GR simulations of collapse of supermassive stars

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Outline of the talk

- Introduction:
    - Formation and properties of supermassive stars (SMSs)
    - Supermassive black hole (SMBH) seed formation
- Nada GRHydro code, EOS and microphysics
- Results
- Conclusions

Introduction

- Large observational evidence: MBH exist in the centre of most nearby galaxies (e.g. orbital motion of stars in Sgr-A* suggest MBH~$4 \times 10^6 M_\odot$).

- Luminous quasars at $z \geq 6$ implies that SMBH with masses ~$10^9 M_\odot$ formed within the first billion years after Big-Bang.

Still unknown: <u>How SMBH form and grow to such high masses in such a short time</u>

Dark matter halo

$T_{vir} < 10^4 K$
Z=0, H_2 cooling

Collapse of Pop-III stars
BH grow via merger and accretion

Gas unable to cool below $T_{vir} \sim 10^4 K$
$Z < Z_{crit}$ and radiation field to avoid fragmentation
Gas dynamical processes in which:

Gas contracts and cools until rotational support halts the collapse before reaching densities required for BH formation.

Forming a supermassive object.

Introduction

Depending on how fast and efficiently mass accumulation proceeds:

“quasistars”
(Begelman et al 2006, Begelman 2009).

Outer layers of the star not thermally relaxed before the collapse of core to BH

SMSs with mass above ~ $5 \times 10^4 M_\odot$

Evolve as equilibrium configurations dominated by radiation pressure (Hoyle&Fowler 1963)

➔ **Supermassive dark matter stars** (Spolyar et al 2008, Freese et al 2010): shine due to WIMP annihilation and could reach masses of about $10^5 M_\odot$

➔ When DM fuel is exhausted, short phase hydrogen burning before collapse to SMBH

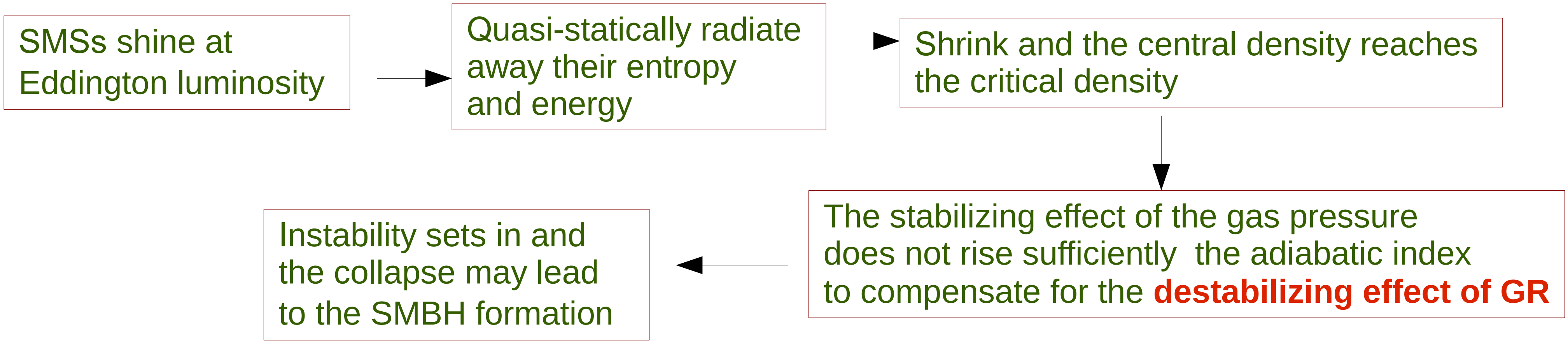
- **Gravitational instability and collapse to SMBH (>$10^4 M_\odot$)**: substantial jump towards its growth to $10^9 M_\odot$

- The **peak GW frequency expected for the collapse** of a SMS of $10^6 M_\odot$ is around 10^{-2} Hz, **in the middle of LISA frequency band**

Main properties of SMSs

- Supported against gravitational collapse by radiation pressure.
- Plasma correction and GR effect are small though cannot be neglected for the evolution
- Adiabatic index of the equation of state takes the form: $\Gamma_{SMS} \approx \frac{4}{3} + \frac{\beta}{6}, \text{ where } \beta = \frac{P_g}{P_r} \ll 1$
- Critical density: GR lead to the existence of a maximum for the equilibrium mass as a function of the central density for SMS with constant entropy.

