Formation and Coalescence of Cosmological Supermassive Black Hole Binaries in Supermassive Star Collapse

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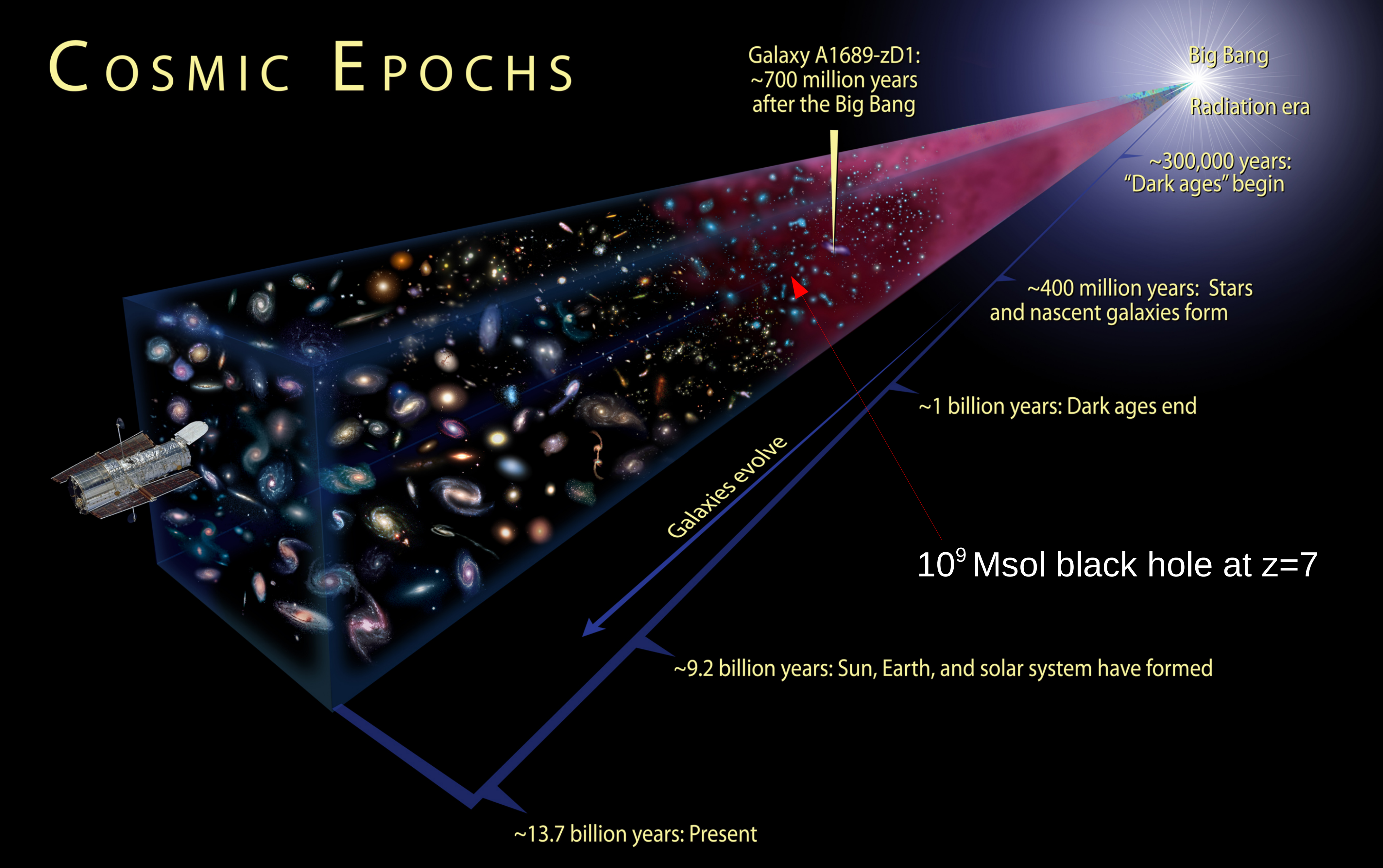
Formation and Coalescence of Cosmological Supermassive Black Hole Binaries in Supermassive Star Collapse

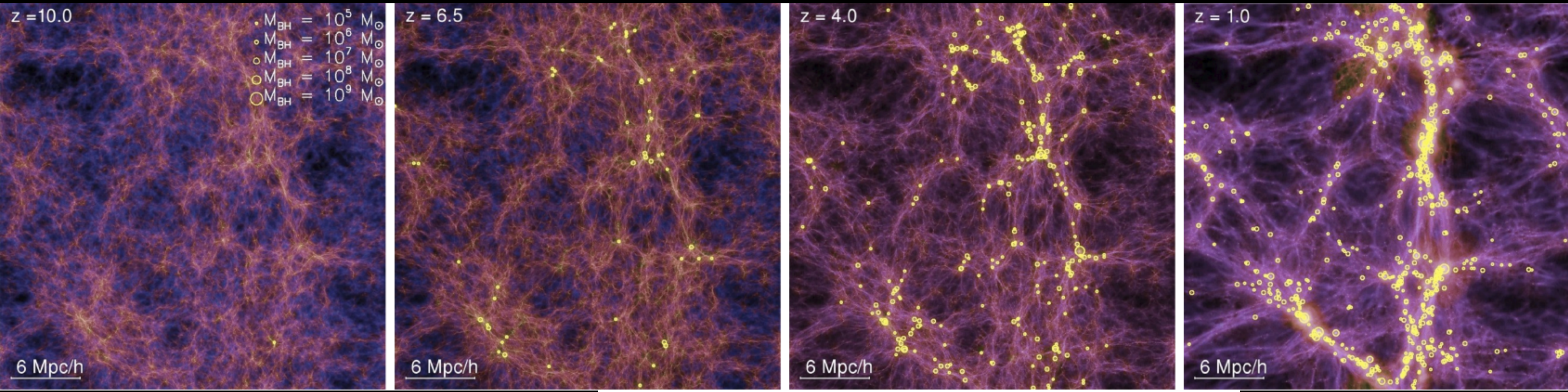
- Motivation Supermassive black holes, formation scenarios, supermassive stars
- Computational Modeling Numerics, Multipatches
- Results Simulations, remnant properties, gravitational wave detectability



Cosmic Epochs
Galaxy A1689-zD1: ~700 million years after the Big Bang
Big Bang
Radiation era
~300,000 years: "Dark ages" begin
~400 million years: Stars and nascent galaxies form
~1 billion years: Dark ages end
Galaxies evolve
10^9 Msol black hole at z=7
~9.2 billion years: Sun, Earth, and solar system have formed
~13.7 billion years: Present

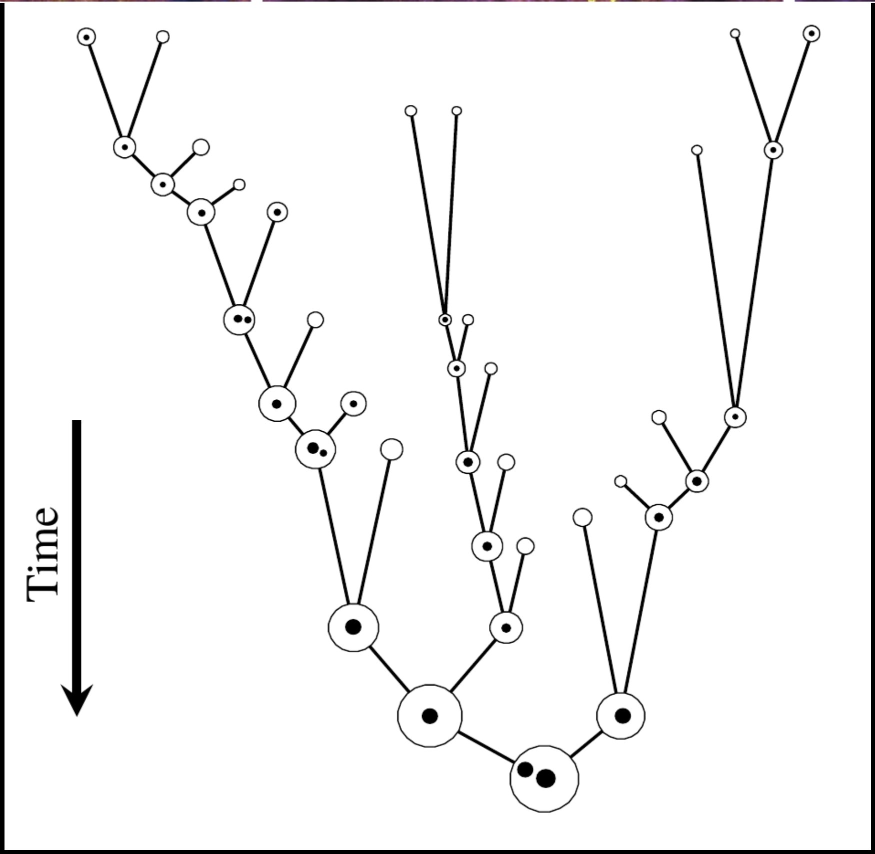
Motivation: 10^9 Msol black hole at z=7

How is that possible?



e.g., Di Matteo et al 2008

Not enough time!



