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Numerical simulations of fallback core-collapse supernovae: the lower mass gap and multi messenger signals

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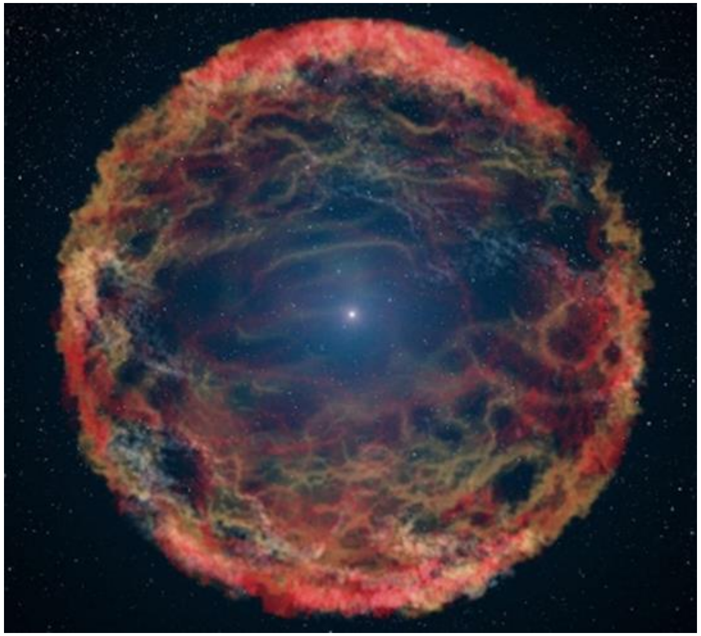
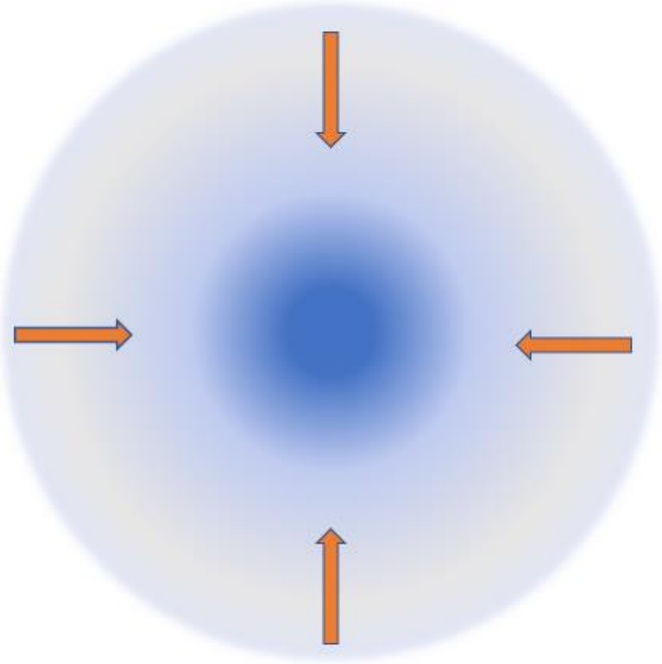
Core-collapse supernovae and fallback





Massive stars (> 8 $\mathrm{M}_\odot$) would end their lives as a core-collapse supernova (CCSN).

Many CCSN explosion calculations have confirmed the existence of fallback and studied its dynamics and effects.

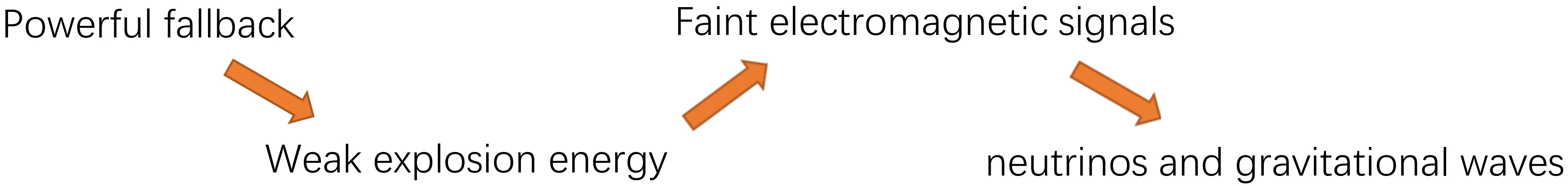
Fallback in core-collapse supernovae

Fallback might be related to a number of the observed phenomena:

- the peculiar supernovae
- the late-time neutrino emission
- the neutron star /black hole kick
- the long-duration gamma-ray bursts

The intensity of the fallback:

supernova explosion energy VS the binding energy of the star



Powerful fallback

Weak explosion energy

Faint electromagnetic signals

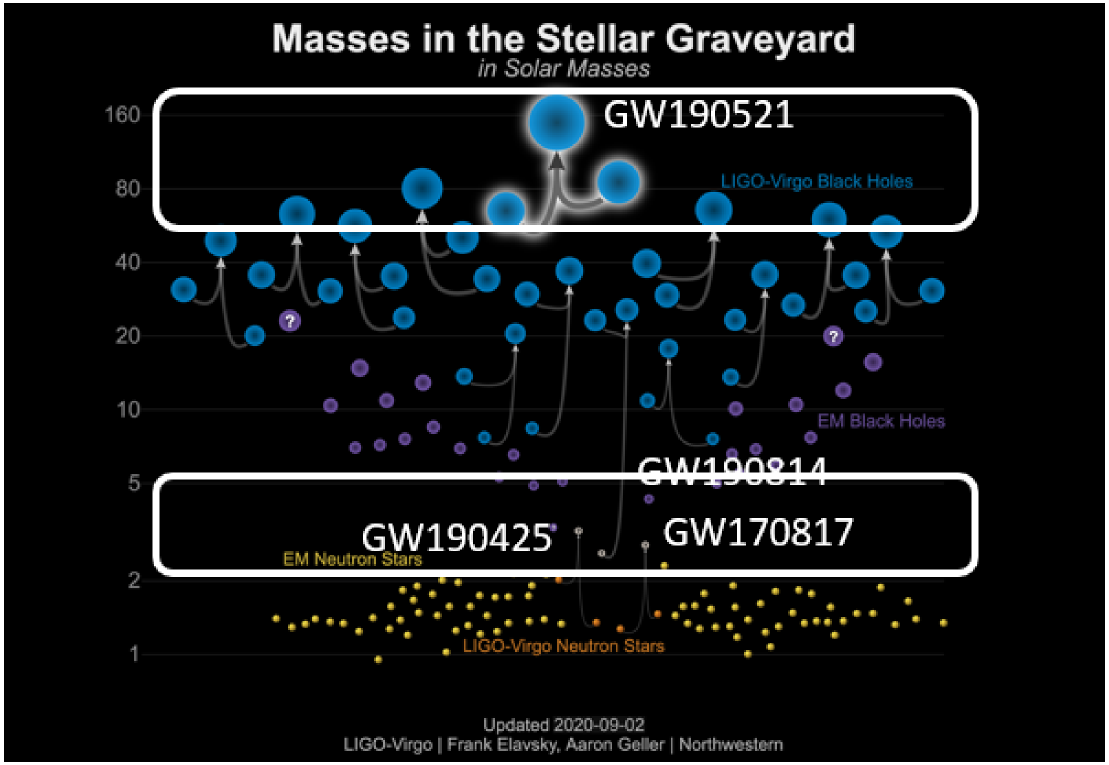
neutrinos and gravitational waves

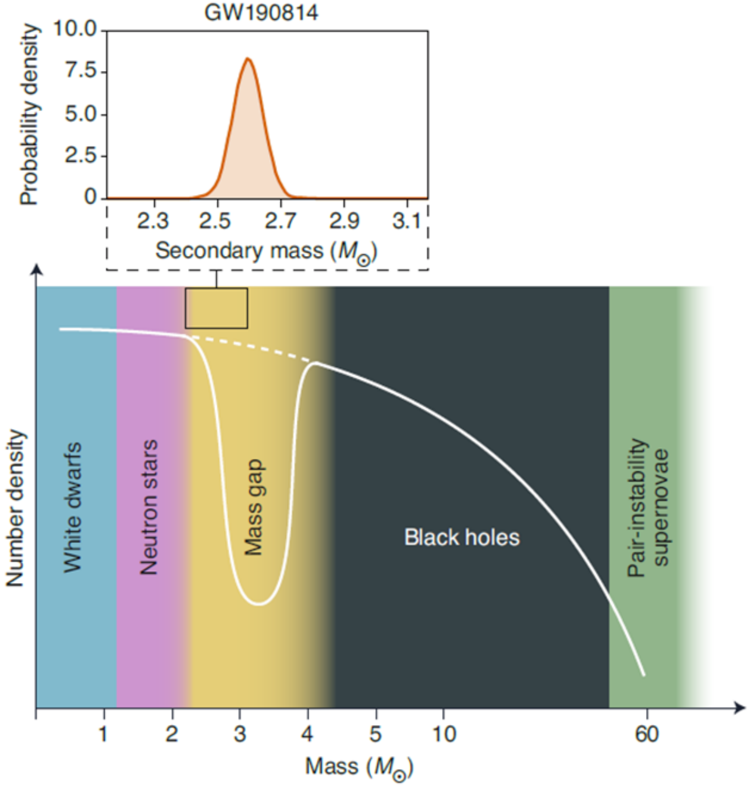
Two works in fallback supernova

- 1. The lower mass gap.

- 2. Neutrinos and gravitational waves signals from black hole neutrino-dominated accretion flows in fallback core-collapse supernovae.

The lower mass gap





Safarzadeh (2020)

CCSN simulation (piston approach)

- pre-SN models (KEPLER code)
- initial progenitor mass in range of 20-40 $M_\odot$
- metallicities $Z/Z_\odot$ = 0, 0.01, 1
- Athena++ code
- piston approach (one-dimensional CCSN simulations)
- initial explosion energies E=2, 4, 8B (1B= 10^{51} erg)

Results

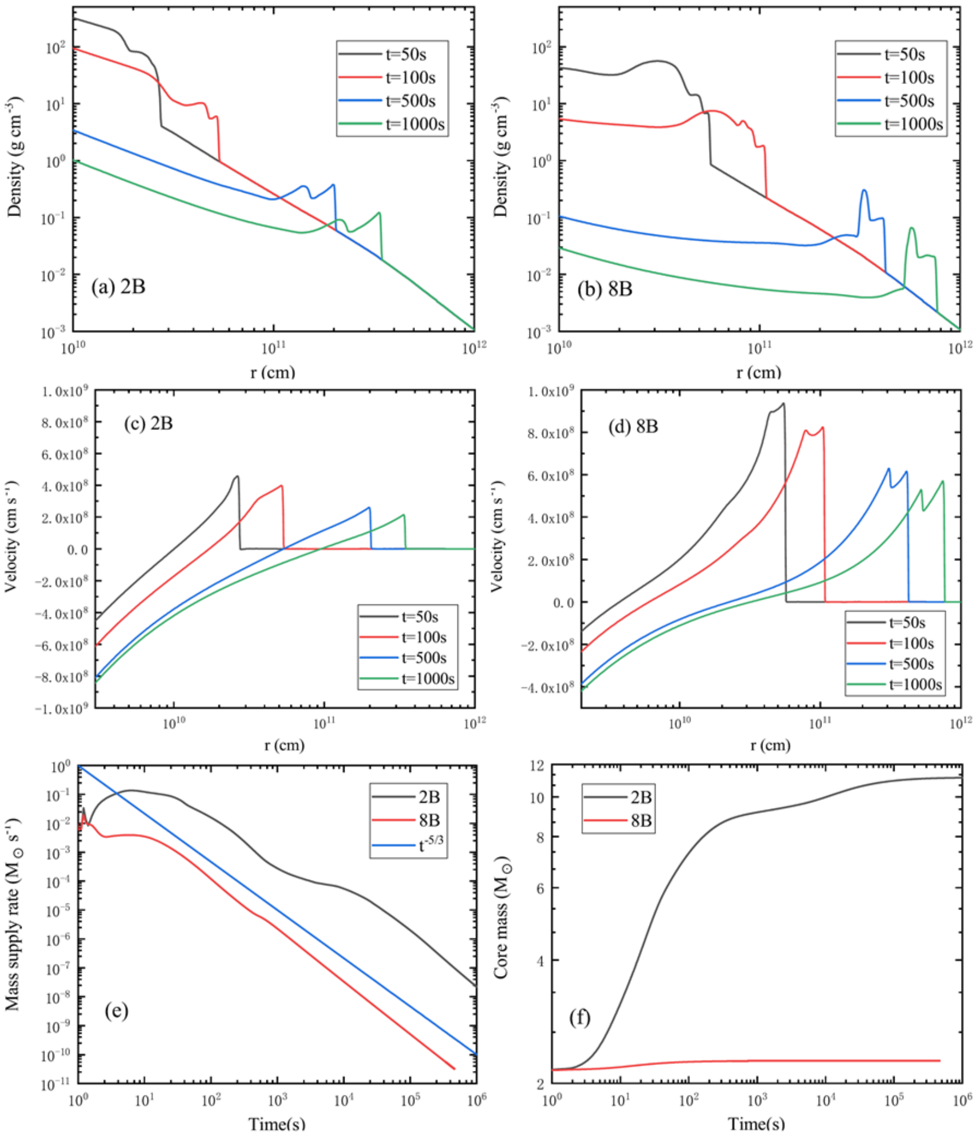


Figure 1. Profiles of density and velocity at 50 s, 100 s, 500 s, and 1,000 s and time evolutions of mass supply rate and core mass for $E = 2B$ and 8B with progenitor mass 30 $M_\odot$ and $Z/Z_\odot = 0.01$.

