STOCHASTIC GRAVITATIONAL WAVES FROM PRIMORDIAL BLACK HOLES

Ruifeng Dong

In collaboration with Dr. William Kinney
and Dr. Dejan Stojkovic

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University at Buffalo The State University of New York

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Formation of primordial black holes

Large primordial inhomogeneity (e.g. from quantum fluctuation during inflation)

When over-density region > Jeans scale $R \lesssim H^{-1}$, collapse to BH

The over-density region won't form separate closed universe $R \gtrsim H^{-1}$

Narrow mass spectrum center around $\frac{4\pi}{3}\rho H^{-3}$

Early matter domination, phase transition, etc.

Example: At Planck time $10^{-43}s, M{\sim}10^{-5}g$
At Big bang nucleosynthesis $1s, M{\sim}10^{5}M_{\odot}$

Anisotropies in collapse and further accretion lead to BH rotation

We will assume uniform initial mass, and various possible angular momentum

Black hole evaporation

- BH thermal radiation at $T = \frac{\hbar c^3}{8\pi G M k_B} \sim 10^{-7} (\frac{M}{M_\odot})^{-1}$K (Hawking 1974)
- All particle species are democratically emitted, scalar, spinor, vector, tensor fields
- Particles need to overcome gravitational barrier to get emitted (depending on BH spin and particle spin)

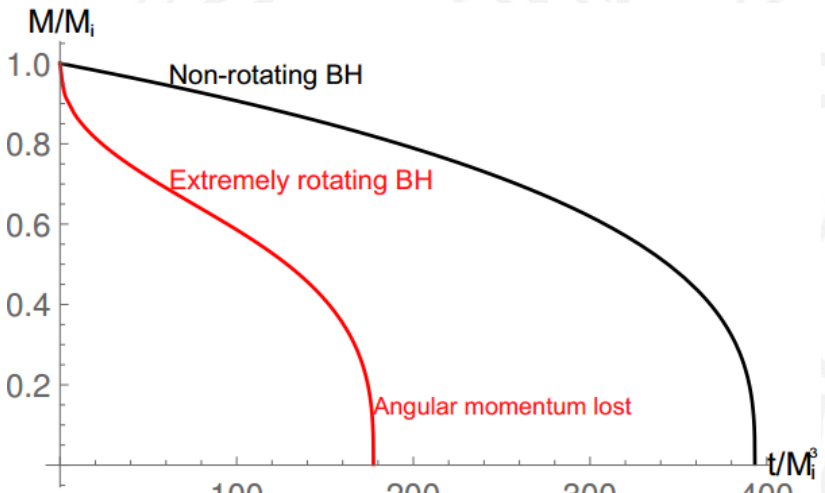
For rotating PBH, high-energy high-spin particle emission is enhanced (particle spin coupled with BH angular momentum)

J/M^2	Scalar	Spinor	Vector	Tensor
0	4.6%	91%	4.2%	0.47%
0.99999	0.13%	0.93%	3.4%	96%

Page, PRD 14(1976)