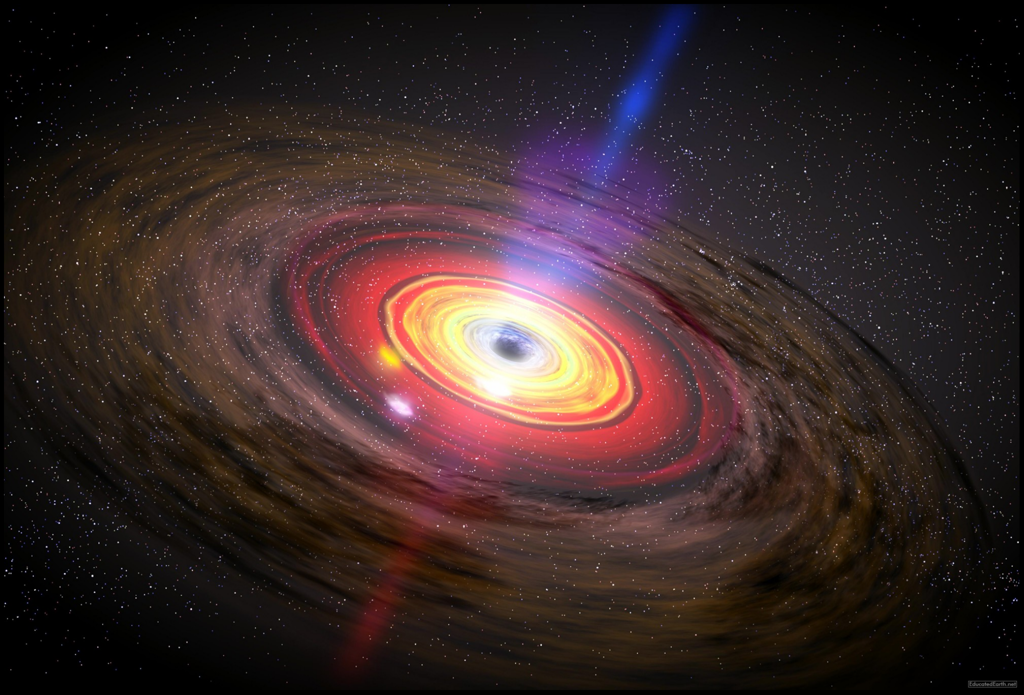
Motivation: 10^9 Msol black hole at z=7

How is that possible?

Growth via accretion from a collapsed ~100Msol Pop III initial seed star?

→ Accretion at Eddington rate, otherwise 10^9 Msol BH not reached within 1 Gyr

Not possible! Strong radiative feedback limits growth rate!



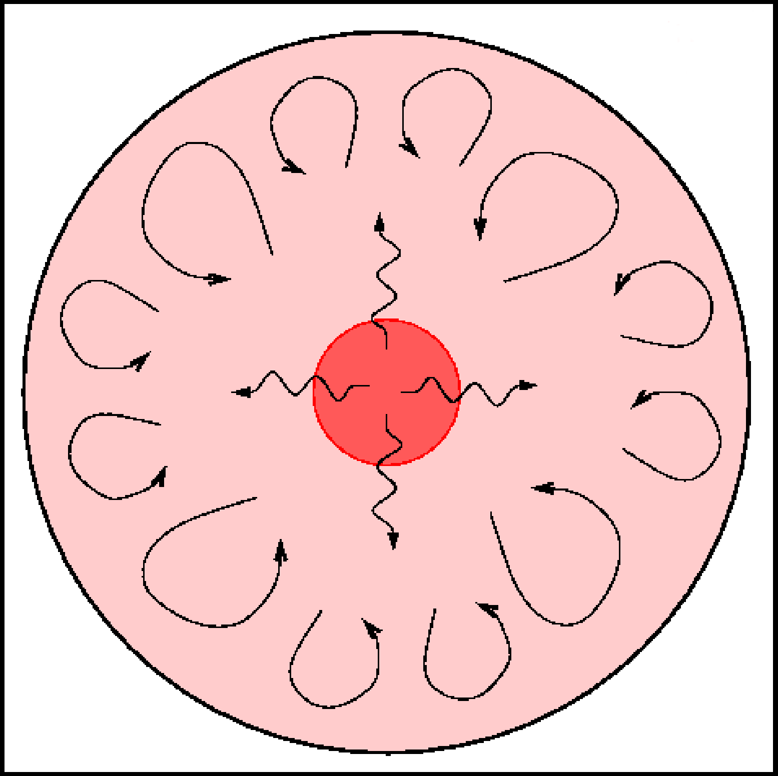
Motivation: Supermassive Stars

Supermassive stars offer sufficient seed mass!

Originally suggested by Hoyle&Fowler 1963

Basic properties:

- Mass $>10^4$ Msol
- Very low metalicity
- Sustained by hydrogen/helium burning
- Radiation pressure dominated (Gamma=4/3)
- Life < 1Myr



The Fate of Supermassive Stars

Cooling and contraction leads to onset of gravitational collapse

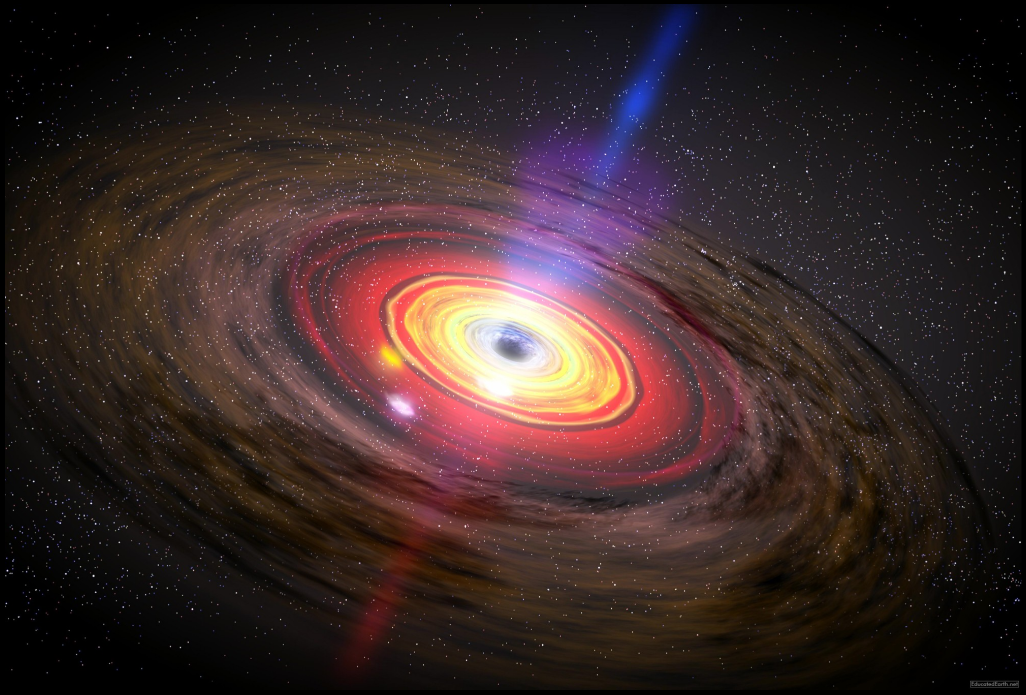
Depending on mass, rotation, metalicity (e.g. Montero et al 2012)

At T>10^9K: e^+e^- pair creation

→ loss of pressure

Thermal bounce due to hot CNO cycle

Collapse to supermassive black hole



Powerful supernova explosion $\sim 10^4$B

Motivation: How to form a Supermassive Star?