Results

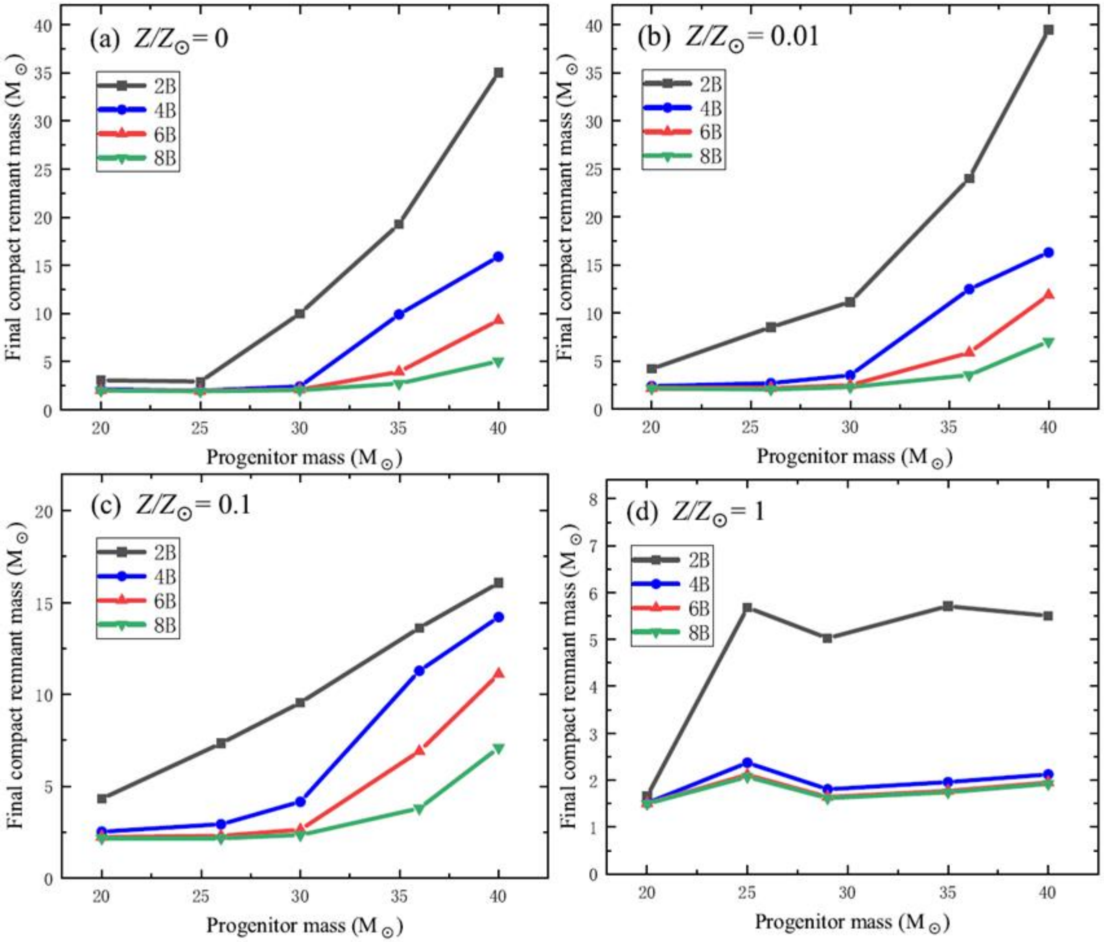
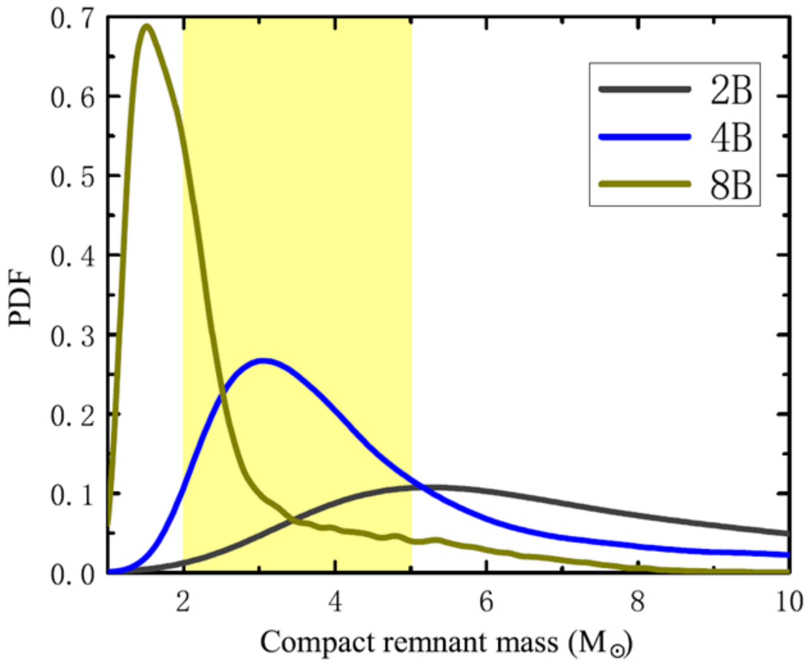
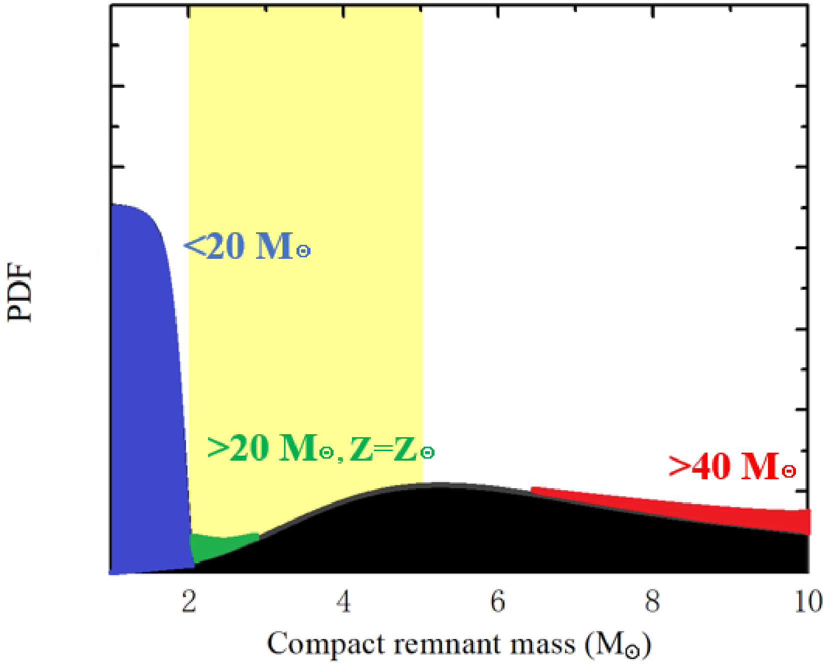


Figure 1. Final compact remnant masses in the center of the CCSNe with different explosion energies (2B, 4B, 6B, and 8B, where $1\mathrm{B} = 10^{51}$ erg) for the progenitor masses in the range of $20 - 40\ M_\odot$ and with a metallicity of $Z/Z_\odot = 0, 0.01, 0.1$, and 1.