Spherically symmetric case: $\rho_{crit} = 1.994 \times 10^8 \left(\frac{0.5}{\mu}\right)^3 \left(\frac{M}{M_{sun}}\right)^{-7/2} g\,cm^{-3}$



SMSs shine at Eddington luminosity

Quasi-statically radiate away their entropy and energy

Shrink and the central density reaches the critical density

The stabilizing effect of the gas pressure does not rise sufficiently the adiabatic index to compensate for the **destabilizing effect of GR**

Instability sets in and the collapse may lead to the SMBH formation

Baumgarte & Shapiro (1999): rotating SMSs at mass shedding limit at the point of the instability.

Nuclear burning

Key question: Energy liberated through hydrogen burning during the collapse can cause a thermonuclear explosion?

- If Z=0, only proton-proton chain (pp-chain) and helium burning (triple-α) are possible
- If $0<Z<Z_{crit}$ then CNO-cycle and hot-CNO cycle (at $T \leq 0.5 \times 10^9$K) limited by the beta-decays of ^{14}O and ^{15}O, become the main sources of nuclear energy release
- At $T>0.5 \times 10^9$K the break-out of the hot-CNO cycle is possible via $^{15}O(\alpha,\gamma)^{19}Ne$ (rp-process) Wallace & Woosley (1981)

Last investigation of nuclear burning during the collapse and explosion of SMSs by Fuller(1986):

Post-Newtonian approximation and only spherical SMSs
Detailed EOS including electron-positron pairs
Neutrino losses and nuclear reactions describing CNO cycles and rp-process
Stars with $M \geq 10^5 M_\odot$ and initial metallicities $Z \geq 0.005$ do explode.

GR-simulations with Γ-law EOS and no nuclear burning:

Shibata&Shapiro (2002) studied the axisymmetric collapse of rotating SMSs found that BH will contain 90% of the total mass

Saijo&Hawke (2009) 3D simulations of non-uniformly rotating SMSs and computed the GWs emission.

Nada code

2D-axisymmetric code solving the couple system of Einstein and GR hydrodynamic eqs:

- BSSN formulation & Cartoon method & Moving puncture gauge
- HRSC methods to evolve the GRH eqs.
- Tests & simulations of self-gravitating tori around BH (PM, Font, Shibata PRD 2008,2010)

EOS, microphysics and nuclear energy generation rates:

➔Contribution of baryons and radiation separately: $P = \frac{1}{3} a T^4 + \frac{R \rho T}{\mu}$

➔In addition, use a table to take into account the electron-positron pair creation: at T>10^9K part of the energy is used to create pairs and therefore reducing the adiabatic index below 4/3 and thus reducing stability of the star.

➔Temperature obtained by Newton-Raphson (Neutrino losses as post-process step)

➔Nuclear energy rates: pp-chain, 3-alpha, CNO cycles and rp-process

e.g. CNO cycle (Shen &Bildstein 2007):

$$\frac{\partial e}{\partial t} = 4.4 \times 10^{25} \rho X_H Z_{CNO} [[\frac{\exp(-15.231/T_9^{1/3})}{T_9^{2/3}}] + [8.3 \times 10^{-5} \frac{\exp(-3.0057/T_9)}{T_9^{3/2}}]] erg\, g^{-1} s^{-1}$$

Initial model and numerics

Focus on two initial models that are dynamically unstable:

1) Spherical SMS rest-mass≈ $10^6 M_0$, $\rho_c = 2.8\times10^{-3}$ (gcm^{-3}), $T_c \approx 10^7$K

2) Uniformly Rotating SMS rest-mass≈ $10^6 M_0$, $\rho_c = 1.0\times10^{-1}$ (gcm^{-3}), $T_c \approx 6\times10^7$K, $T/|W|=0.0088$
pp-chain and 3-alpha reactions

Numerics:

Uniform Cartesian grid in 2D ($0<x,z<L$)
The "regriding technique" (Shibata&Shapiro) to follow the evolution:

Initial phase:

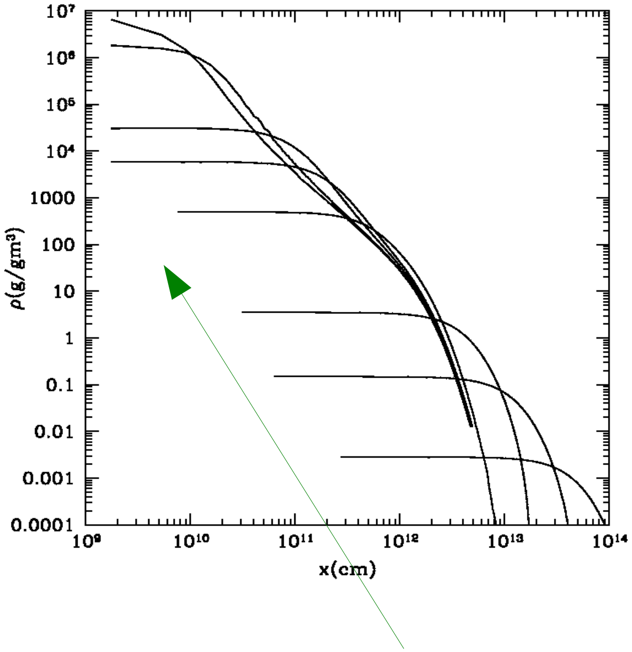
Rezone the computational domain
Keep the number of grid points, NxN= 300x300, L=1200M
Moving the outer boundary inward decreasing the grid spacing
Repeat 3 times until the collapse timescale in centre is much shorter than in envelope

Next:

$0.9>\alpha>0.8$, NxN= 600x600, L=400M
$0.8>\alpha>0.3$, NxN= 1200x1200, L=200M
$0.3>\alpha$, NxN= 1800x1800, L=60M ⟶ Phase of BH formation and accretion onto BH

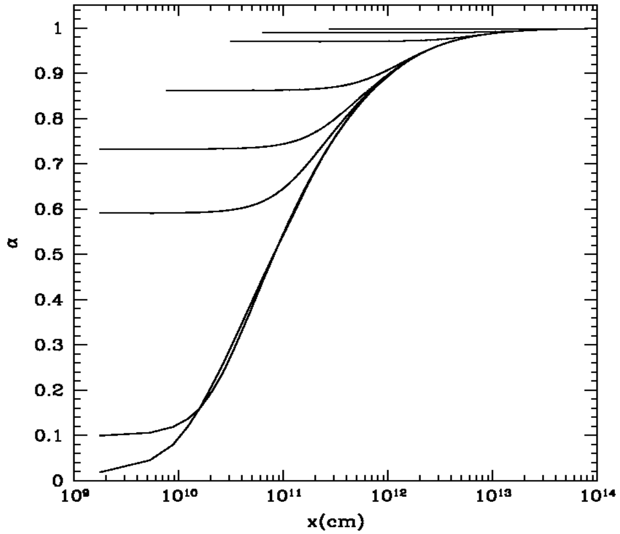
Results: spherical collapse

Rest-mass density profiles:

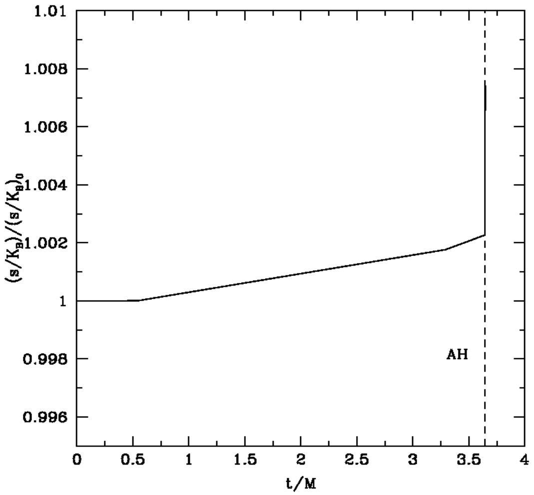


Regriding

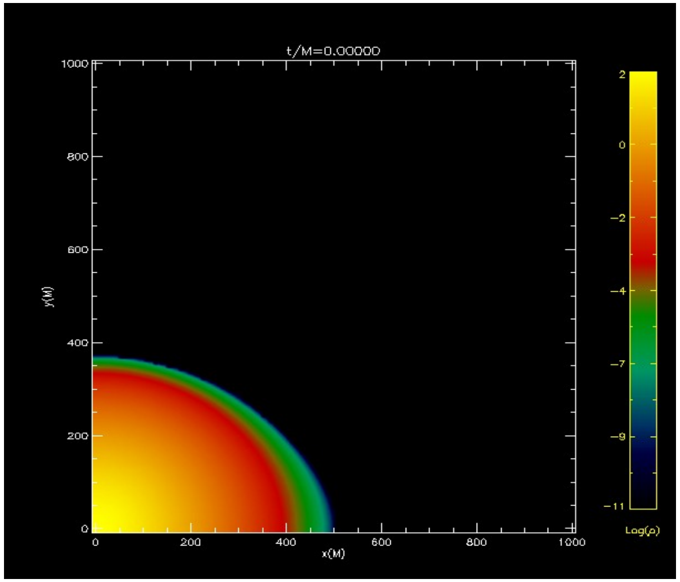
lapse profiles:

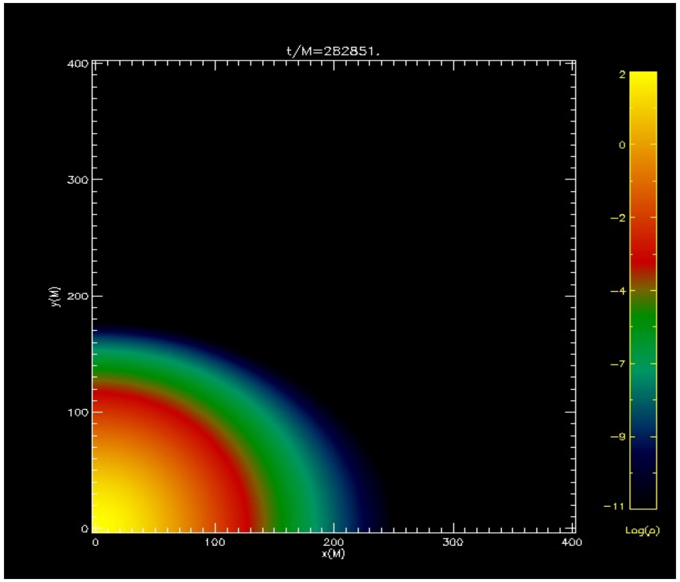


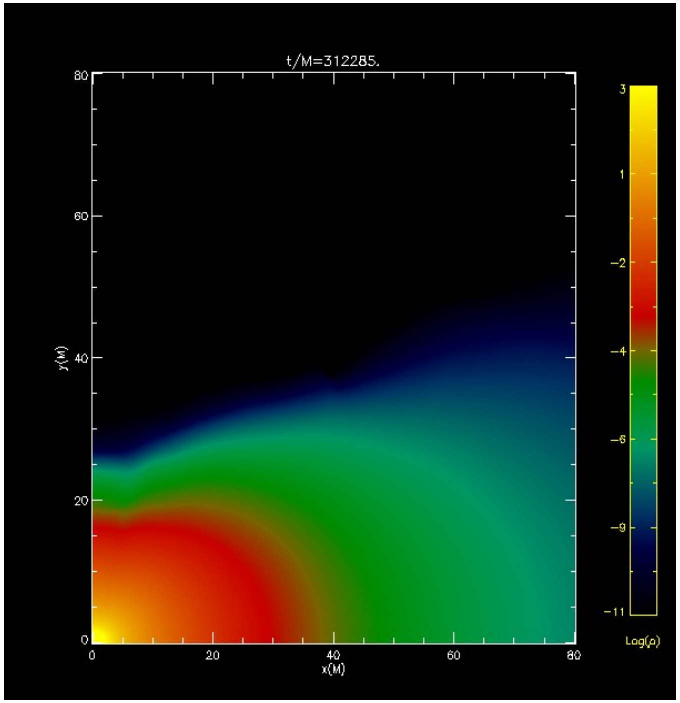
Conservation specific entropy:

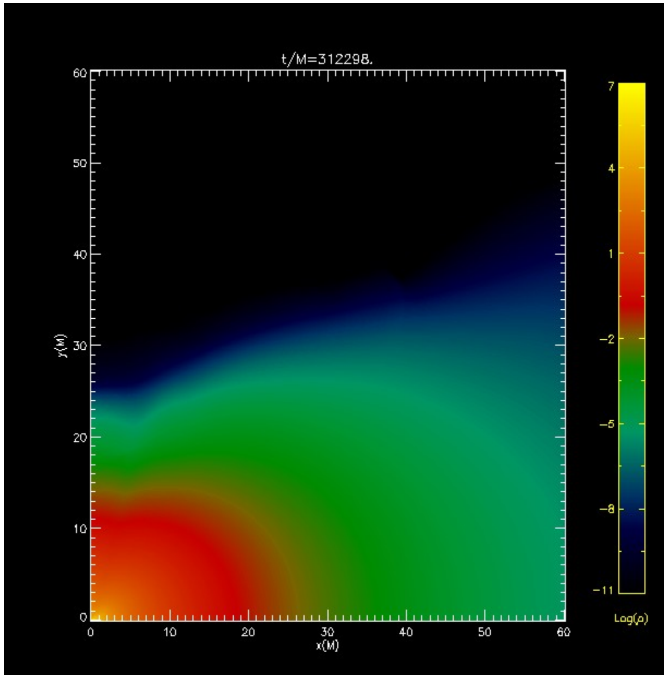


Results: rotating collapse









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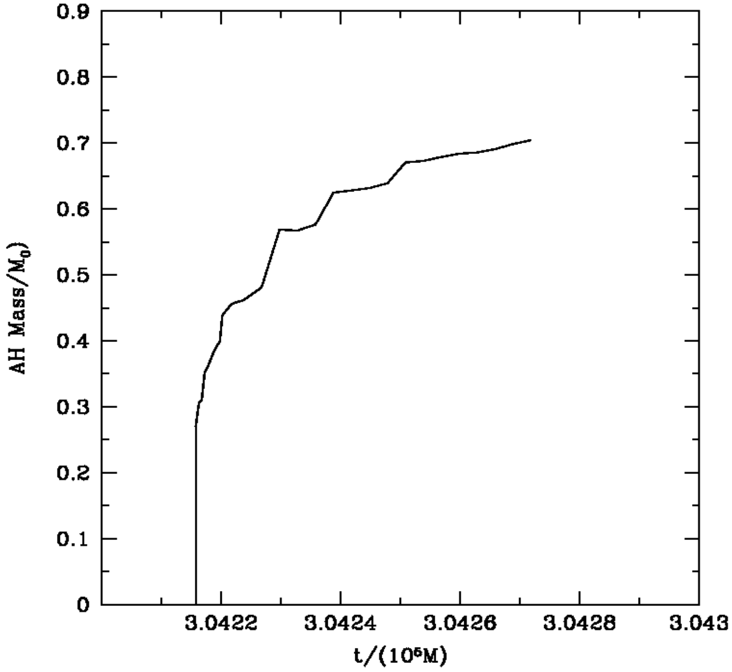

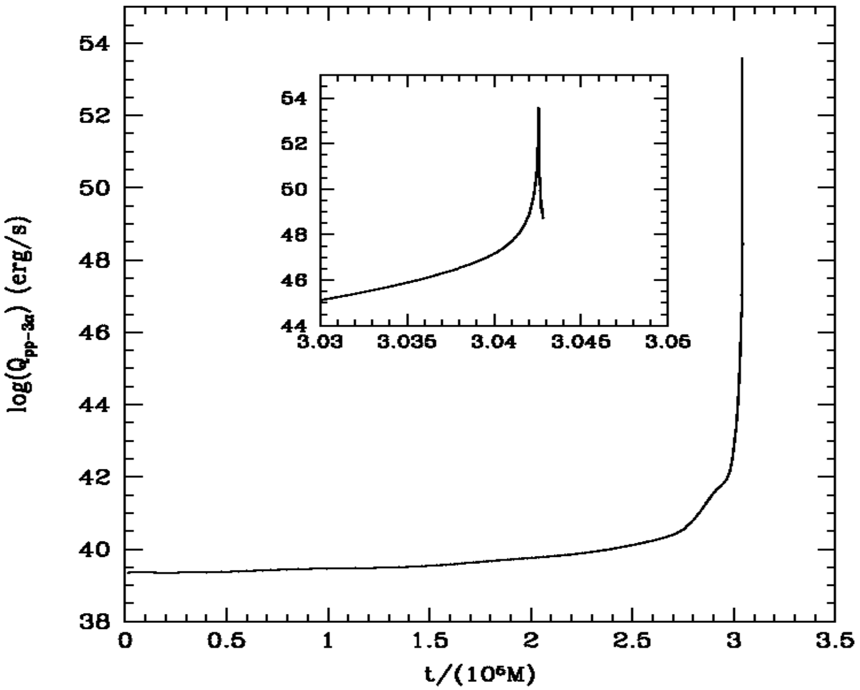

Mass of the AH normalized to the ADM mass

approximately 90% of the rest-mass is
will accrete.

Nuclear energy release rates (erg/s) due to H and He burning.

Accumulated nuclear energy released is two order of magnitud lower than initial gravitational binding energy.

Conclusions

- Investigating collapse of SMSs and SMBH formation take into account:

  General relativity
  EOS which includes creation of pairs
  Nuclear burning of main net reactions for H and He burning expected to take place

- First models considered show:

  Neutrino luminosities agree with those of Linke et al.(2000)

  Rotating SMSs with Z=0 collapse to BH

  Confirm results of Woosley $Z=5\times10^{-3}$ lead to explosions even in rotating stars

  Currently investigating more models and advecting the main species

- Potential observations to distinguish between BH seeds may come from JSWT telescope and LISA GW detector.