Production site: Direct collapse of a primordial gas cloud with $T_{vir} > 10^4$K

We require rapid accretion rates ~0.1-1.0 Msol/yr:

→ No fragmentation allowed!
→ No pulsational instabilities allowed!
  (Inayoshi et al 2013)
→ Radiative feedback must be small!
  (Hosokawa 2012)
→ Angular momentum barrier must be overcome!
  (e.g. Choi et al 2013)

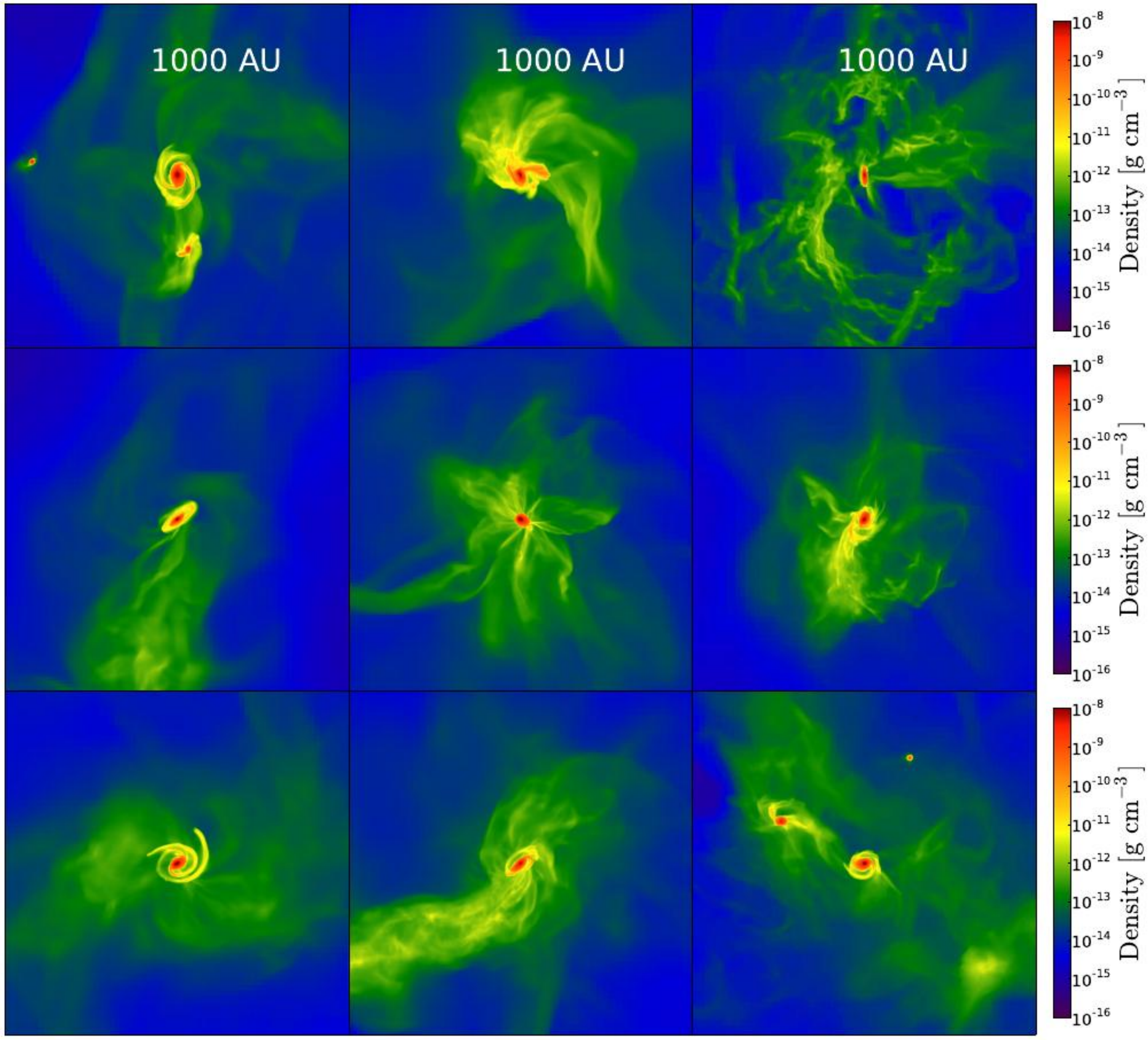
No fragmentation if:

→ no molecular H_2 cooling (H_2 is dissociated in Lyman-Werner UV background)

→ supersonic turbulence

Conditions easier to realize than previously thought!

From Latif et al 2013



Computational Modeling

(Ideal) Computational Modeling

- Magneto-Hydrodynamics → Dynamics of stellar fluid
- General Relativity → Gravity
- Nuclear and Neutrino Physics → Nuclear EOS, nuclear (neutrino) interactions, nuclear burning
- Boltzmann Transport Theory → Neutrino transport

- Modeling on massively parallel computers

Adaptive mesh refinement, task-based parallelism, 3D Monte-Carlo radiation transport, Discontinuous Galerkin Methods...

EXTREMELY CHALLENGING!

Computational Modeling

(~~Magneto-~~)Hydrodynamics	Dynamics of stellar fluid
General Relativity	Gravity
Gamma-law EOS	Approximation to radiation pressure dominated fluid
~~Boltzmann Transport Theory~~	~~Neutrino transport~~

- Modeling on parallel computers (256-512 cores)

Adaptive mesh refinement, multiblocks, high-resolution shock capturing finite volume scheme

Straight forward!

Multiblocks

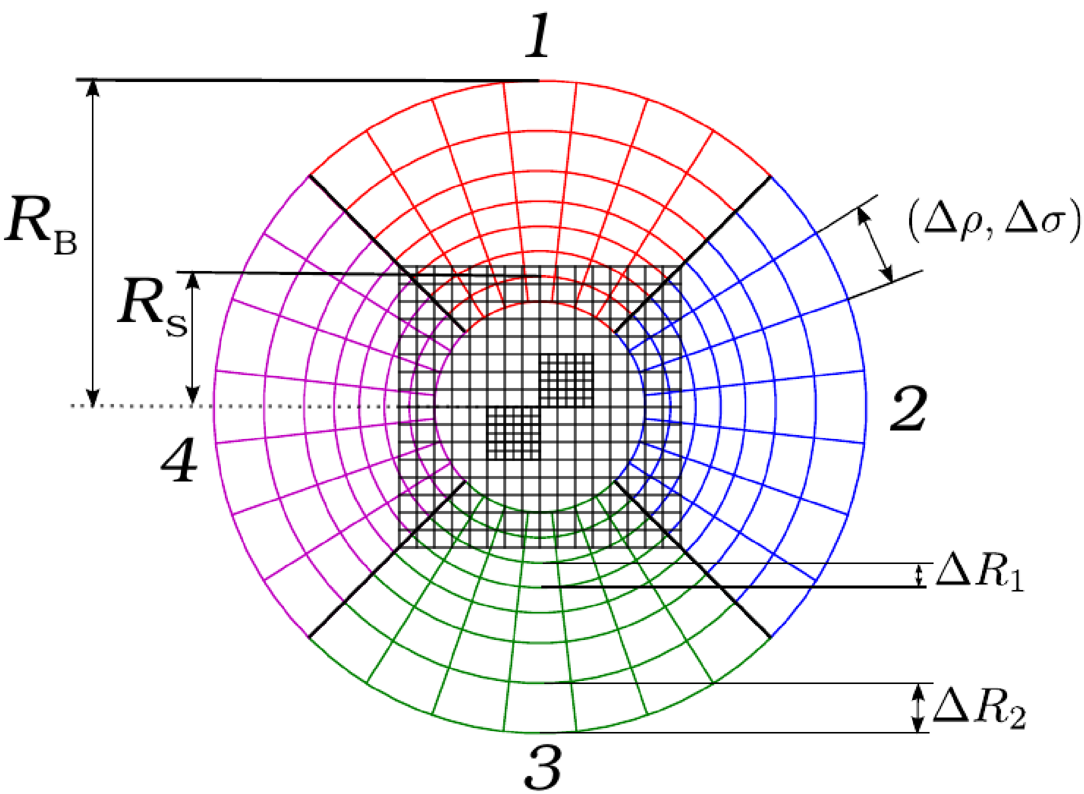
- A set of curvilinear grid patches covers the domain