Applications on the lower mass gap





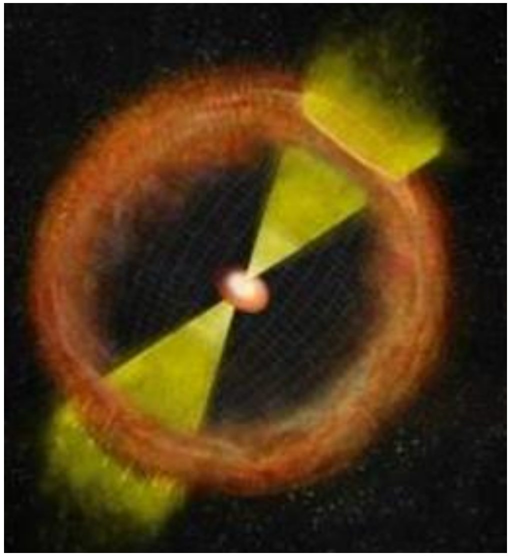
The lower explosion energy naturally causes more efficient fallback accretion for low-metallicity collapsars, and then the newborn BHs in the center of the CCSNe can escape from the gap, but neutron stars cannot easily collapse into BHs in the gap; nevertheless, the final remnants of the solar-metallicity progenitors stick to the gap.

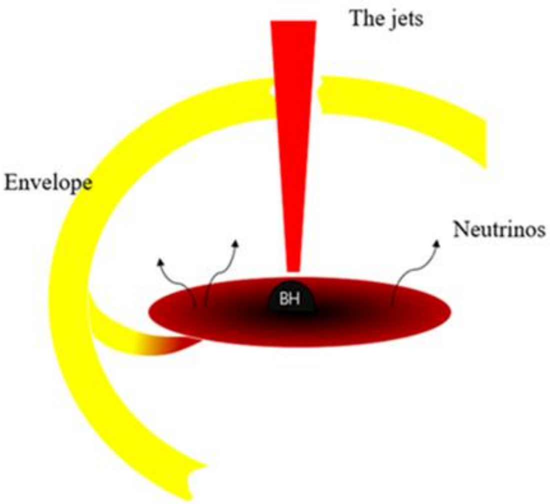
The process of black hole accretion ?

Black hole (BH) hyperaccretion in CCSN

Infalling material with enough angular momentum would be slowed by the rotation and be piled into a disk.

If the accretion rate is extremely high and neutrino cooling is dominant, the hyperaccretion should be in the phase of the neutrino-dominated accretion flows (NDAFs)



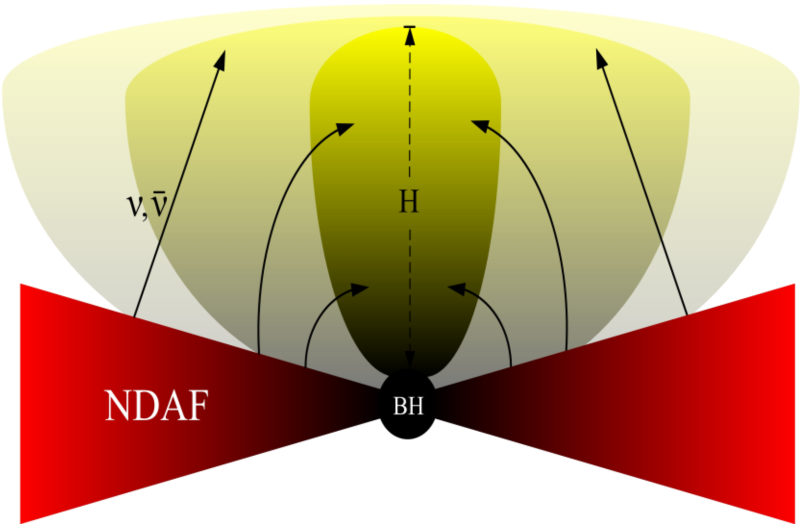


Neutrino dominated accretion flows (NDAFs)

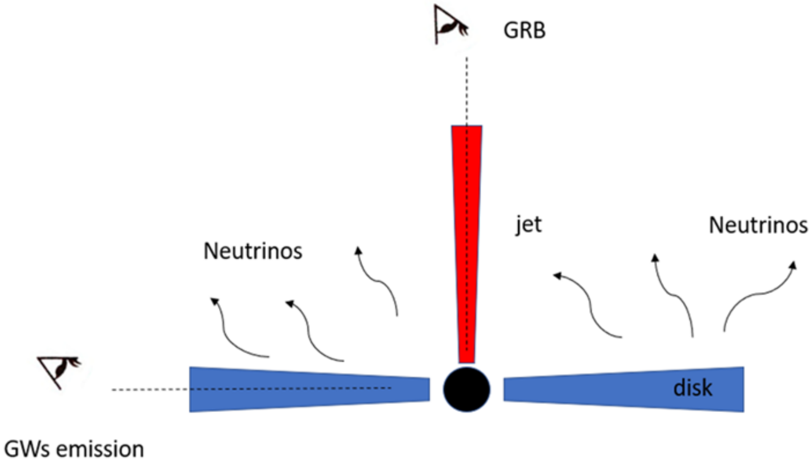
NDAFs around stellar-mass black holes are plausible candidates for the central engine of gamma-ray bursts.

