OTHER INTERESTING TOPICS ABOUT BLACK HOLES

Lecture 16, Introduction to Black Hole Astrophysics

NTHU, 6/15/2021

SYLLABUS

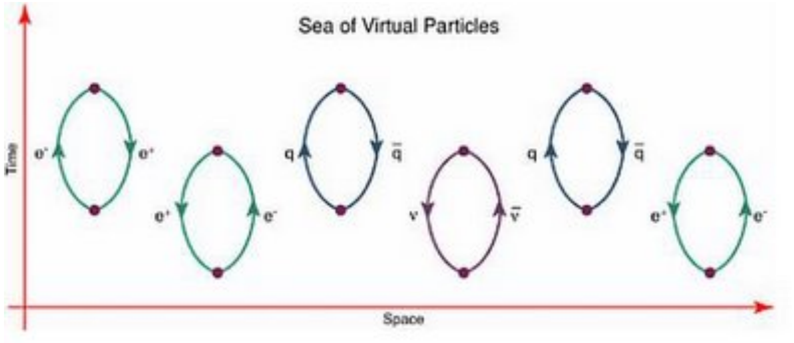
Week 1 (2/23): A brief history of black holes (BHs)
Week 2 (3/2): Einstein's theory of special relativity
Week 3 (3/9): Einstein's theory of general relativity
Week 4 (3/16): Schwarzschild BHs and Kerr BHs
Week 5 (3/23): Observational discovery of BHs
Week 6 (3/30): The birth of stellar mass BHs
Week 7 (4/13): BH accretion disks
Week 8 (4/20): Measuring BH masses and spins
Week 9 (4/27): Supermassive BHs (SMBHs) and Active Galactic Nuclei (AGN)
Week 10 (5/4): The SMBH at our Galactic center
Week 11 (5/11): AGN Jets
Week 12 (5/18): AGN feedback on galaxies
Week 13 (5/25): SMBHs origin and growth
Week 14 (6/1): Recent triumphs of GR – the first image of BH
Week 15 (6/8): Recent triumphs of GR – gravitational waves
Week 16 (6/15): Other interesting topics (primordial BHs, Hawking radiation, information paradox)

HAWKING RADIATION

HAWKING RADIATION

- In 1974, Stephen Hawking made an attempt to put together Quantum Field Theory (QFT) and black holes as described by GR
- He discovered the weird fact that, strictly speaking, BHs are not totally black, but they can emit ***blackbody radiation*** – Hawking radiation
- The rigorous derivation requires full knowledge of the QFT; however, the simple picture we often see is enough to capture the essential points

VACUUM FLUCTUATIONS & VIRTUAL PARTICLES



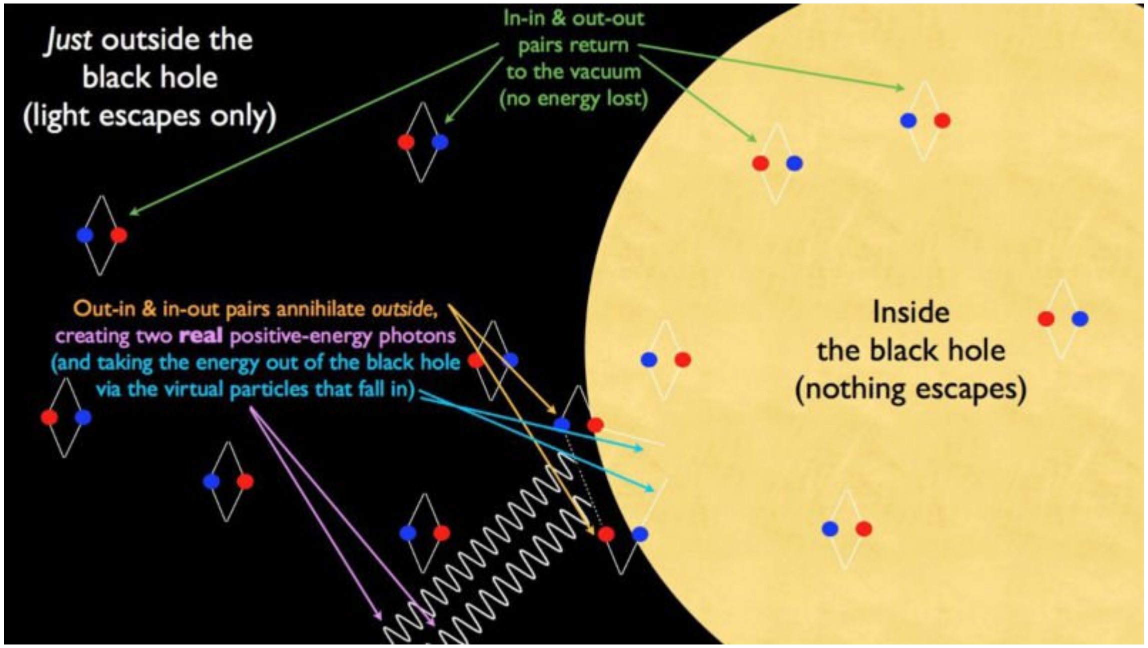
- QFT predicts that vacuum is not exactly empty, but there are ***vacuum fluctuations***
- Due to the uncertainty principle,