E.g. PBH with $M < 10^9 g$ would evaporate by BBN

PBH with $M > 10^{15} g$ would survive today

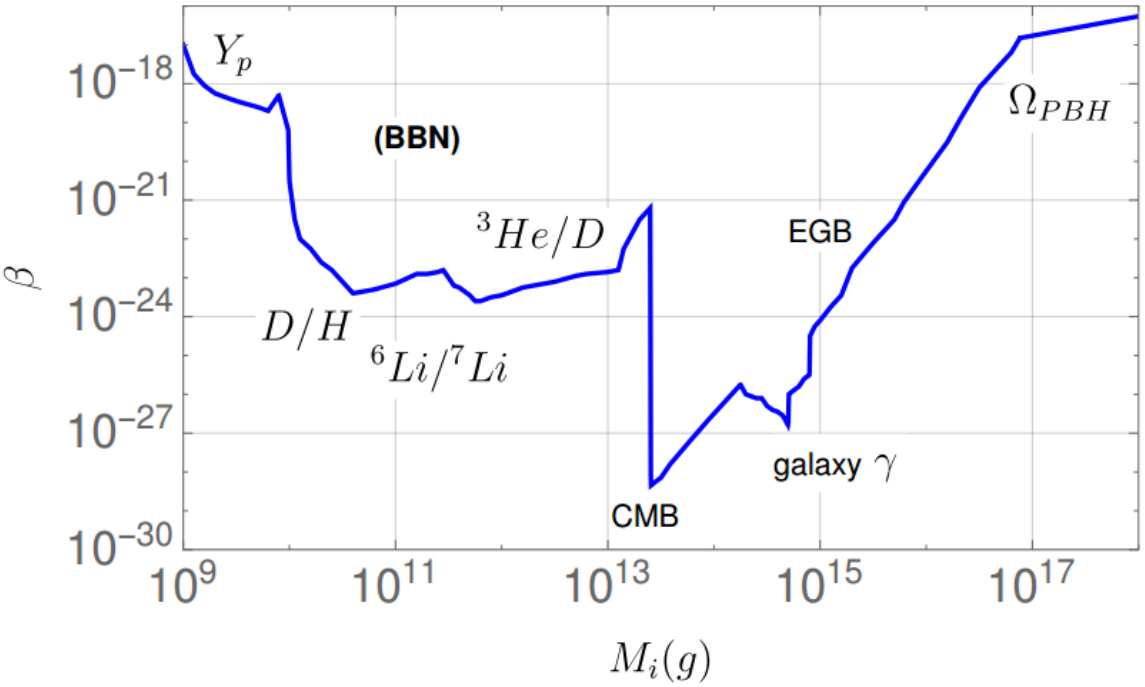


PBH mass fraction β

$M \lesssim 10^9 g$, PBH evaporates before BBN, no constraints

$M > 10^9 g$, constraints from BBN, CMB and γ rays

$M > 10^{15} g$, PBH are dark matter candidates, $\Omega_{PBH} \leq \Omega_{DM}$



Carr, Kohri, Sendouda and Yokoyama, PRD 81(2010)

Graviton emission spectrum

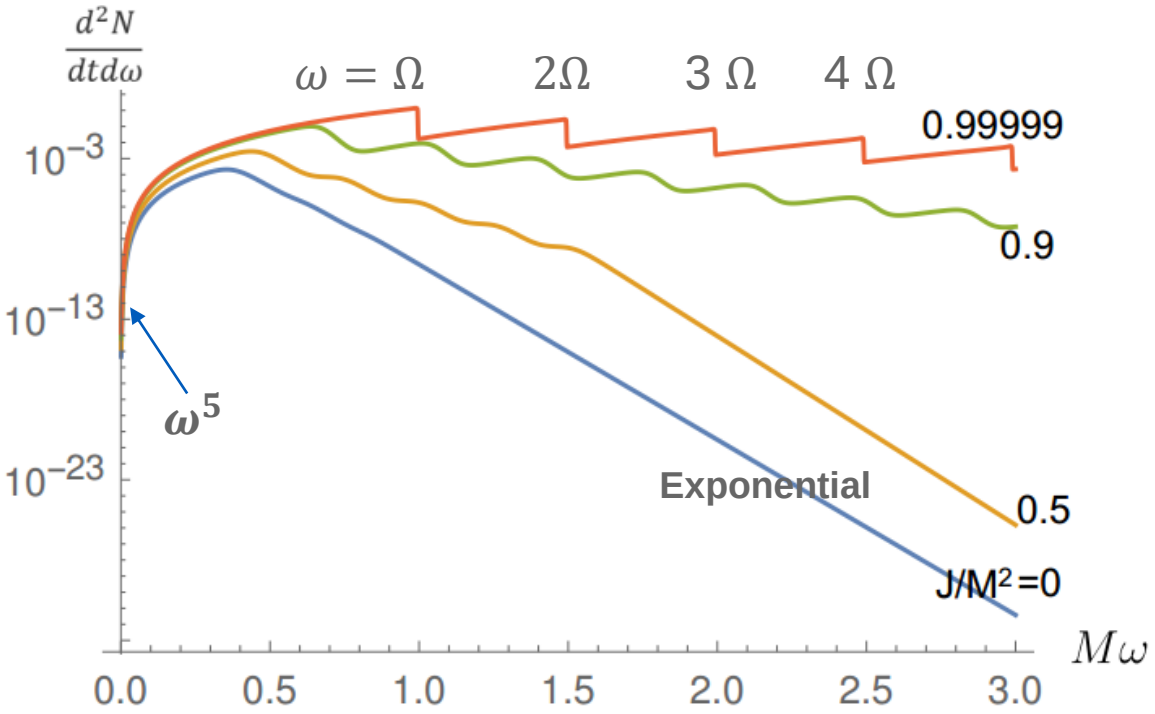
$$\frac{d^2N}{dtd\omega} = \sum_{plm} \frac{\gamma_{2lm}(J, M\omega)}{e^{(\omega - m\Omega)/T_H} - 1}$$

Hawking temperature T_H

- $\propto (J_{max} - J)^{1/2}$
- Peaks at $\omega = \Omega, 2\Omega, 3\Omega..$

Grey-body factor γ_{2lm}

- Probability to overcome gravitational potential
- Wave amplification for J close to J_{max}



TODAY'S GRAVITON SPECTRUM

We know the initial PBH and mass fraction, and its instantaneous GW emission. Then how does spectrum evolve to present time?