In the inner region of hyperaccretion disk T$\sim 10^{10} - 10^{11}$K, $\rho \sim 10^{6} - 10^{13}$g cm^{-3}

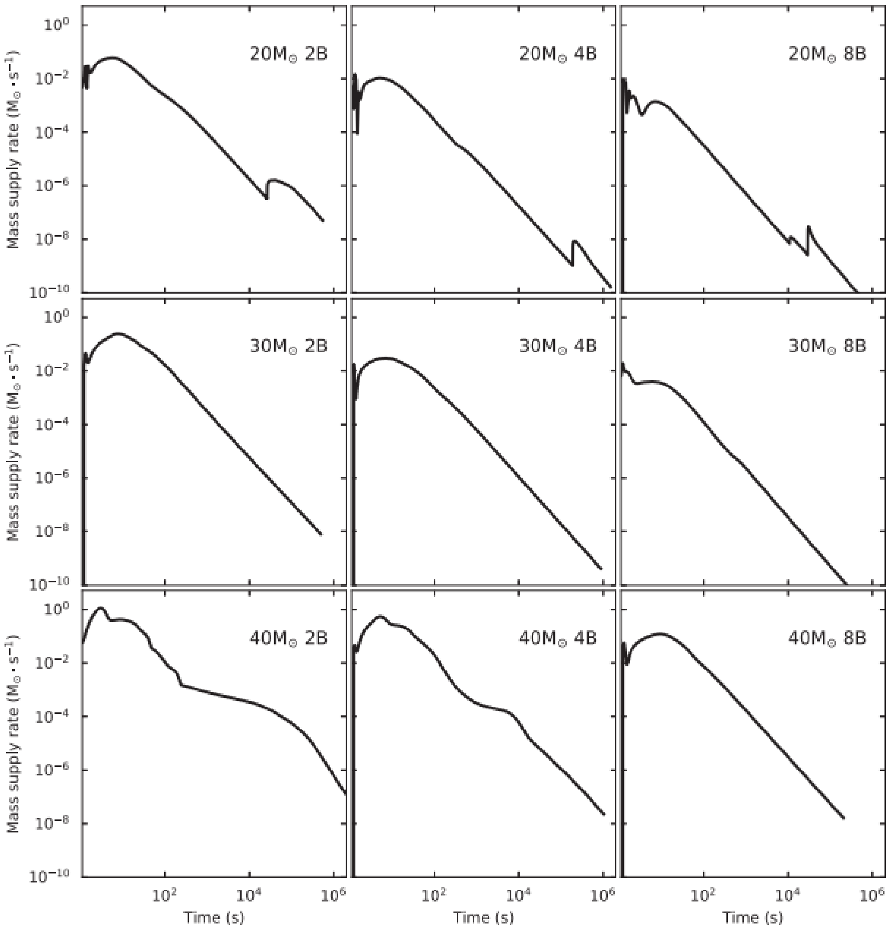
- Neutrino physics (Urca processes; electron-positron pair annihilation;⋯)
- Gravitational wave emission (anisotropic neutrino radiation)



Liu et al. (2015)



Mass supply rate



According to the high accretion rates, the NDAFs would be triggered.

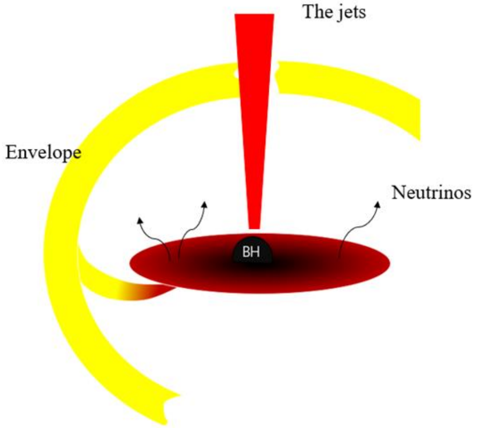
BH evolution

The mass and spin of a BH surrounded by a hyperaccretion disk will violently evolve within a short period.

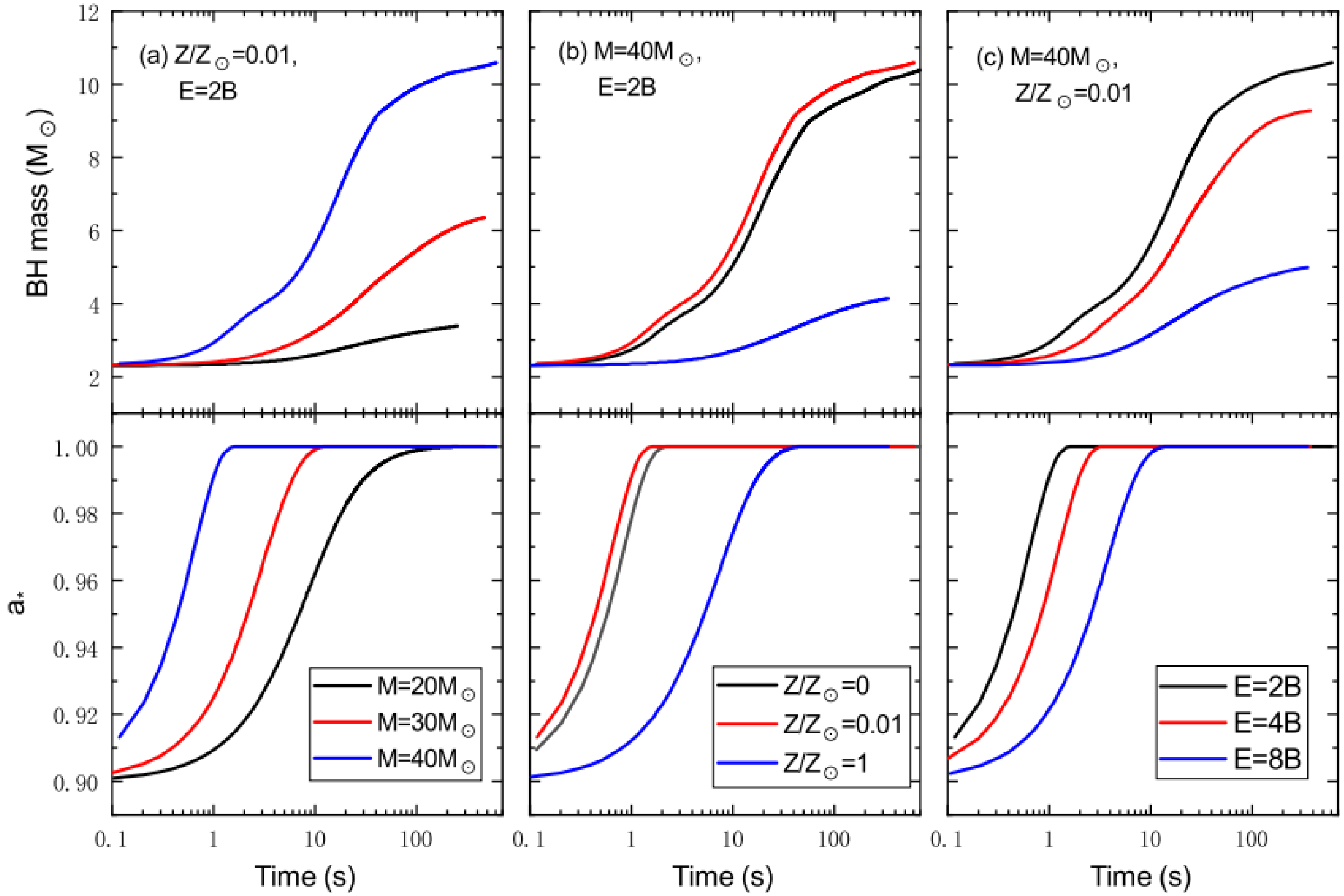
$$\frac{dM_{\rm BH}}{dt} = \dot{M} e_{\rm ms}, \qquad e_{\rm ms} = \frac{1}{\sqrt{3x_{\rm ms}}}\left(4 - \frac{3a_*}{\sqrt{x_{\rm ms}}}\right),$$

