Neutrino Emission upon Black Hole Formation in Core Collapse Supernovae

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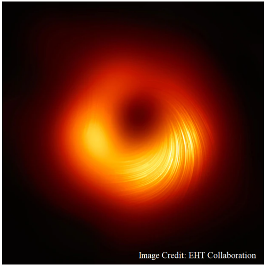
Black Hole Formation in CCSN

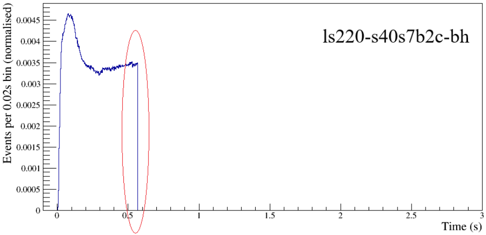
- Core-collapse supernovae are the very final stage of the evolution of massive stars ($M > 10M_\odot$)
- If the progenitor mass exceeds 20 $M_\odot$, the proto-neutron star (PNS) of the CCSN may collapse into a black hole (BH) $\rightarrow$ a failed or weak shock revival[a]
- A major fraction or the entire stellar envelope accretes onto the coalescing PNS until it exceeds the neutron star mass limit
- A distinct indication of the event is a sharp decline in luminosity, i.e., a cut-off



[a] A. Burrows and D. Vartanyan, Core-Collapse Supernova Explosion Theory, Nature 589, 29 (2021)

Black Hole Cut-Off

- How sharp is the cut-off?
  - SN simulations tend to terminate when the BH is formed $\rightarrow$ perfect cut-off as a result of manual intervention
  - The only full ray-trace study considered only radial emissions *Baumgarte et al. (1996)*
- *Baumgarte et al. (1996)* has also pointed out the need for non-radial ray-tracing, which is essential for a full general relativistic treatment



Garching group model: https://wwwmpa.mpagarching.mpg.de/ccsnarchive/archive.html

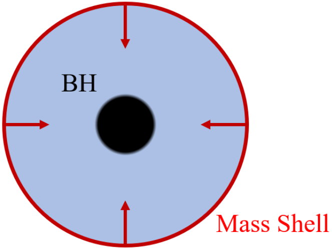
- Our approach comes in two stages:
  - Ray trace studying the Spacetime effects
    - J. Wang, J. Tseng, S. Gullin and E. O'Connor, *Phys. Rev. D*, 104, 104030 (2021) (arXiv: 2109.11430)
  - Full simulation including the neutrino interactions $\rightarrow$ flavour!
    - S. Gullin, E. O'Connor, J. Wang and J. Tseng, *Astrophys. J.*, 926, 212 (2022) (arXiv: 2109.13242)
- These studies also explored the behaviour of two different contributions to the cut-off profile:
  - Neutrino emissions from the collapsing core surface (neutrinosphere)
  - Accretion-delayed neutrinos $\rightarrow$ "echo"

Luminosity of a Collapsing Surface

- *Podurets (1965)* showed that the luminosity of a non-rotating free-falling mass shell is asymptotically characterised by a sharp exponential $exp(-\frac{t}{3\sqrt{3}M})$
- This result has been widely applied in later studies on neutrinos, such as *Beacom et al. (2001)*
- The transition to the exponential decay is not known
- To investigate in this, we will discuss two cases: non-rotating (Schwarzschild metric) and rotating (Kerr metric) (with planar emission, disc model)
- J. Wang, J. Tseng, S. Gullin and E. O'Connor, *Phys. Rev. D*, 104, 104030 (2021) (arXiv: 2109.11430)

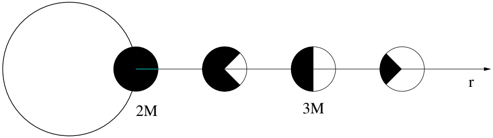
Ray Tracing from a Collapsing Surface

- We evaluate the luminosity profile by performing a ray-tracing Monte Carlo
- For simplicity, we start the discussion with a free-falling spherical mass shell starting from rest at $r = r_0$
- We considered two cases: $r_0 = 5M$ (PNS radius) and $10M$ (shock front radius)
- Assuming null rays for the neutrinos
- At each time step, a fixed number of neutrinos are generated from the collapsing surface, and each neutrino will be traced all the way to Earth