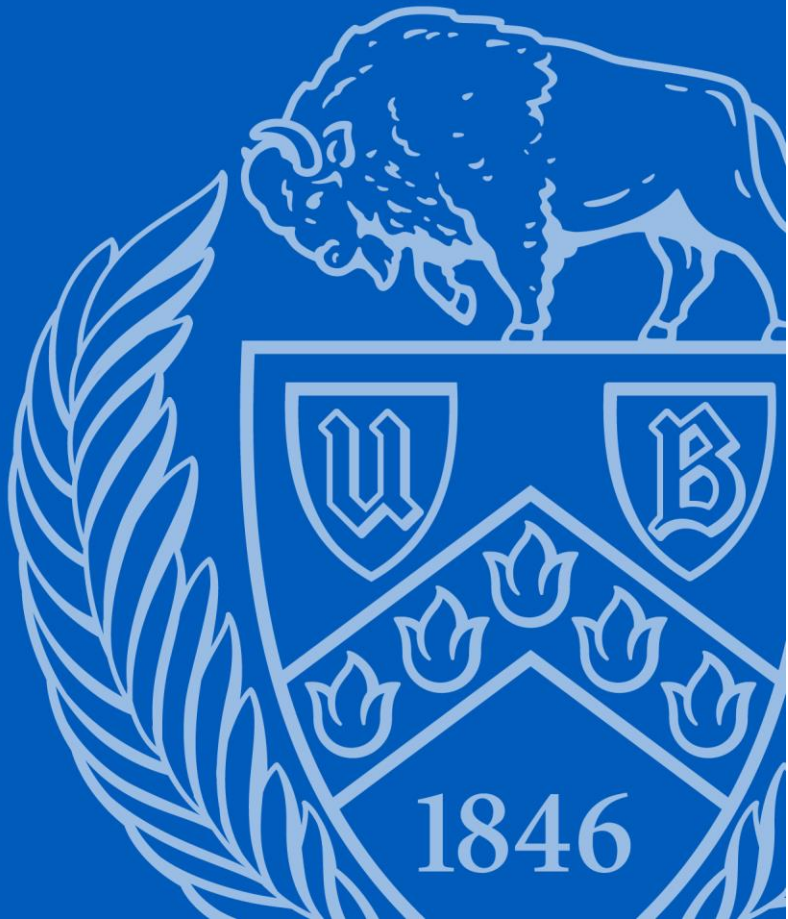
$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

$$= \frac{f}{\rho_c}\int_0^{t_{PBH}} dt\, N_{BH}^{co}(t)\left(\frac{d^2E}{dtdf_r}\right)\Big|_{f_r = f/a(t)}\left(J(t), M(t)\right)$$

Cosmic history

Emission spectrum

BH evolution



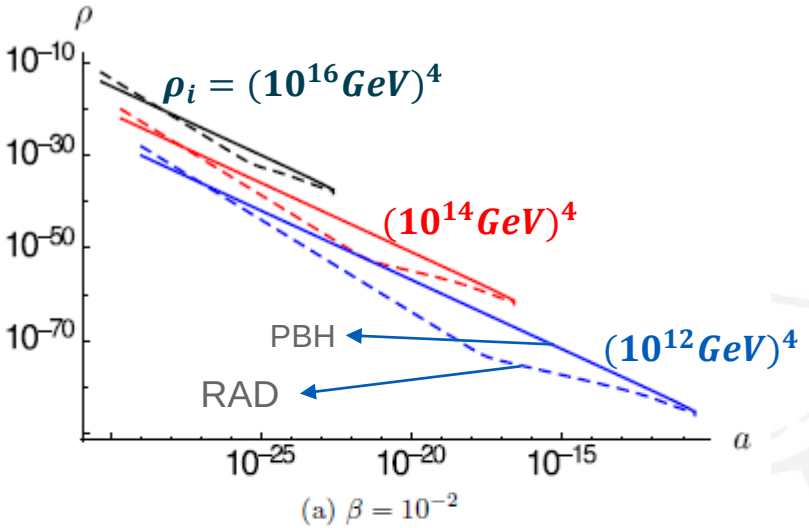
Cosmic evolution

Initial high mass fraction $\beta \gtrsim \frac{1}{10}\rho_i^{1/2}$

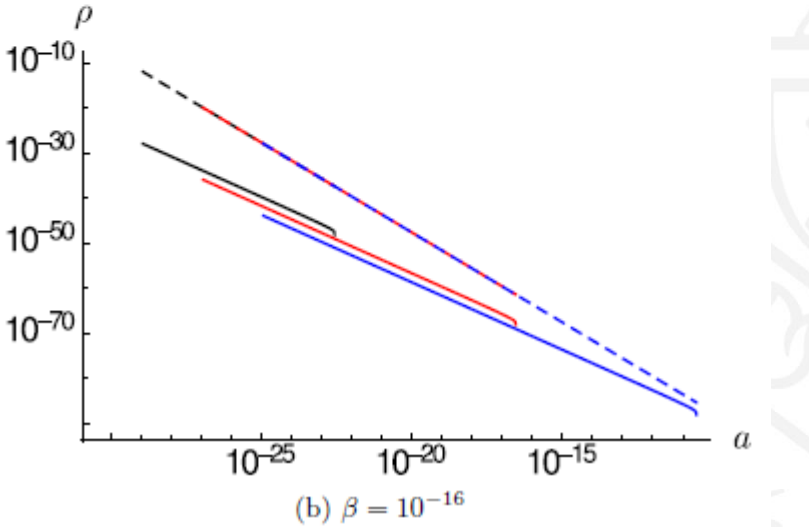
- $\rho_{PBH} \sim a^{-3}, \rho_{RAD} \sim a^{-4}$
- PBH dominates before evaporation
- {ρ_{PBH}, ρ_{RAD}, a(t)} co-evolve
- More cosmic expansion
- After evaporation, RAD dominates