$$\frac{dJ_{\rm BH}}{dt} = \dot{M} l_{\rm ms}, \qquad l_{\rm ms} = \frac{2\sqrt{3}GM_{\rm BH}}{c}\left(1 - \frac{2a_*}{3\sqrt{x_{\rm ms}}}\right),$$

$$\frac{da_*}{dt} = \frac{2\sqrt{3}\dot{M}}{M_{\rm BH}}\left(1 - \frac{a_*}{\sqrt{x_{\rm ms}}}\right)^2$$



Evolutions of mass and spin of BHs



The initial BH mass and spin are set as MBH = 2.3 $M_{\odot}$ and a= 0.9, respectively.

Neutrinos from NDAFs

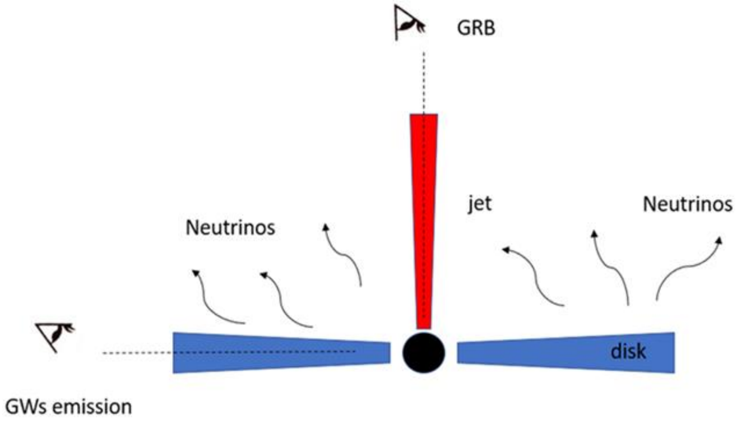
$$\log Q_{\bar{\nu}_e} = 41.40 - 0.23 m_{\rm BH} + 0.58 a_* + 1.85 \log \dot{m} - 3.96 \log r,$$

$$\log T = 11.23 - 0.4 m_{\rm BH} + 0.10 a_* + 0.23 \log \dot{m} - 0.86 \log r,$$

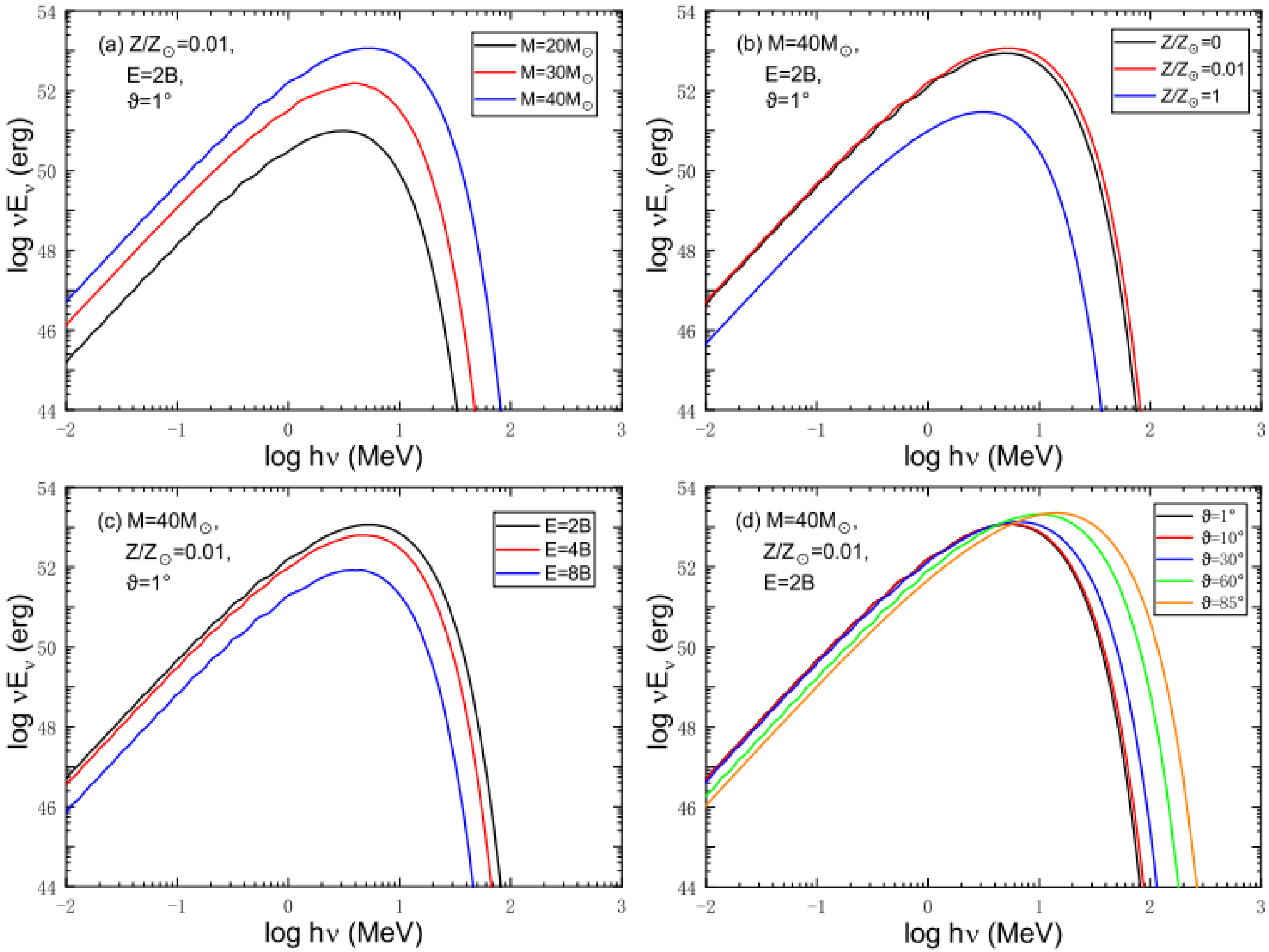
$$\log L_\nu = 52.80 - 0.03 m_{\rm BH} + 1.01 a_* + 1.08 \log \dot{m},$$