  → Grids can be adapted to problem symmetry

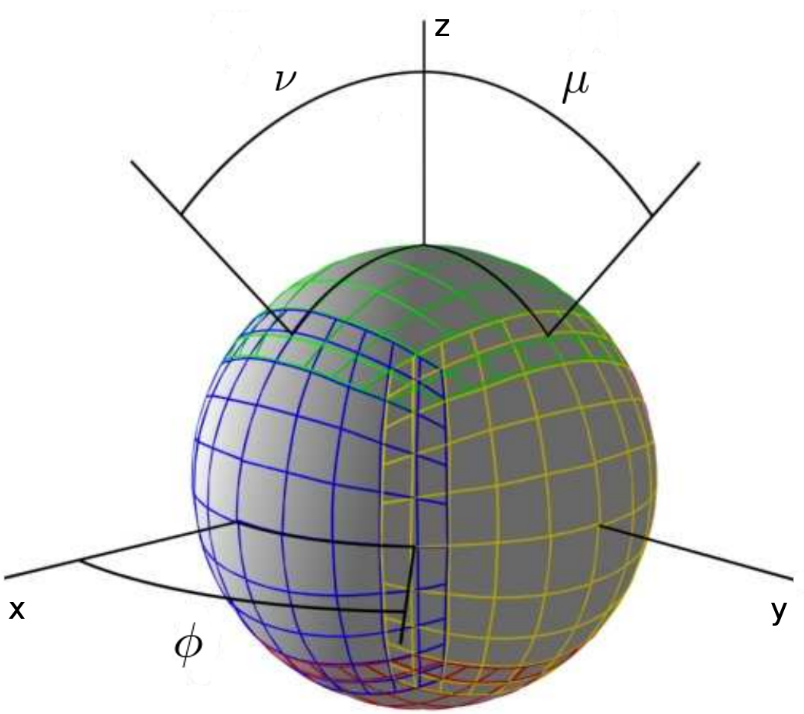
- Useful patch system: Central Cartesian patch with AMR

  Spherical grids for exterior region

Inflated-cube grid

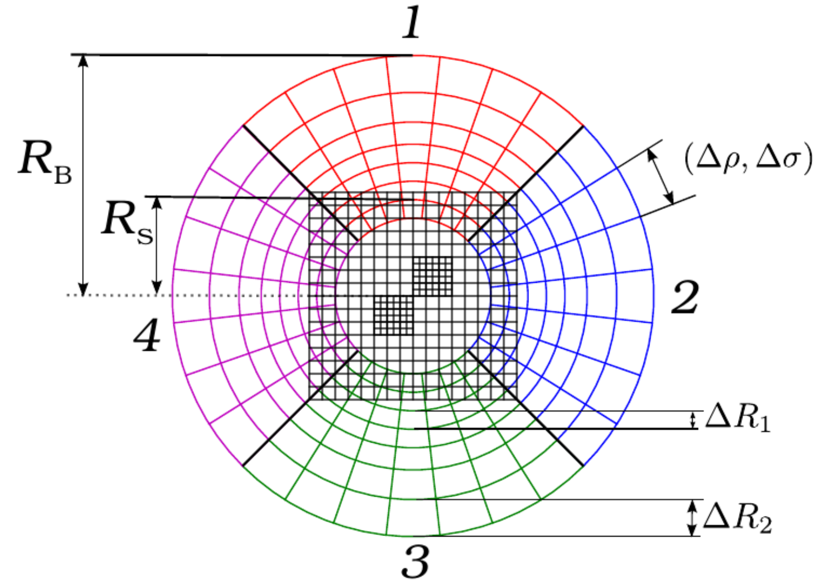


Radial stretching



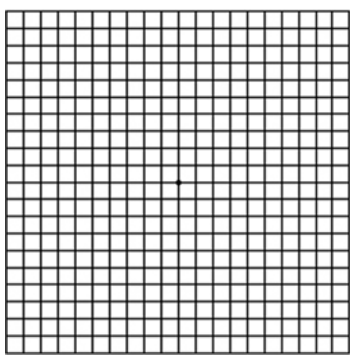
Multiblocks

- Each grid patch is locally Cartesian



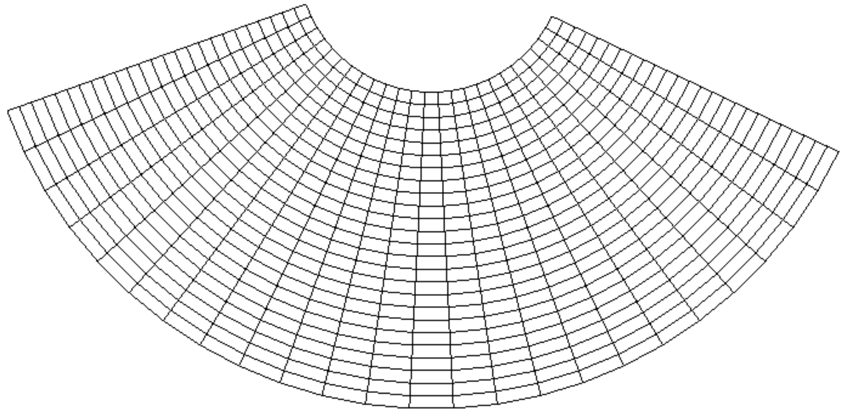
Generic Strategy

- Solve fluid evolution in local coordinates, curvature evolution in global coordinates
- Coupling in global tensor basis



$$\frac{\partial x^\mu}{\partial u^\nu}$$

$$\frac{\partial u^\mu}{\partial x^\nu}$$



$$g_{\mu\nu},\ T_{\mu\nu}$$

$$\tilde{g}_{\mu\nu},\ \tilde{T}_{\mu\nu}$$

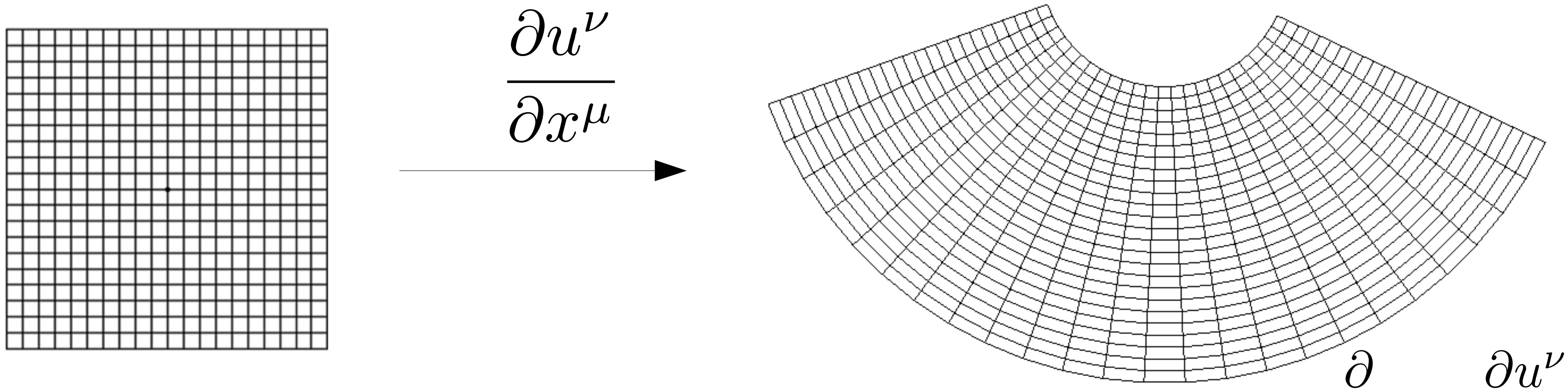
Need Jacobian transformations to transform between local and global frame

Multiblocks: Spacetime Solver

- Finite difference derivatives approximated in local basis:

$$\frac{\partial}{\partial u^\nu}$$

$$\frac{\partial u^\nu}{\partial x^\mu}$$



$$\frac{\partial}{\partial x^\mu} = \frac{\partial u^\nu}{\partial x^\mu}\frac{\partial}{\partial u^\nu}$$

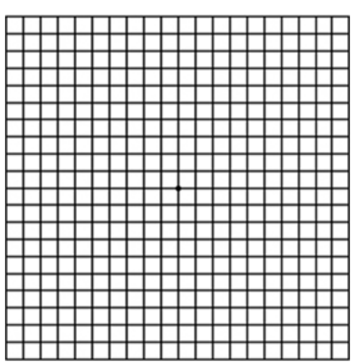
- Evolution equations are evaluated in global basis
- Can keep original Cartesian code; only need to replace derivative operators!