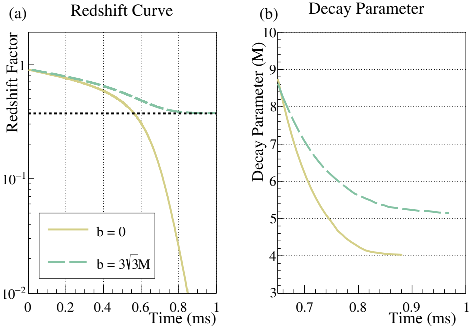
Trajectory - Schwarzschild Case

- Each generated neutrino is randomly assigned an emission angle ψ_{FF} in the free-fall frame which indicates the impact parameter $b = \sqrt{(1 - \cos^2 \psi_S) \frac{r^2}{C}}$ that determines the trajectory, where $C = 1 - \frac{2M}{r}$ and ψ_S is the emission angle in the static frame
- There is a critical parameter $b_c = 3\sqrt{3}M$ where the ray will enter an unstable circular orbit at $r = 3M$, and below which rays will plunge into the BH
- Escapable trajectories form the "escape cone"



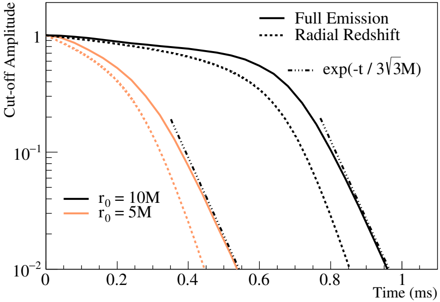
Redshift - Schwarzschild Case

- This factor can be divided into two components: Gravitational redshift and Doppler shift
- The redshift of the ray can be expressed as (*Ames et al. (1968)*):
  $\zeta = \frac{\nu_E}{\nu_*} = \sqrt{C} \times \frac{\sqrt{1-\beta_S^2}}{1+\cos\psi_S}$
- The radial redshift profile approaches a decay constant of $4M$, whereas the critical approaches $3\sqrt{3}M$



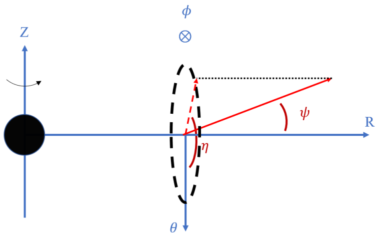
Result - Schwarzschild Case

- There is a slow drop in the luminosity for several tenths of ms, followed by a steepening which rapidly approaches a decay parameter of $3\sqrt{3}M$
- The tail of $3\sqrt{3}M$ decay parameter is dominated by emissions from the photon sphere at $r = 3M$

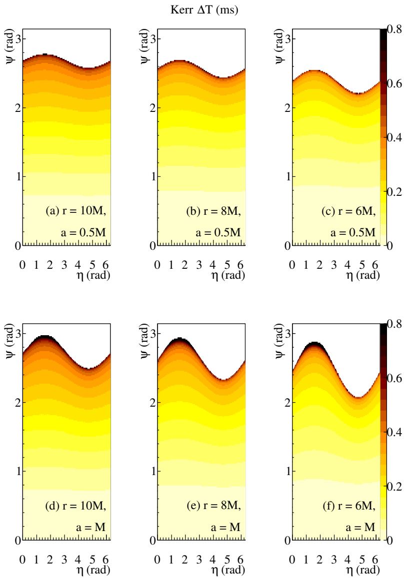


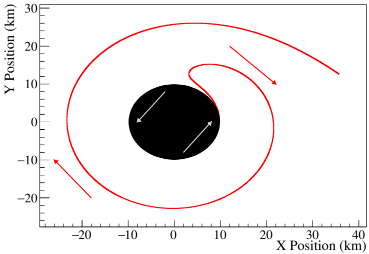
Ray Trace of Rotating Black Hole

- Though it is usually assumed that not much angular momentum will be left when the progenitor reaches the stage of collapse, it is still interesting to see how things would evolve when black holes are formed with considerable rotation
- We present the first ray-tracing study on rotating black holes using the Kerr metric
- Not spherically symmetric → extra dimension in emission angle
- To simplify matters, we consider a disc model where emitters are all situated on the equatorial plane



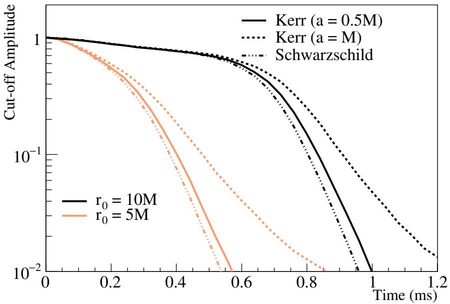
Trajectory and Redshift - Kerr Case





Result - Kerr Case

- The cut-off is further soften by rotation
- Unlike the non-rotating case, the tail does not approach a limiting value