$$F_{E_{\rm obs}} = \int_{\rm image} g^3 I_{E_{\rm em}} d\Omega_{\rm obs},$$

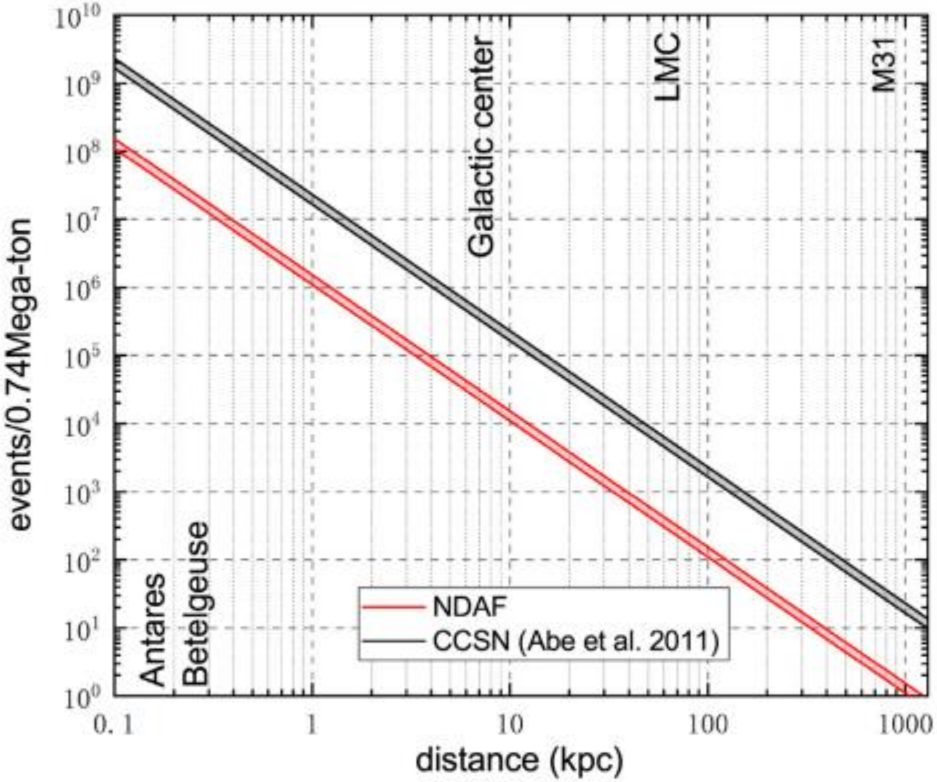
$$I_{E_{\rm em}} = Q_{\bar{\nu}_e} \frac{F_{E_{\rm em}}}{\int F_{E_{\rm em}} dE_{\rm em}},$$



Time-integrated electron antineutrino spectra of NDAFs



MeV neutrino detection



Electron antineutrinos can be detected via inverse beta decay (IBD) reaction by the upcoming Hyper-Kamiokande (Hyper-K) detector

$$\bar{\nu}_{\mathrm{e}} + p \rightarrow n + e^{+}$$

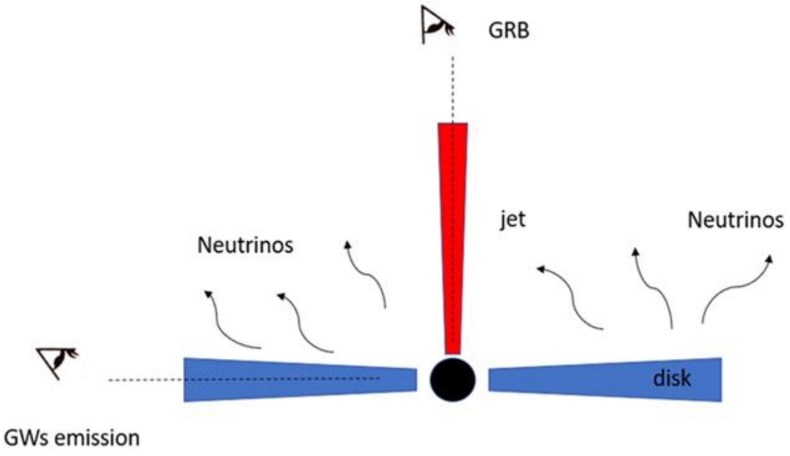
Approximately 165 000−230 000 inverse beta events are expected to be detected by Hyper-K for a typical CCSN at a distance of 10 kpc.

GWs from NADFs

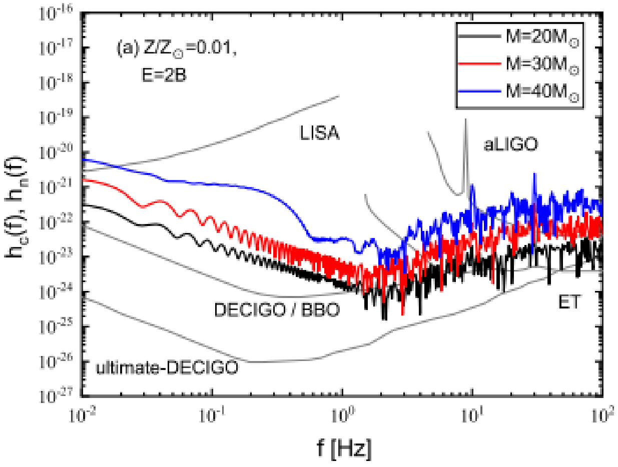
$$\log L_\nu = 52.80 - 0.03 m_{\rm BH} + 1.01 a_* + 1.08 \log \dot{m}$$

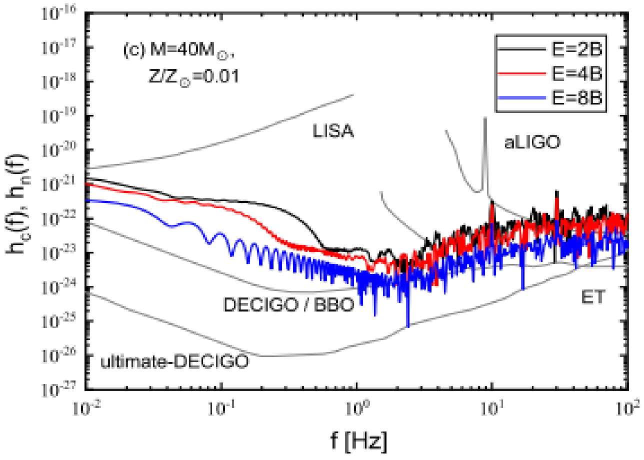
$$h_{+,\rm eq}^{TT}(t) = \frac{2G}{c^4 D} \int_{-\infty}^{t-D/c} \alpha(t') L_\nu(t')\, {\rm d}t',$$