Pollney et al, Phys.Rev.D 83, 2011

Multiblocks: Hydro Solver

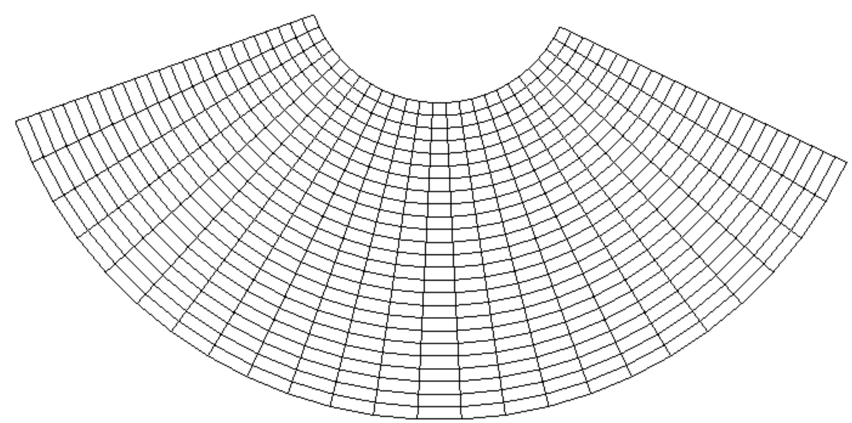
- Hydrodynamic equations are solved via HRSC finite volume method (GRHydro)
- GRHydro is based on uniform grids

→ solve hydro eqns. in local basis (where grids are uniform!)



$$\frac{\partial u^{\nu}}{\partial x^{\mu}}$$

→



Other modeling improvements

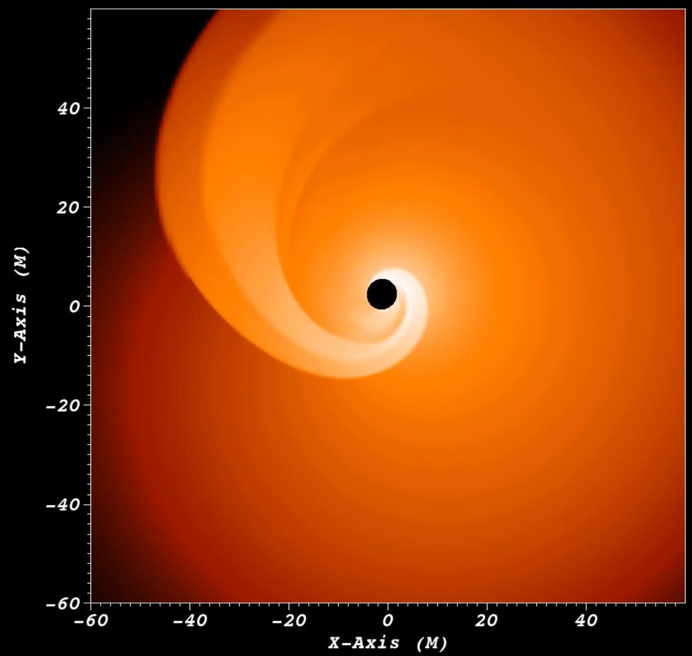
- Cell-centered AMR
- Flux conservation at AMR boundaries
- Multirate Runge-Kutta scheme (RK2-RK4)
- Enhanced piecewise parabolic, WENO5, MP5 reconstruction
- Z4c spacetime evolution system

→ Improved numerical efficiency / accuracy!

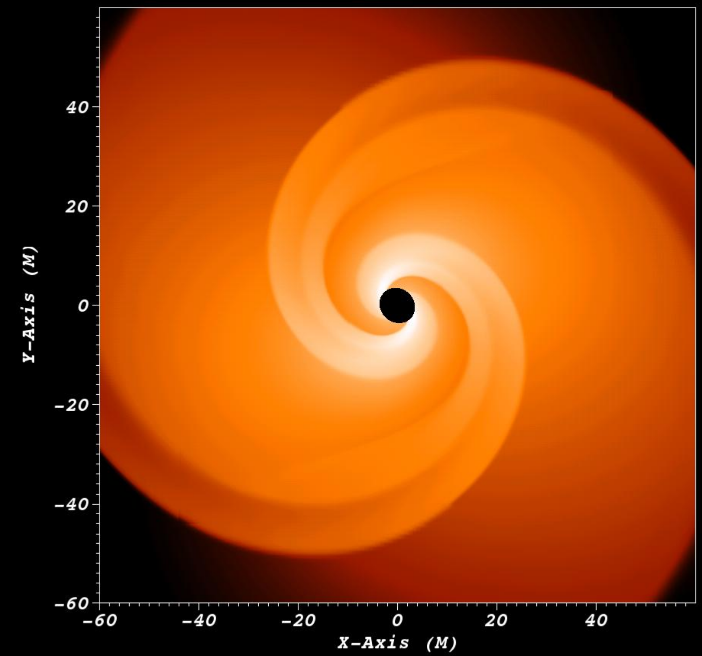
Convergence Tests...