Initial low mass fraction $\beta \lesssim \frac{1}{10}\rho_i^{1/2}$

- PBH always subdominant
- Not affecting cosmic history



(a) $\beta = 10^{-2}$



(b) $\beta = 10^{-16}$

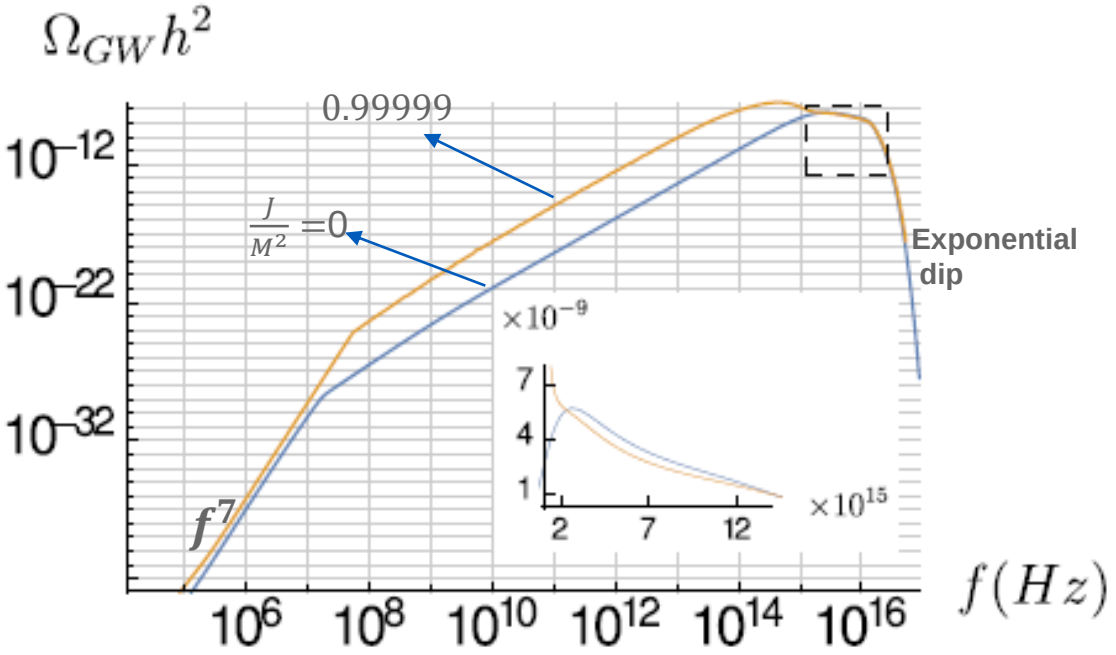
Effects of BH rotation

Low frequency: marginally magnified

Intermediate frequency: enhanced by 10^3, wave magnification

High frequency: Low rotating BH lives longer, less red-shifted