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

for finite duration events, energy does not need to be strictly conserved as it could not be precisely defined

- Since $E=mc^2$, it means that even in the vacuum, a pair of ***virtual particles*** (a particle and an anti-particle) could be spontaneously created, as long as they annihilate within a short time

HAWKING RADIATION



- When the virtual particle pair is created near the event horizon, there would be chances where one virtual particle is inside and the other is outside the event horizon
- The virtual particle inside the event horizon could have ***negative energy*** due to curved spacetime, similar to what happens in the ergosphere during the Penrose process
- This virtual particle with negative energy would fall into the BH, reducing the mass-energy of the BH
- The other virtual particle could escape the BH, become real particles, annihilate with other particles near the horizon and emit photons

PROPERTIES OF THE HAWKING RADIATION

- The radiation has a blackbody form with a temperature of

$$\mathrm{T} = \frac{\hbar c^3}{8\pi G M k_B} \approx 6\times 10^{-8}\left(\frac{M}{M_{sun}}\right)^{-1} K$$

- For typical astrophysical black holes, M > 3 M_{sun}, T is extremely low and the process is extremely slow
- For mini black holes with M < M_{sun} (e.g., primordial BHs), the radiation could be significant
- Because the radiated energy comes from the BH itself, the BH mass must decrease with time, i.e., BHs could ***evaporate***!

BLACK HOLE EVAPORATION

- For blackbody radiation, the luminosity at temperature T can be expressed as

$$\mathrm{L} = \sigma T^4 A = \left(\frac{\pi^2 k_B^4}{60\hbar^3 c^2}\right)\left(\frac{\hbar c^3}{8\pi G M k_B}\right)^4 4\pi\left(\frac{2GM}{c^2}\right)^2$$

$$\Rightarrow \dot{M}c^2 = -\frac{\hbar c^6}{15360\pi G^2 M^2}$$

$$\Rightarrow M^3(t) = M_0^3 - \frac{\hbar c^4}{5120\pi G^2} t$$

$$\Rightarrow t_{evap} = 2.66\times 10^{-33} M_0^3\ yrs$$

BLACK HOLE EVAPORATION

$$\boxed{t_{evap} = 2.66 \times 10^{-33} M_0^3 \; yrs}$$

- Compare this ***evaporation timescale*** with the age of the universe, 13.8 Gyr, we can conclude that only mini BHs with mass $< 1.7 \times 10^{14}$ g will have had a chance to evaporate by now
- Because the radiative power (L) is proportional to M^{-2}, nearly all energy emitted is confined to the very last moments of the BH's life

PRIMORDIAL BLACK HOLES

PRIMORDIAL BLACK HOLES (原初黑洞)

- Mini BHs with $M < M_{sun}$ might be formed out of ***primordial fluctuations***, if within some region of space density fluctuations are large enough to overcome pressure and collapse into primordial BHs (PBHs) due to gravity
- PBHs formed at time t after the Big Bang will have a mass

$$\mathrm{M} \sim 10^{15} \left(\frac{t}{10^{-23} s} \right) g$$

- Plausible mass range of PBHs: 10^{-5} g (t = Planck time = 10^{-43} s) to 10^{5} M_{sun} (t ~ 1s)
- Why are PBHs interesting/important?
  - PBHs are non-baryonic, thus a plausible candidate for dark matter
  - PBHs, if existent, could contribute to the populations of massive smbhs or IMBHs