Reisswig et al 2013, PRD

Results Reisswig et al '13

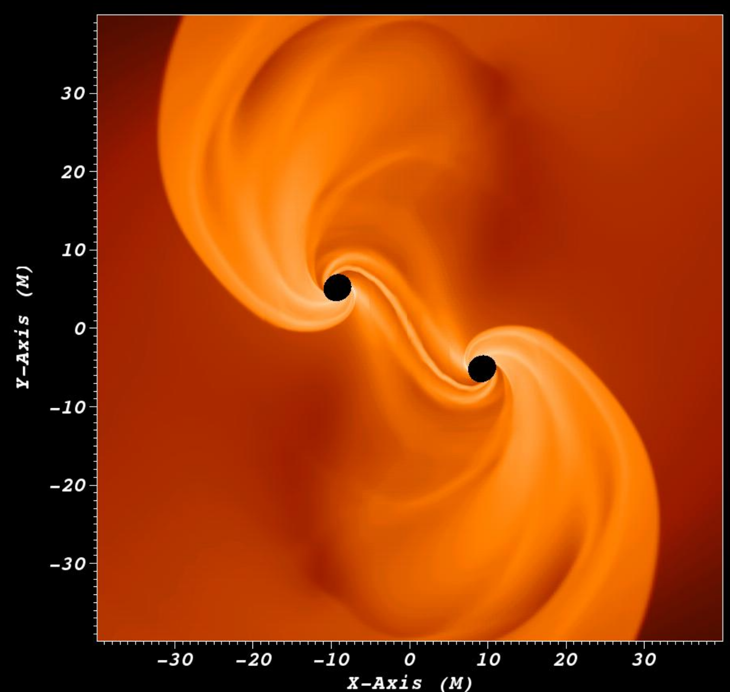


M1G1



M2G1

3 Models



M2G2

Initial Models

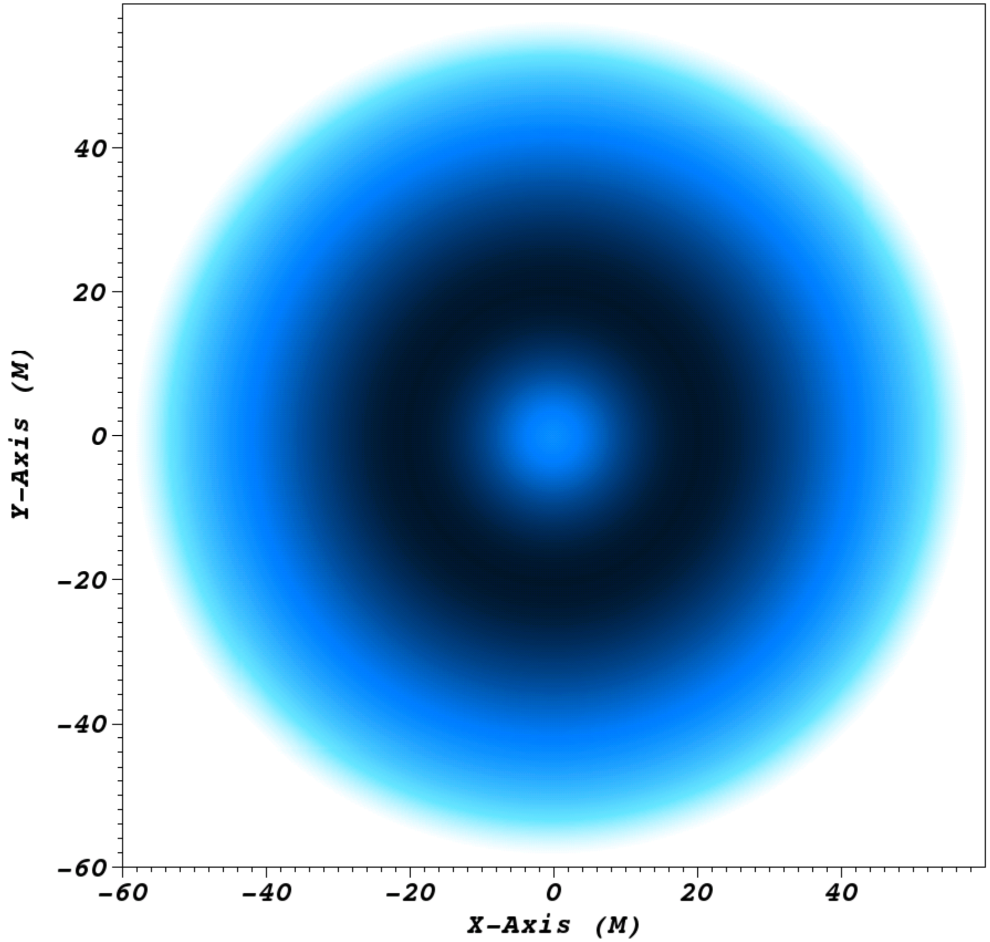
Rapidly differentially rotating marginally stable polytropes

(quasi-toroidal configurations)

Central density: $\rho_c = 3.38 \times 10^{-6}\, M^{-2}$

Axes ratio: $r_p/r_e = 0.24$

Degree of differential rotation: $A = 1/3$



Initial Models

Rapidly differentially rotating marginally stable polytropes

(quasi-toroidal configurations)

In physical units:

$$\text{Example} \quad M = 10^6 M_\odot \text{ supermassive star}$$

$$\text{Central density } \rho_c = 3.38 \times 10^{-6} M^{-2} \simeq 2.1\,\mathrm{g\,cm^{-3}}$$

$$\text{Radius } R_e \simeq 1.2 \times 10^8\,\mathrm{km} \simeq 0.8\,\mathrm{AU}$$

$$\text{Unit time } T = 1M \qquad \rightarrow \qquad \mathrm{t} \simeq 4.93\,\mathrm{sec}$$

Initial Models

Rapidly differentially rotating marginally stable polytropes
(quasi-toroidal configurations)

Unstable to non-axisymmetric perturbations (Zink et al 2006,2007)
→ fragmentation into self-gravitating, collapsing components

$$\text{Density perturbation: } \rho_{\text{ini}} \to \rho_{\text{ini}} \left(1 + A_m r \, \sin(m\phi)\right)$$

$$A_m = 10^{-3}/r_e \approx 1.22 \times 10^{-5}$$

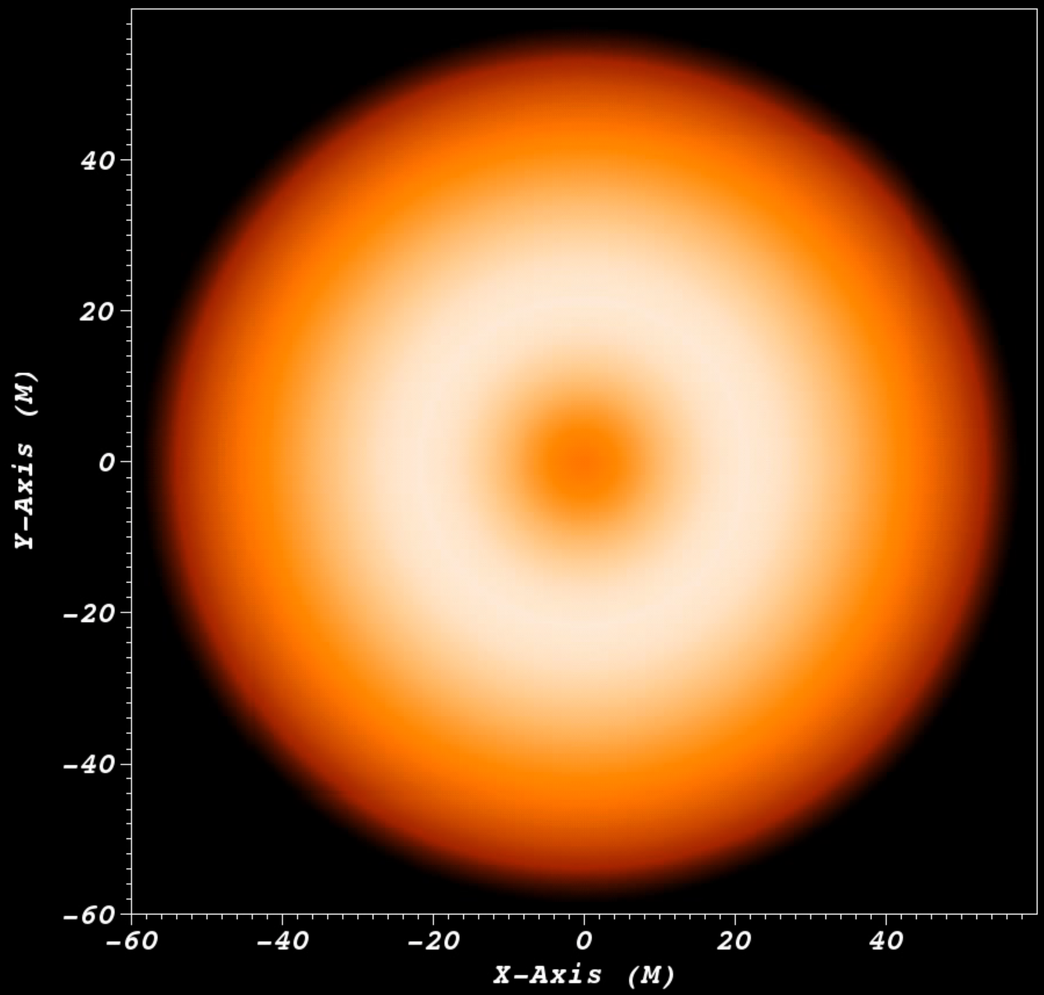
$$\text{M1G1, M2G1: Collapse induced by reducing } K \to 0.999K$$