Measurement of Black Hole Cut-Off

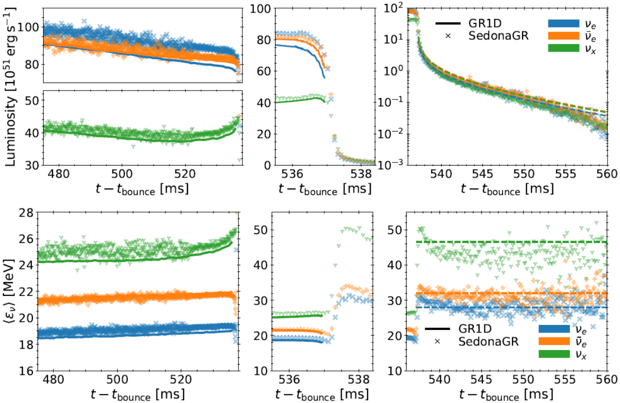
- For a Schwarzschild BH originating from a $40M_\odot$ progenitor at 10 kpc, JUNO (20 kilotonne) and SuperK (22.5 kilotonne) are expected to see about 15 events per millisecond before the cut-off followed by a tail of 0.7 events
- In the case of HyperK (220 kilotonne), the count becomes 100 events before the cut-off and 5 events in the tail $\rightarrow$ possible measurement!
- The decay constant of the tail, i.e. $3\sqrt{3}M$, could be potentially used to measure the BH mass
- The slowly decay part, with enough events, might also hint the collapsing velocity profile
- For $a = 0.5M$ one sees a 20% increase in the tail, whereas for $a = M$ it is doubled
- Deviations from exponential might also be used to infer rotation

Other Contributions After Black Hole Formation

- Our calculation is clearly very simplistic and so far have only considered the contributions from the core
- “Echos”: neutrinos emitted before the BH formation that get delayed by scattering with the infalling material
- For this study, we had to perform more detailed simulation of the matter configuration during the collapse
- Neutrino interactions, and thus flavour, plays a role!
- S. Gullin, E. O’Connor, J. Wang and J. Tseng, *Astrophys. J.*, 926, 212 (2022) (arXiv: 2109.13242)

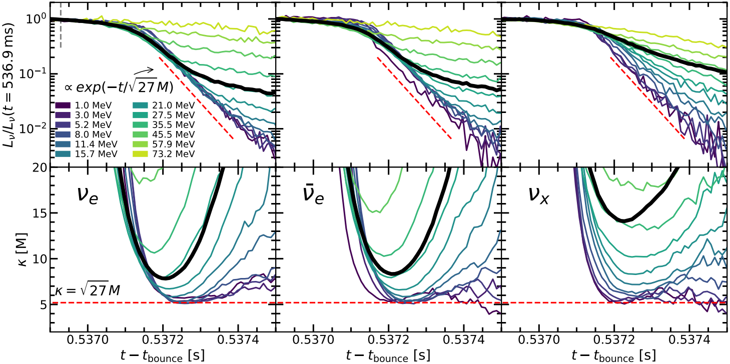
Neutrino Echo

- Main physical process is neutrino-nucleus scattering
- The sudden rise of mean energy is the sign of dominance of neutrino echos



Convolution with Core Emissions

- The majority of the neutrinos exhibit the $3\sqrt{3}M$ feature just following BH formation, whereas this behaviour sustains longer in the case of low energy neutrinos
- The overall profile follows the expected exponential behaviour in the 200 μs time window $t = 0.5371 - 0.5373$ s



Detection of Neutrino Echos

- With enough events, one can identify the core signal and neutrino echos via energy stratification
- A measurement of this signal might provide information of the density profile and, hence, accretion flows during BH formation
- We count the events within a 30 ms time window: 7 ms before and 23 ms after BH formation

Detector	Target	Mass [kT]	Counts in Neutrino Echo	
			baseline	truncated
Super-K	Water	32	5.2	4.4
JUNO	L. Scint.	20	4.7	4.0
DUNE	Argon	40	9.4	7.6
Hyper-K	Water	220	35.9	30.4

Further Studies - Flavours!

- Our studies have not considered neutrino oscillations so far
- Studying the flavour composition of supernova neutrinos could lead to information regarding the mass hierarchy
  - H-resonance of MSW
  - Detection time difference between ν_e and $\bar{\nu}_e$
- What about the BH signature?
  - Provides a standard time reference
  - Terrestrial MSW measurements across the globe!