PRIMORDIAL BLACK HOLES (原初黑洞)

$$\boxed{\mathrm{M} \sim 10^{15}\left(\frac{t}{10^{-23}s}\right)g}$$

- PBHs that formed before t ~ 10^{-23} s would have M < 10^{15} g. These BHs would have evaporated already due to Hawking radiation
- These BHs should produce radiation around 100MeV, but observational limit on the gamma-ray background at this energy implies that their density could not exceed 10^{-8} of the average density of the universe -> PBHs of this mass range is not a significant component of the universe and cannot account for dark matter

OTHER CONSTRAINTS ON PBHS

- Though proposed ~50 years ago, there is still no evidence for PBHs. The recent LIGO detections of BHs with > 30 M_{sun} reignited people's interests in PBHs
- Some of the available observational constraints on masses and abundance of PBHs:
    - Lensing of gamma-ray bursts
    - Capture of PBHs by NSs
    - Ignition of WDs
    - Microlensing of stars
- The exact mass ranges and limits on PBHs are still under debate. Current data generally suggests that PBHs could exist in some limited mass ranges, e.g., asteroid masses ($10^{16} \sim 10^{17}$ g), sub-lunar masses ($10^{20} \sim 10^{24}$ g) and smbhs/IMBHs ($10 \sim 10^3\ M_{sun}$).
- It is an ongoing work to determine whether PBHs do exist and whether they can be a significant component of dark matter.

INFORMATION PARADOX

THE INFORMATION PARADOX

- The ***no hair theorem*** says that BHs only have three attributes: M, Q, and J, implying that all other information is lost to the outside world during the BH formation
- It wasn't a problem if the information is hidden within the event horizon forever
- However, the problem occurs if we consider a BH that could ***evaporate*** within the age of the universe due to Hawking radiation
- Hawking radiation, being blackbody radiation, does not encode information about the BH formation
- After the BH completely evaporates, the information about BH formation would be permanently lost in the universe!
- This violates a core concept in quantum physics – the value of a wave function of a physical system at one point in time should determine its value at any other time, i.e., the ***information should be conserved***

HOW TO RESOLVE THE PARADOX

- Option 1: information is indeed permanently lost
  - Penrose: information may not be preserved in the presence of strong gravity

- Option 2: information is preserved
  - Stored in a Planck-sized remnant after evaporation
  - Holographic principle (from string theory): A volume of space can be encoded on a lower-dimensional boundary to that region. Therefore, information can be stored on the surface of the event horizon and emit with the Hawking radiation

- The solution to the information paradox is still an open question and could lead to deeper understanding of quantum gravity

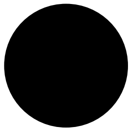
SUMMARY

- Weird things happen when quantum effects are considered close to BHs
- ***Hawking radiation***:
  - BHs emit blackbody radiation when virtual particles from vacuum fluctuations are created near the event horizon
  - Temperature of the Hawking radiation is inversely proportional to BH mass
  - Astrophysical BHs with $M > M_{sun}$ have no time to evaporate; mini BHs with $M < 10^{14}$ g could have evaporated

SUMMARY

- ***Primordial BHs (PBHs)***:
  - Density fluctuations in the early universe, if large enough, could collapse into PBHs with masses ranging from 10^{-5} g to 10^{5} M_{sun}
  - For PBHs <~ 10^{15} g, they should have evaporated and emit Hawking radiation in MeV ranges. Observations suggest that they don't have a significant contribution to the average density in the universe
  - PBHs in certain mass ranges are still being tested against observational data
- ***Information paradox***:
  - Whether information is lost or not when things fall into the BH and the BH later evaporates
  - The solution remains an open question

BLACK HOLES



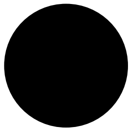
BLACK HOLES

Tidal disruption events

Stellar-mass black holes

Black hole shadows

X-ray binaries



Radio galaxies

Gravitational lensing

Supermassive black holes

Accretion disks

Relativistic jets

Active galactic nuclei

Special relativity

General relativity

Seyfert galaxies

Blazars

Gravitational waves

Galaxy evolution

Cosmology

Hawking radiation

Quantum gravity