dark sector of physics.
- Connecting the Extremes: A Story of Supermassive Black Holes and Ultralight Dark Matter.

Hooman Davoudiasl, Peter B. Denton, and Julia Gehrlein,
Supermassive Black Holes, Ultralight Dark Matter, and Gravitational Waves from a First Order Phase Transition,
Phys. Rev. Lett. **128**, *081101 (2022)*
arXiv: 2109.01678v2 [astro-ph.CO] 23 Feb 2022

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- The formation of ultra-rare supermassive black holes (SMBHs), with masses of $\mathcal{O}10^9\, M_\odot$, in the first billion years of the Universe remains an open question in astrophysics.
- At the same time, ultralight dark matter (DM) with a mass in the vicinity of $\mathcal{O}10^{-20}$ eV has been motivated by small scale DM distributions.

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- At ~ 10 keV temperatures, a model with a confining first order phase transition facilitates the production of $\mathcal{O}10^9\ M_\odot$ primordial SMBHs.
- Such a phase transition can also naturally lead to the implied mass for a motivated ultralight axion DM candidate, suggesting that SMBHs and ultralight DM may be two sides of the same cosmic coin.
- This model also expects primordial gravitational waves to be generated from the assumed first order phase transition, characterized by frequencies of $\mathcal{O}10^{-12} - 10^{-9}$ Hz.

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- In this model, a first-order phase transition (FOPT) in the early Universe, before the matter-radiation equality era, provided the catalyst for the formation of horizon-sized primordial SMBHs (pSMBHs).
- A cosmological phase transition is akin to a more familiar type of phase transition: bringing water to a boil. When water reaches the exact right temperature, it erupts into bubbles and vapor. Imagine that process taking place with a primordial state of matter. Then, shift the process in reverse so it has a cooling effect and magnify it to the scale of the universe.
- Before galaxies existed, the universe was hot and dense, and that is well established. How the universe cooled down to what we observe today is a matter of interest because we don't have experimental data describing how that happened.

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- Here, particles in the dark sector could undergo a phase transition that enables matter to very efficiently collapse into black holes.
- When the temperature of the universe is just right, the pressure can suddenly drop to a very low level, allowing gravity to take over and matter to collapse.
- Our understanding of known particles indicates that this process wouldn't normally happen.

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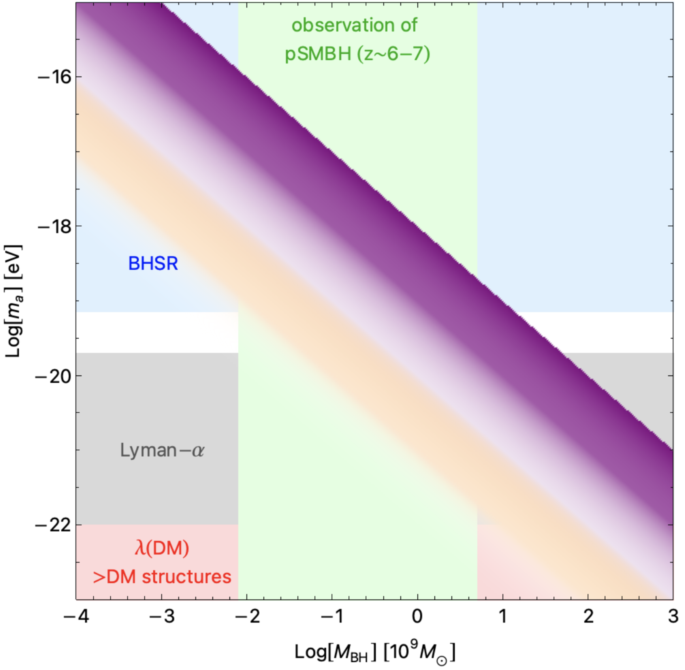
- The frequency of interactions between known particles suggests matter, as we know it, would not have collapsed into black holes very efficiently.
- But, if there was a dark sector with ultralight dark matter, the early universe might have had just the right conditions for a very efficient form of collapse.
- This model tells us about a dark sector of the universe where yet-to-be-discovered particles abound and rarely interact. Among these particles could be ultralight dark matter, predicted to be 28 orders of magnitude lighter than a proton.