High end: PBH sheds initial angular momentum, evolving as Schwarzschild BH

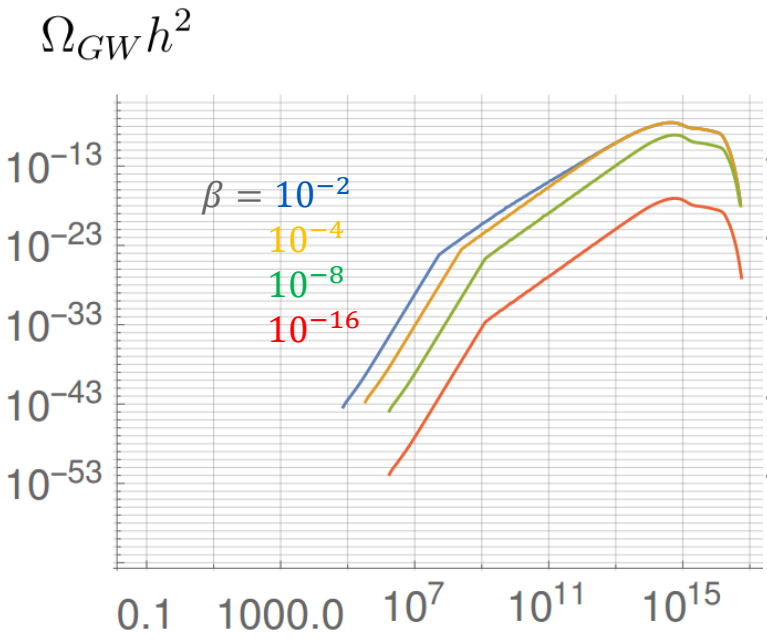


Exponential dip

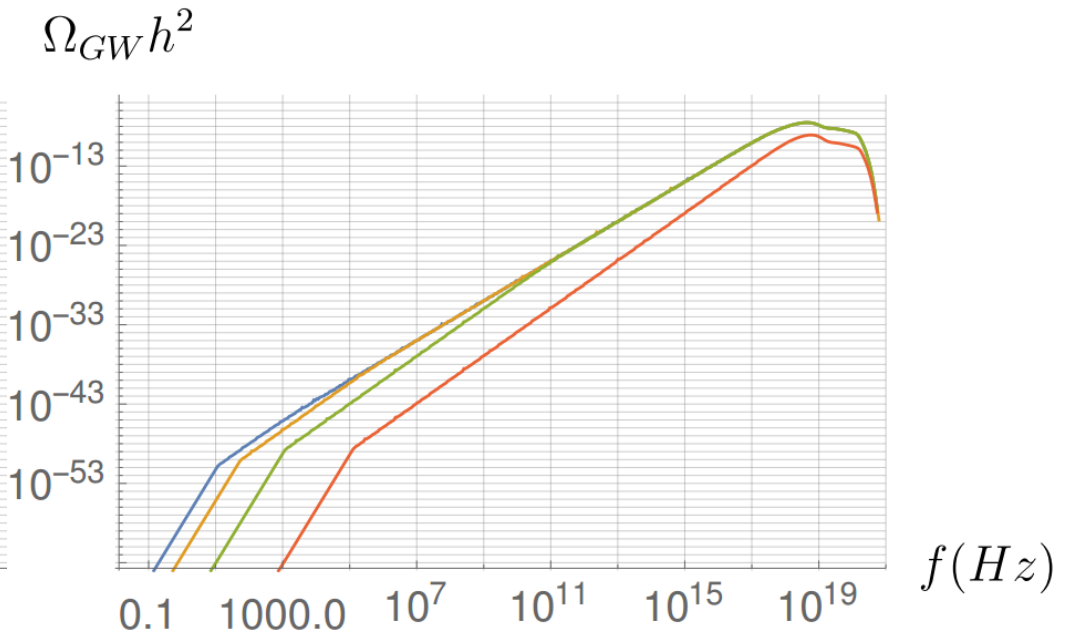
Too high frequency for observation, because PBH is much hotter than environment

Effects of PBH mass fraction

Ω_{GW} not proportional to β, cosmic history affected
Effect most significant for low frequencies
Effect vanishes at high frequency, because redshift is determined only by PBH lifetime



