Neutrino Burst-Generated Gravitational Radiation From Collapsing Supermassive Stars

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Abstract

We estimate the gravitational radiation signature of the electron/positron annihilation-driven neutrino burst accompanying the asymmetric collapse of an initially hydrostatic, radiation-dominated supermassive object suffering the Feynman-Chandrasekhar instability. An object with a mass $5 \times 10^4\, M_\odot < M < 5 \times 10^5\, M_\odot$, with primordial metallicity, is an optimal case with respect to the fraction of its rest mass emitted in neutrinos as it collapses to a black hole. The optimal case collapse will radiate several percent of the star's rest mass in neutrinos and, with an assumed small asymmetry in temperature at peak neutrino production, produces a characteristic linear memory gravitational wave burst signature. The timescale for this signature, depending on redshift, is ~ 1 s to 10 s, optimal for proposed gravitational wave observatories like DECIGO. Using the response of that detector, and requiring a signal-to-noise ratio SNR $>$ 5, we estimate that collapse of a $\sim 5 \times 10^4\, M_\odot$ supermassive star could produce a neutrino burst-generated gravitational radiation signature detectable to redshift $z \lesssim 7$.

Supermassive Stars

- Supermassive stars are hydrostatic, high entropy, and fully convective configurations, with the stellar mass $M_{\rm SMS} \gtrsim 5 \times 10^4 M_\odot$. They are radiation dominated and most of the entropy is carried by photons and electron/positron pairs.
- The high entropy attendant to a hydrostatic SMS implies that these objects possess copious electron/positron pairs in electromagnetic equilibrium. This, coupled with the strong temperature dependence ($\propto T^9$) of $e^\pm$-pair annihilation into escaping neutrino pairs of all flavors, guarantees that SMS collapse constitutes a prodigious engine for neutrino production.
- For a $10^5\ M_\odot$ SMS:
  - entropy per baryon $s \approx 300\ k_b$,
  - total neutrino energy 3.6×10^{57} erg,
  - neutrino emission timescale 1 s

Creating an anisotropic neutrino energy flux

- A modest rotation of the SMS could change the pressure of the bulk, thereby creating a small anisotropy in the temperature and neutrino emissivity anisotropy.
- A neutrino emissivity asymmetry can be transformed to the outgoing neutrino flux by differential blueshift-redshift effect in a collapsing but otherwise neutrino-transparent star: neutrinos will gain energy, *i.e.*, experience blueshift, as they stream toward the center of the star and lose energy, suffer redshift, as they stream away from the center.
- This can give a time-changing quadrupole moment in the neutrino mass-energy field and, hence, gravitational radiation.
- Fig. 1 illustrates the geometry of this differential blueshift-redshift effect. We estimate that this capture can lock in $\alpha \approx 2\%$ of emission asymmetry.

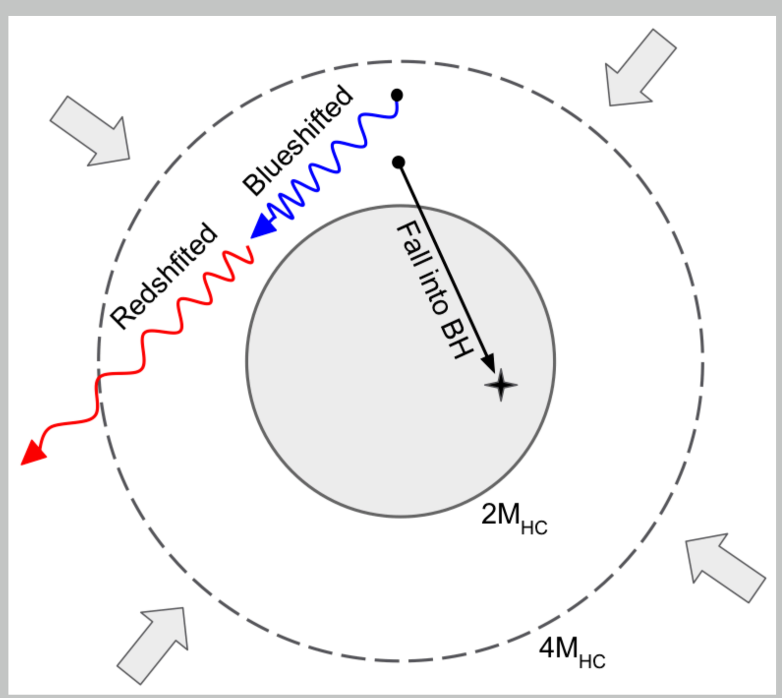

Figure 1: Illustration of the anisotropic neutrino emission production.