observation of
pSMBH (z~6–7)
BHSR
Lyman–α
λ(DM)
>DM structures
Log[m_a] [eV]
−16
−18
−20
−22
−4
−3
−2
−1
0
1
2
3
Log[M_{BH}] [$10^9 M_\odot$]

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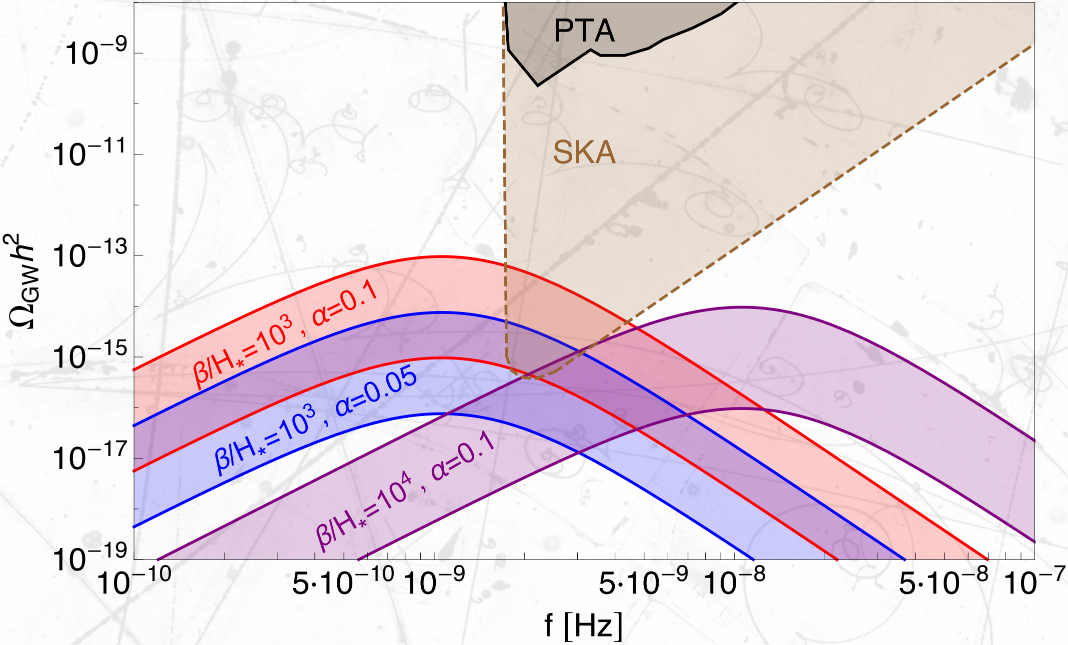
- Such a phase transition would be a dramatic event, even for something as spectacular as the universe.
- These collapses are a big deal. They emit gravitational waves. Those waves have a characteristic shape, so the model makes a prediction for that signal, and its expected frequency range.
- Current gravitational wave experiments aren't sensitive enough to validate the theory, but next-generation experiments may be able to detect signals of those waves.
- Based on the waves' characteristic shape, physicists could then narrow in on the details of supermassive black hole formation.


PTA
SKA
$\beta/H_*=10^3$, $\alpha=0.1$
$\beta/H_*=10^3$, $\alpha=0.05$
$\beta/H_*=10^4$, $\alpha=0.1$
$\Omega_{GW}h^2$
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-10}
$5\cdot10^{-10}$
10^{-9}
$5\cdot10^{-9}$
10^{-8}
$5\cdot10^{-8}$
10^{-7}
f [Hz]

Thank you for your attention!

Mathematical derivations to be continued ...