$\rho_i = (10^{16} GeV)^4$

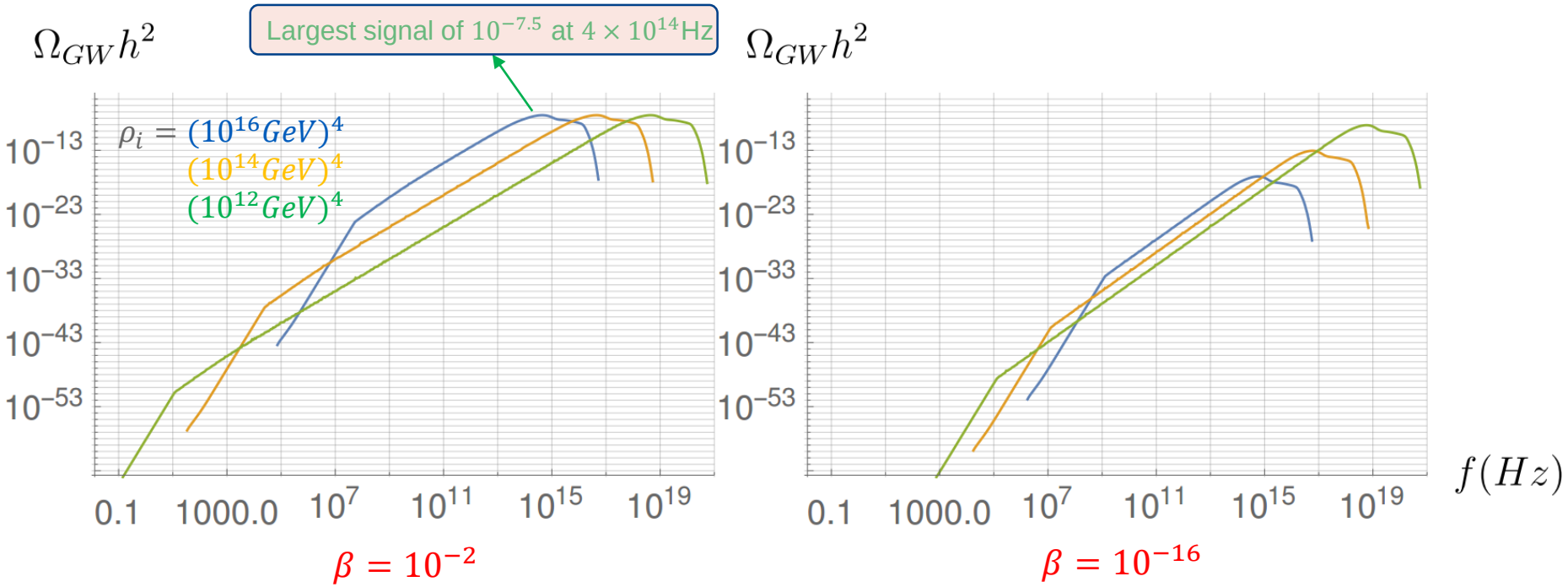


$\rho_i = (10^{12} GeV)^4$

Effects of initial energy scale

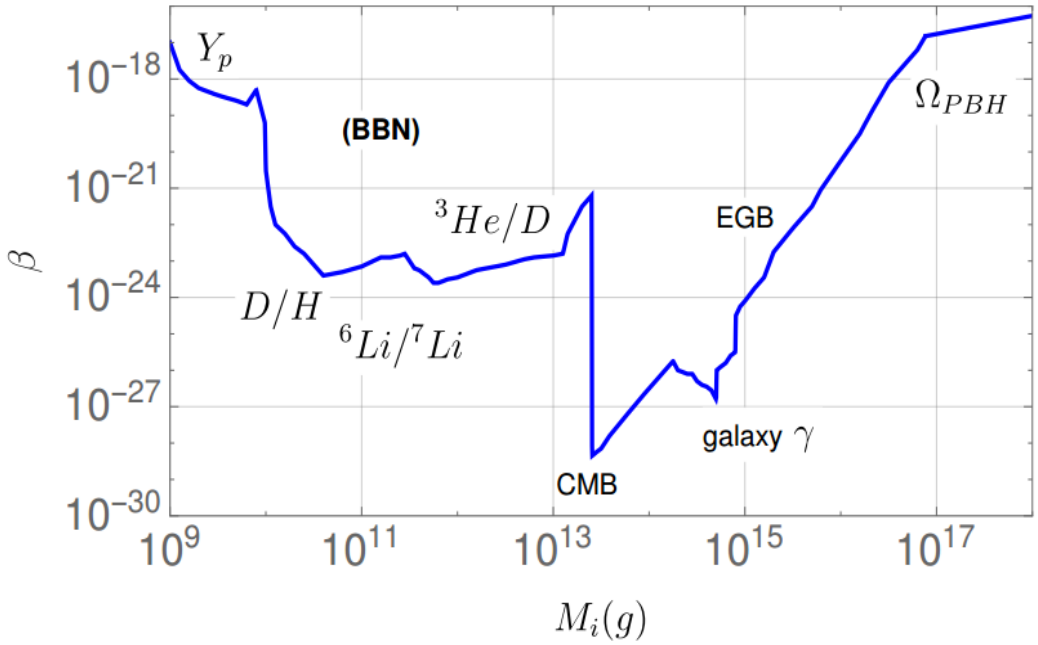
More e-folds experienced by PBH for lower ρ_i, so larger-f coverage and higher peak-f

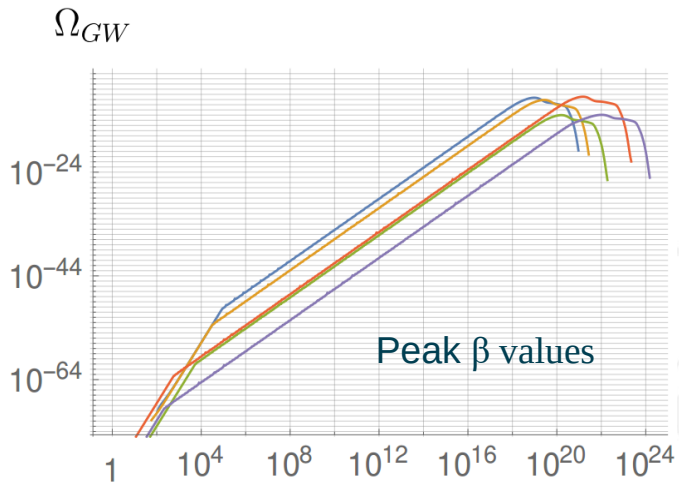
Larger ρ_i, larger PBH fraction during evolution, larger GW signal (more significant for larger β)