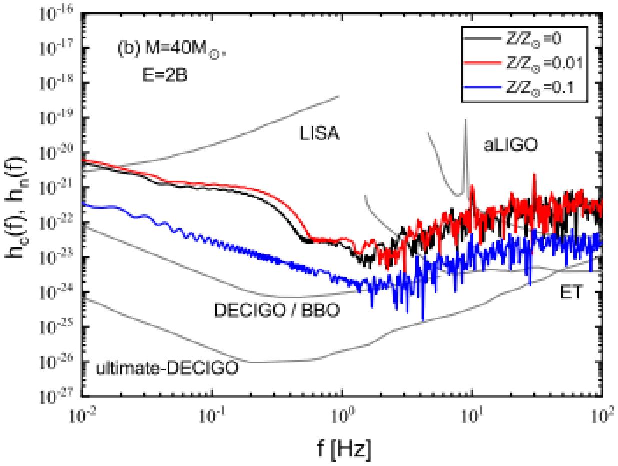
$$\alpha(t) = \frac{1}{L_\nu(t)} \int_{4\pi} \Psi(\vartheta', \varphi') \frac{{\rm d}L_\nu(\vec{\Omega}', t)}{{\rm d}\Omega'}\, {\rm d}\Omega'$$

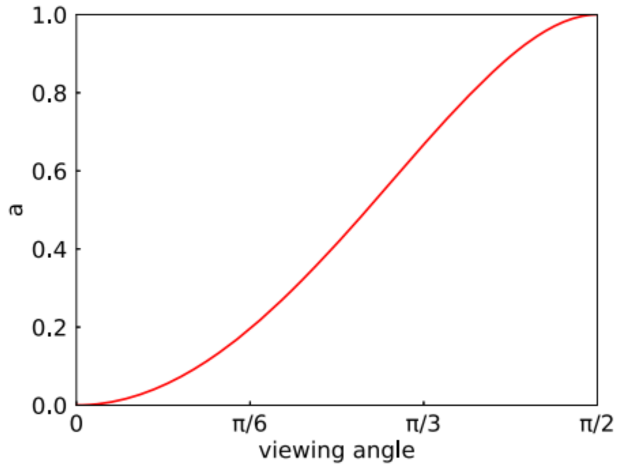


Characteristic amplitudes of GWs from NDAFs

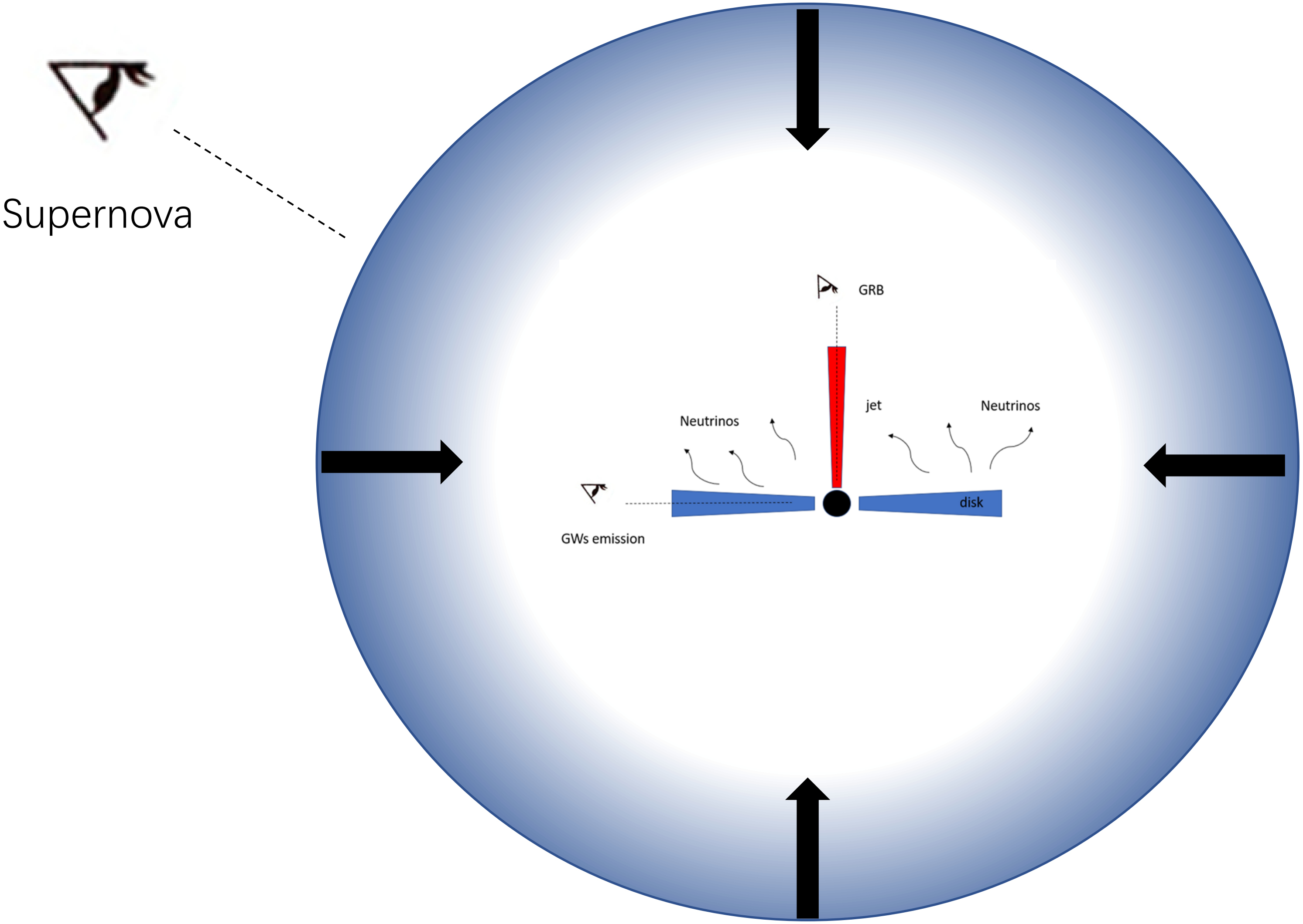








Viewing angle



Summary

- If the typical initial explosion energy of the CCSNe is much lower than that of the observable ones, the lower mass gap will naturally exist.

- The effects of the initial explosion energies, viewing angles, and masses and metallicities of progenitor stars on time-integrated spectra of neutrinos and GW spectra are investigated.

- According to the current CCSN observations, faint or failed CCSNe with low initial explosion energy might be universal, which is beneficial to the detection of the neutrino emission and GW radiation of NDAFs.

- The joint detections of neutrinos and GWs, including the observations of LGRBs associated with CCSN, are meaningful and would help to verify the existence of the central BH hyperaccretion disc.

Thanks