Gravitational Wave Linear Memory

- We examine the gravitational wave linear memory (GWM) generated from the asymmetric neutrino bursts during the collapse of SMS. A neutrino burst-generated GW is termed linear memory GW – a non-oscillatory GW that leaves a net change in the strain after the signal has passed by.
- The neutrino burst-generated gravitational wave memory is

$$\Delta h_+^{\rm TT} = \frac{2}{d}\int_{-\infty}^{t-d} L_\nu\,(t')\, dt' \int F\,(\Omega')\,(1+\cos\theta)\, e^{i2\phi}\, d\Omega'\,,$$

where the $F\,(\Omega')$ stands for the neutrino emission angular distribution:

$$F\,(\Omega') = \frac{1+\alpha\cos^2\theta'}{4\pi\,(1+\alpha/3)}.$$

DECIGO

- Orbit: Earth-like solar orbits
- Armlength: 1000 km
- Strain sensitivity (1 unit): $2 \times 10^{-24}/\sqrt{\rm Hz}$ at 0.1 Hz.
- Constellation:
  - 2 overlap units: cross correlation for stochastic background
  - 2 separate units: increase angular resolution

Results: Table

Table 1: Gravitational waves from collapse of SMS at redshift 7 with a 2% neutrino emission asymmetry.

$M_{\rm SMS} = 1 \times 10^5\, M_\odot$	
$E_{\nu,\ \rm loss}$	3.6×10^{57} erg
Emission asymmetry α	0.02
Fraction of rest mass β	2×10^{-2}
GW strain h	3.0×10^{-23}

Results: Figure

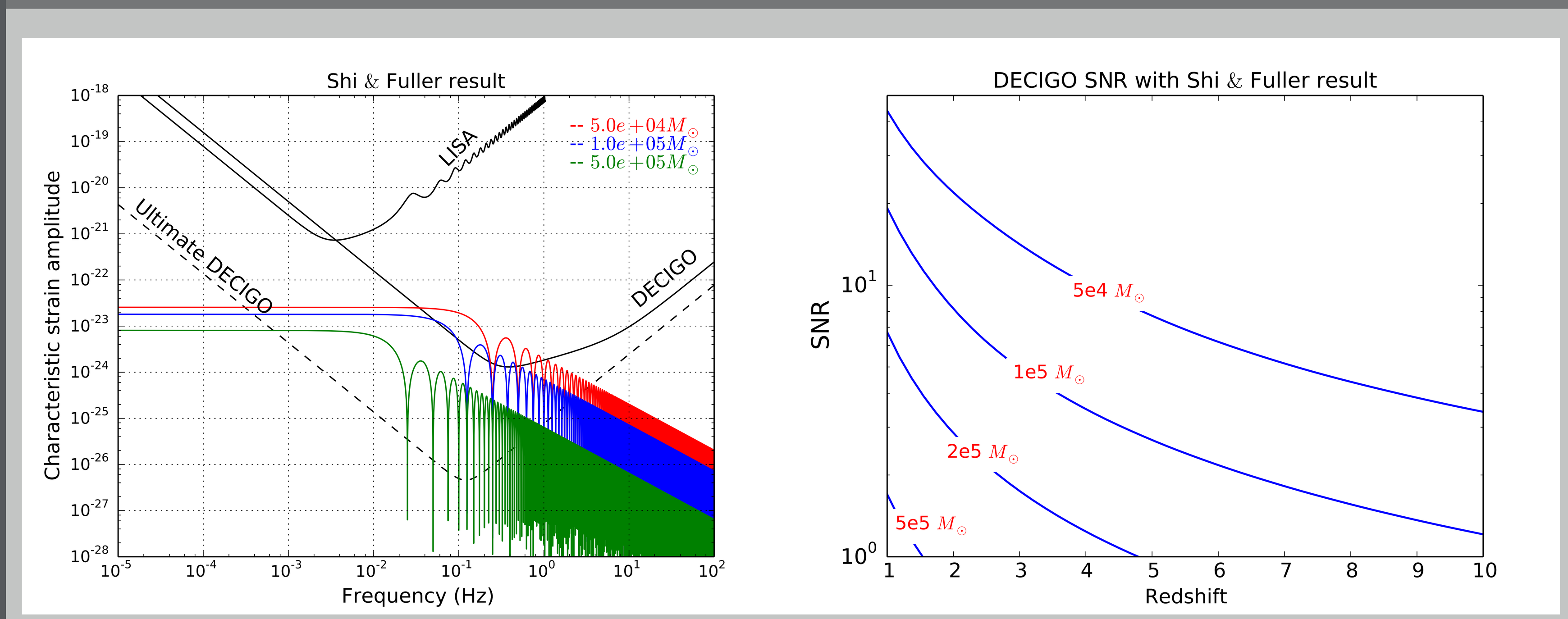

Figure 2: Sky-averaged characteristic strain h_c from the neutrino-burst generated GW memory signal accompanying the collapse of SMSs at $z = 7$ with $\alpha = -0.02$.

Conclusion

- The gravitational collapse of high entropy SMSs engineers prodigious neutrino production which, in turn, gives rise to a relatively unique gravitational wave signal, the GWM. Prospect of detection of these GWM signals is promising in some cases and for some DECIGO configurations ,even from SMS collapse at high redshift. The detection of GWM attributable to the neutrino burst from these high redshift SMSs may provide an intriguing hint toward solving, or narrowing, the problem of the formation of SMBHs in the high-redshift universe.

References

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