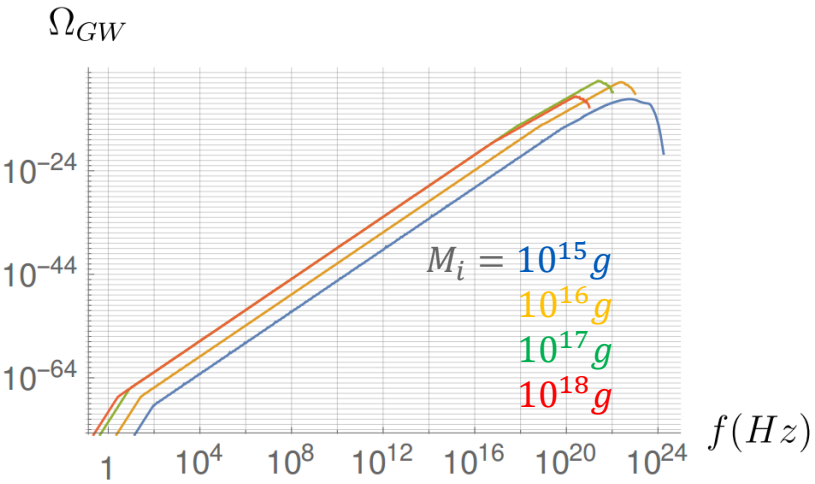


Constrained PBH

Take maximum β to get the largest possible GW signal





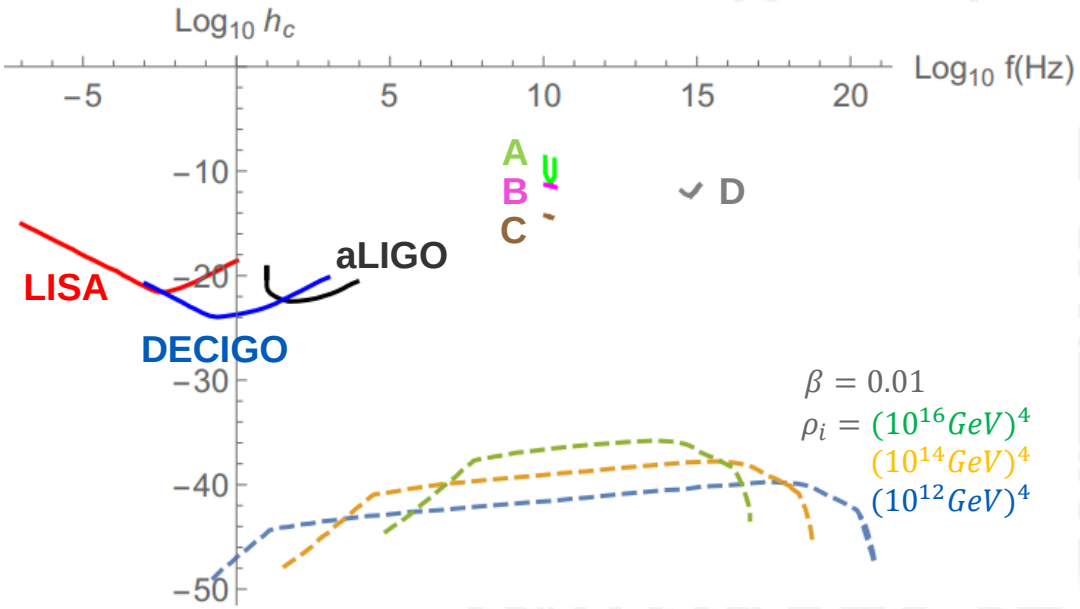


Observation of gravitational waves

Interesting frequency range beyond aLIGO, LISA, etc.

High-frequency GW detectors cover our frequency range, but sensitivity

20 orders lower than required



Kuroda, Ni and Pan, Int.J.Mod.Phys. D24(2015)