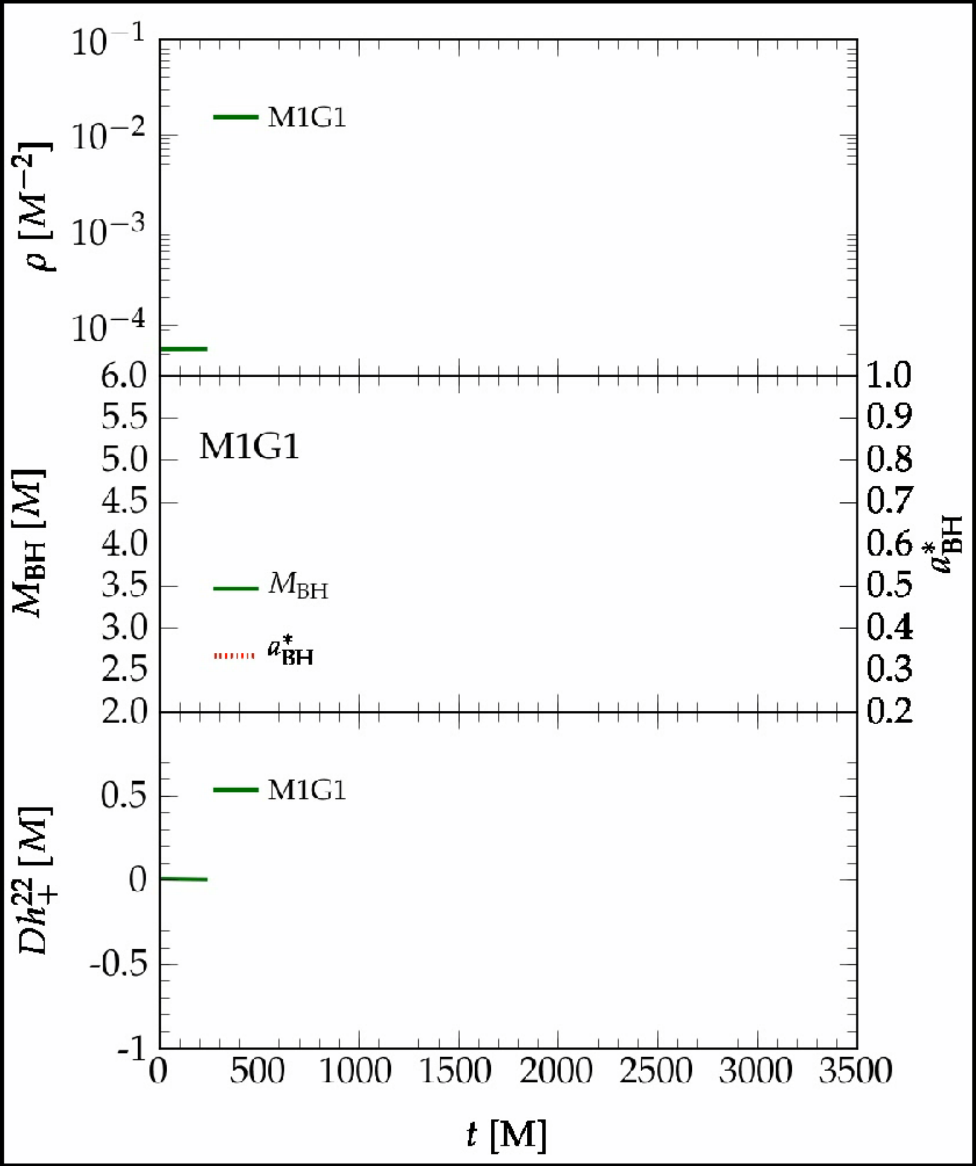
$$\text{M2G2: Collapse induced by reducing } \Gamma = 4/3 \to \Gamma = 1.33$$

Motivated by pressure reduction due to electron-positron pair production at $T>10^9$K

See e.g. Montero et al 2012

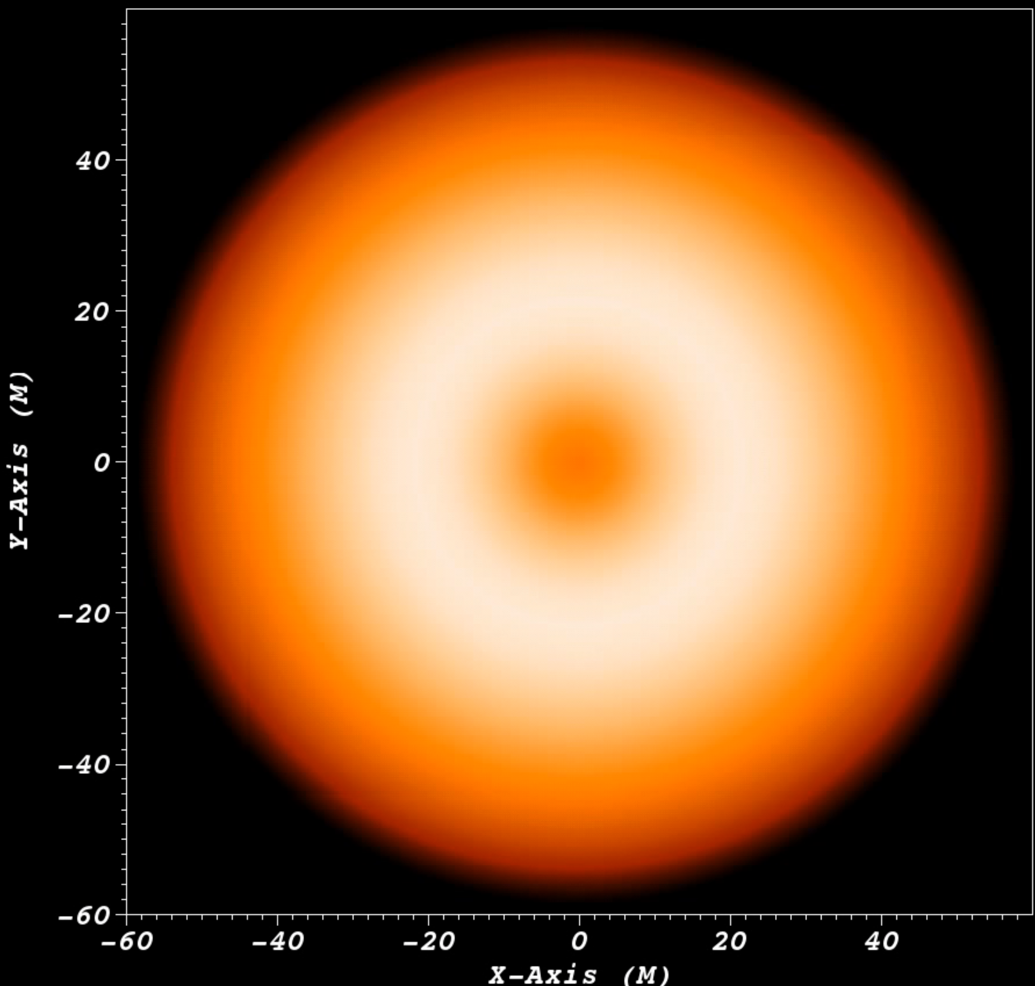
Model: Gamma=4/3, M=1

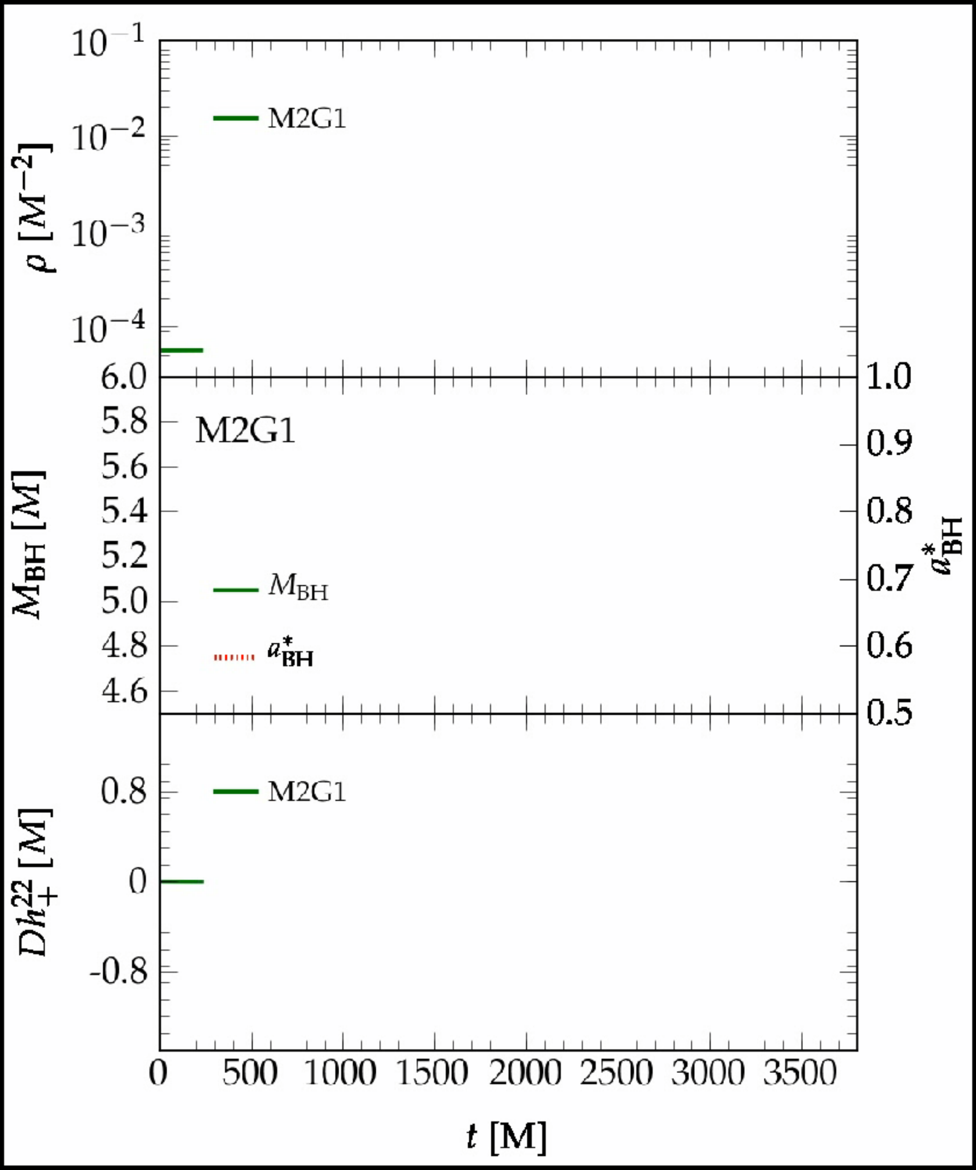




Youtube channel "SXS collaboration"