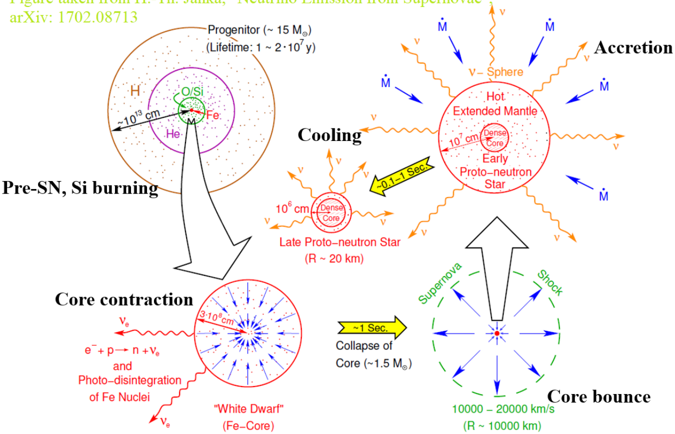
Summary

- For non-rotating black holes, the tail of the luminosity profile is always dominated by the leakages from the critical orbit featured by time constant $3\sqrt{3}M$
- This $3\sqrt{3}M$ time constant could potentially lead to a measurement of the black hole mass, though it could very likely be smeared by neutrino echos
- Rotation can further soften the cut-off, and in the extreme case the tail will be significantly extended
- Detection of neutrino echo itself might reveal some information regarding the density configuration of the accreting stellar material
- This study, though simplistic, capture most of the important features of the core emissions and shows the potential information that such measurements could provide
- Successfully identifying the BH features could in turn help in studying oscillation

Backup

CCSN Phases

Figure taken from H.-Th. Janka, "Neutrino Emission from Supernovae", arXiv: 1702.08713



Neutrino emission channels

- **Pre-SN**:

$\gamma \to e^- + e^+ \to \nu_e + \overline{\nu_e}$

$e^+ + n \to p + \overline{\nu_e}$ (late stage)

$e^- + p \to n + \nu_e$ (late stage)

- **Core collapse**:

$e^- + p \to n + \nu_e$

- **Accretion and cooling**:

- Electron flavour:

$e^+ + n \to p + \overline{\nu_e}$

$e^- + p \to n + \nu_e$

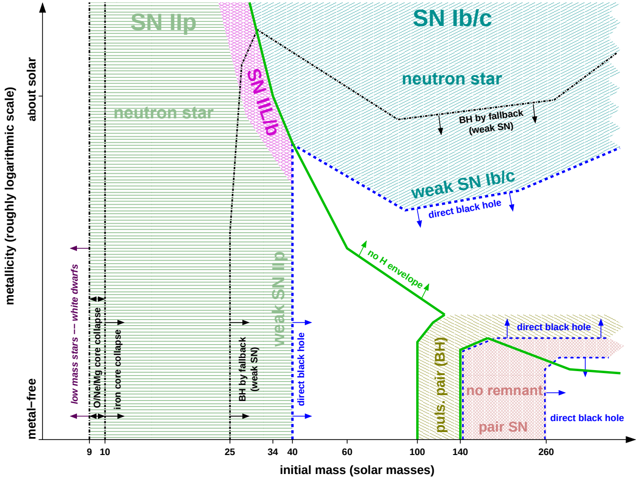
- All flavours:

$\gamma \to \nu + \bar{\nu}$

$e^- + e^+ \to \nu + \bar{\nu}$

$N + N \to N' + N' + \nu + \bar{\nu}$

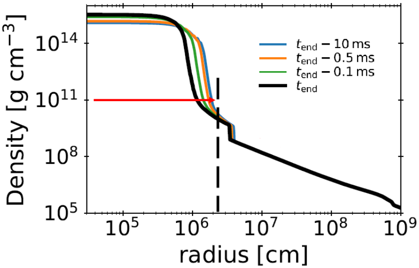
Black Hole Formation in CCSN



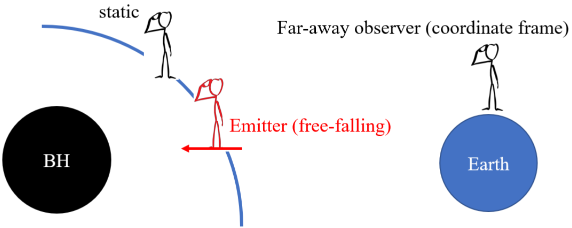
A. Heger *et al.*, Astrophys. J., 591, 288 (2003)

Neutrinosphere

- Analogous to the photosphere in the case of photons
- It is usually defined as the surface at which the optical depth reaches unity
- This usually corresponds to the surface of density $\rho \sim 10^{11}$ g/cm^3