Conclusions

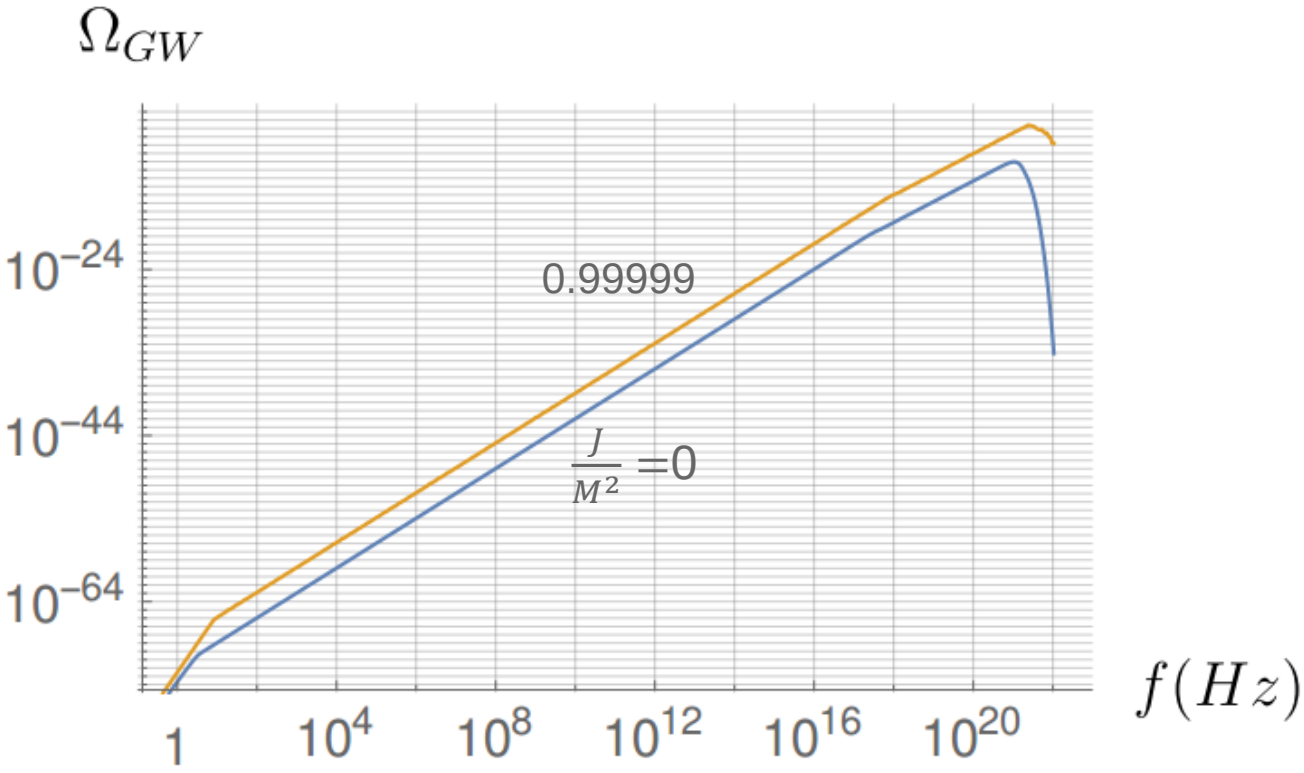
- Largest amplitude $\Omega_{GW} \approx 10^{-7.5}$ at $4 \times 10^{14} Hz$
- Frequency is generally too high for aLIGO etc., amplitude too low for today's high-f detectors
- PBH rotation effects easily seen in intermediate frequencies
- PBH fraction effects seen at low frequencies
- PBH formed at higher energies gives larger signals
- $M_i > 10^9 g$ PBH is too constrained to give significant GW signal


Thank you~
The Sombrero Galaxy — NGC 4594 (M104)
HUBBLESITE.org

Evaporating PBH

Effects of BH rotation easily seen

also at high frequencies



$M_i = 10^{17} g$

Constraints on PBH mass fraction

^4He abundance and D/H ratio for $M_i = 10^9 - 10^{10}$g: Some of the quarks and gluons emitted by PBHs fragment into mesons and antinucleons, which have enough time to get thermalized and then scatter with background nucleons, causing interconversion between protons and neutrons. As a result, this can increase the neutron/proton ratio, and thus change the ^4He and deuterium, D, abundance. The observed ^4He abundances and D/H ratio thus set an upper limit on $\beta(M_i)$.

$^6Li/^7He$ ratio for $M_i = 10^{10} - 10^{12}$g: High-energy nucleons, produced during the PBH evaporation and subsequent fragmentation, can scatter off background nuclei from BBN. Hadrodissociation produces energetic debris including tritium, T, and ^3He, which then scatter with the nuclei background and result in extra production of ^6Li. In this way, $\beta(M_i)$ can be constrained by the well observed $^6Li/^7Li$ ratio.

$^3He/D$ ratio for $M_i = 10^{12} - 10^{13}$g: At the temperature of PBH evaporation, the produced energetic neutrons have time to decay before hadrodissociation, emitting photons with energies comparable to nuclei binding energy. So the photons can dissociate them and as a result, overproduce ^3He or D. The observation of the $^3He/D$ ratio thus constrains $\beta(M_i)$.

Diffuse extragalactic γ ray background for $M_i = 1.8 \times 10^{14} - 10^{17}$g: PBHs produce photons, both through direct Hawking radiation, and also through secondary processes involving the emitted quarks and gluons. The total γ ray spectrum should be within the spectrum of the diffuse extragalactic γ ray background observed by HEAO 1, COMPTEL, EGRET and Fermi LAT. This gives un upper limit on $\beta(M_i)$.

Galaxy γ ray background for $M_i = 5 \times 10^{14} - 10^{15}$g: If there are PBHs residing our galactic halo, an anisotropic γ ray background will be produced. Requiring this spectrum to be consistent with the EGRET observation, we can get the constraints on $\beta(M_i)$.

Cosmic microwave background, CMB, for $M_i = 2.5 \times 10^{13} - 1.8 \times 10^{14}$g: The PBH's emission of electrons and positrons after recombination would cause the damping of small-scale CMB anisotropies, whose measurements thus constrains $\beta(M_i)$.

PBH's relic abundance, Ω_{PBH}, for $M_i \geq 10^{17}$g: For these nearly non-evaporating PBHs, this constraint comes from the requirement that today's PBH mass density is not larger than that of the cold dark matter.