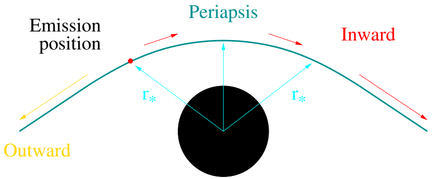


- Coordinate frame: frame of the far-away observer, i.e., us on Earth
- Free-fall frame: the emitter's proper frame
- Static frame: frame of an observer static at the radius at which the emission occurs



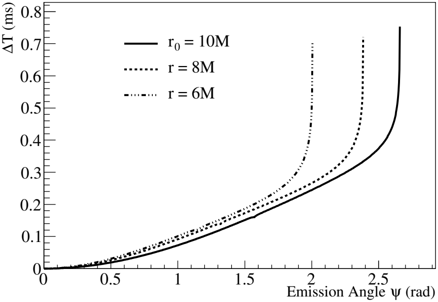
Travel Time - Schwarzschild Case

- The trajectory of the neutrino is determined by the impact parameter $b \equiv L/E$ which depends on the emission angle ψ relative to the radial direction ($b = 0$ corresponds to radial)
- The travel time can then be calculated by $T \equiv \int_{r_*}^{r_E} \frac{r^{5/2}\mathrm{d}r}{(r-2M)\sqrt{r^3-b^2(r-2M)}}$
- Depending on the travelling direction there are two types of trajectories:
    - Outward Travelling: streaming outwards and possibly bent by gravity
    - Inward Travelling: travels pass the periapsis then streams out as in the outward case, gaining an extra Shapiro-like time delay



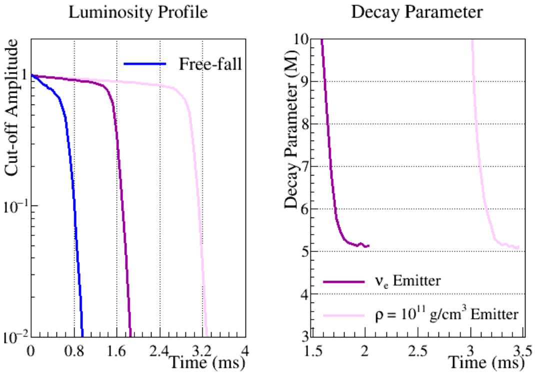
Time Delay vs Emission Angle

- A major fraction of the geodesics lead to time delays with fractions of a millisecond, and as the path approaches the photon orbit the delay diverges (doesn't leave at all)



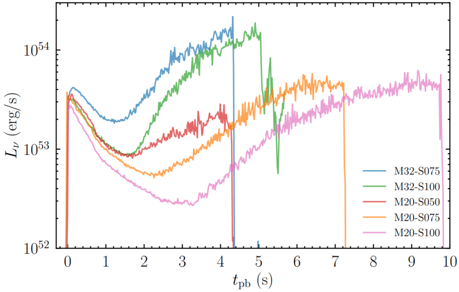
Velocity Profile - Schwarzschild Case

- For a even more realistic approach, we also invoked the velocity profiles from more detailed simulations
- In any case, the end of the decay always approaches $3\sqrt{3}M$ and is dominated by critical emissions
- Note that the slowly decaying part is significantly elongated for these slower profiles



Rotation and Black Hole Formation

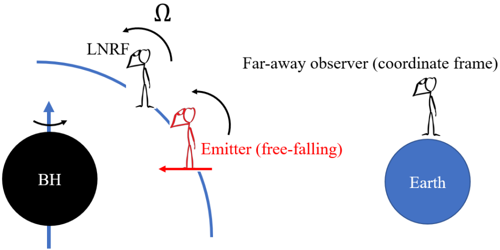
- Though it is usually assumed that not much angular momentum will be left when the progenitor reaches the stage of collapse, it is still interesting to see how things would evolve when black holes are formed with considerable rotation
- In most models, rotation is expected to significantly delay the formation of black holes, e.g., collapsars (Fujibayashi *et al.*, Astrophys.J. 919 (2021) 2, 80)
- It will also be interesting to see how it will modify the luminosity profile after black hole formation



Fujibayashi *et al.*, Astrophys.J. 919 (2021) 2, 80

Observation Frames - Kerr Case

- Stationary observers in the Kerr geometry are not static
- This frame is known as the locally non-rotating frame (LNRF) (*Bardeen et al. (1972)*) in the Kerr geometry
- It is the analogy of the static frame in the non-rotating case, so the subscript S is re-purposed to represent the LNRF



- For this study, we have applied more detailed simulation using GR1D to evolve a $40M_\odot$ solar-metallicity progenitor till the point of BH formation (this model considers a failed supernova)
- SedonuGR is used to handle the neutrino transport
- Uses the standard LS220 equation of state
- BH forms at about 0.5 s after core bounce