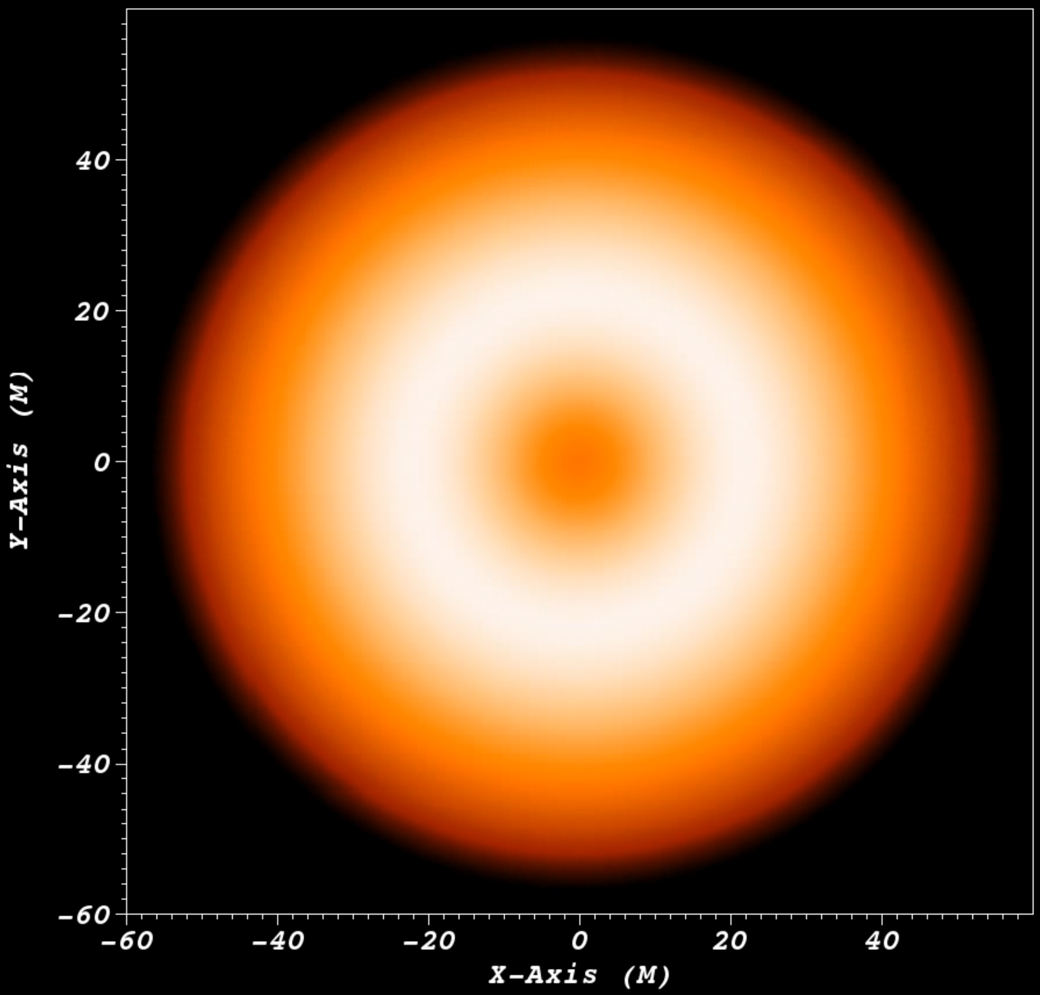
Model: Gamma=4/3, M=2

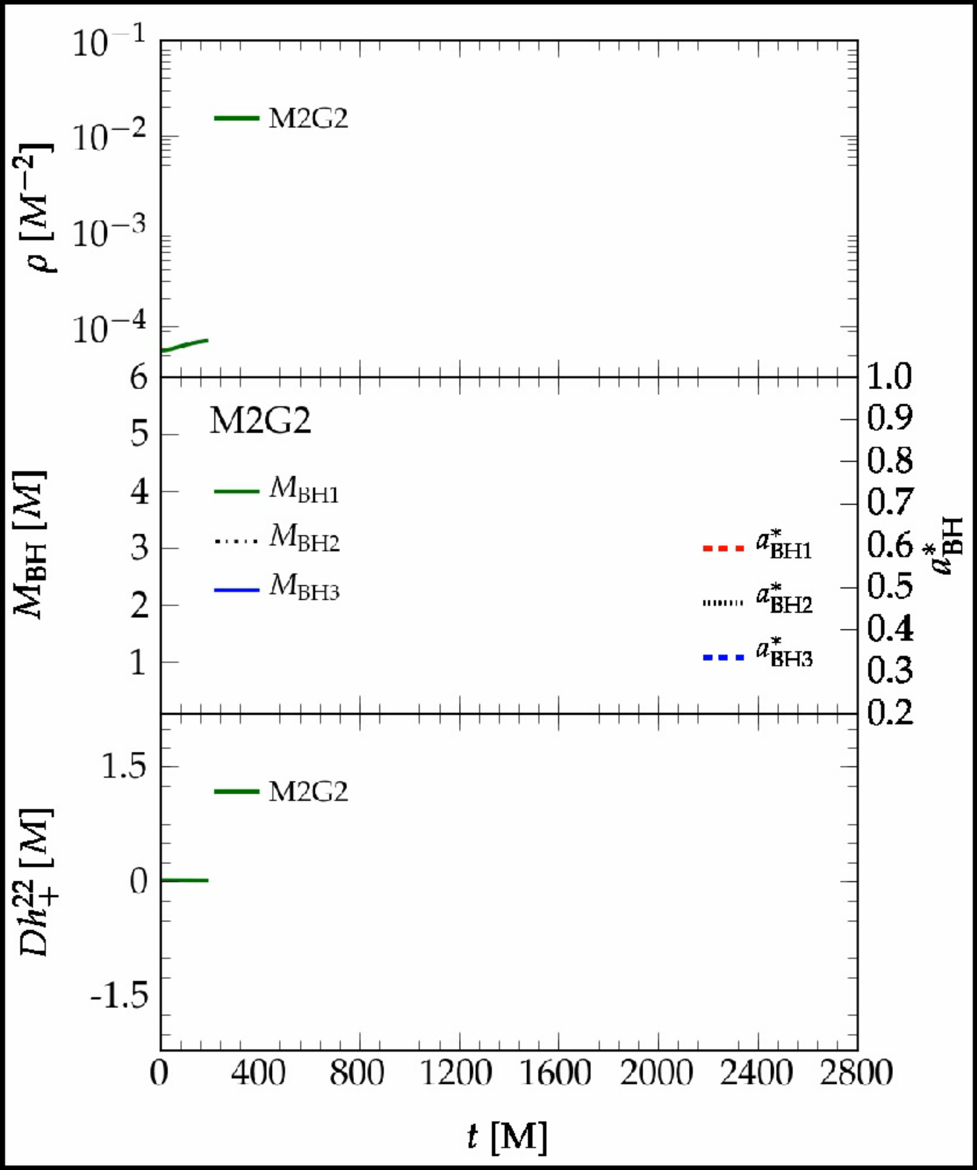




Youtube channel “SXS collaboration”

Model: Gamma=1.33, M=2





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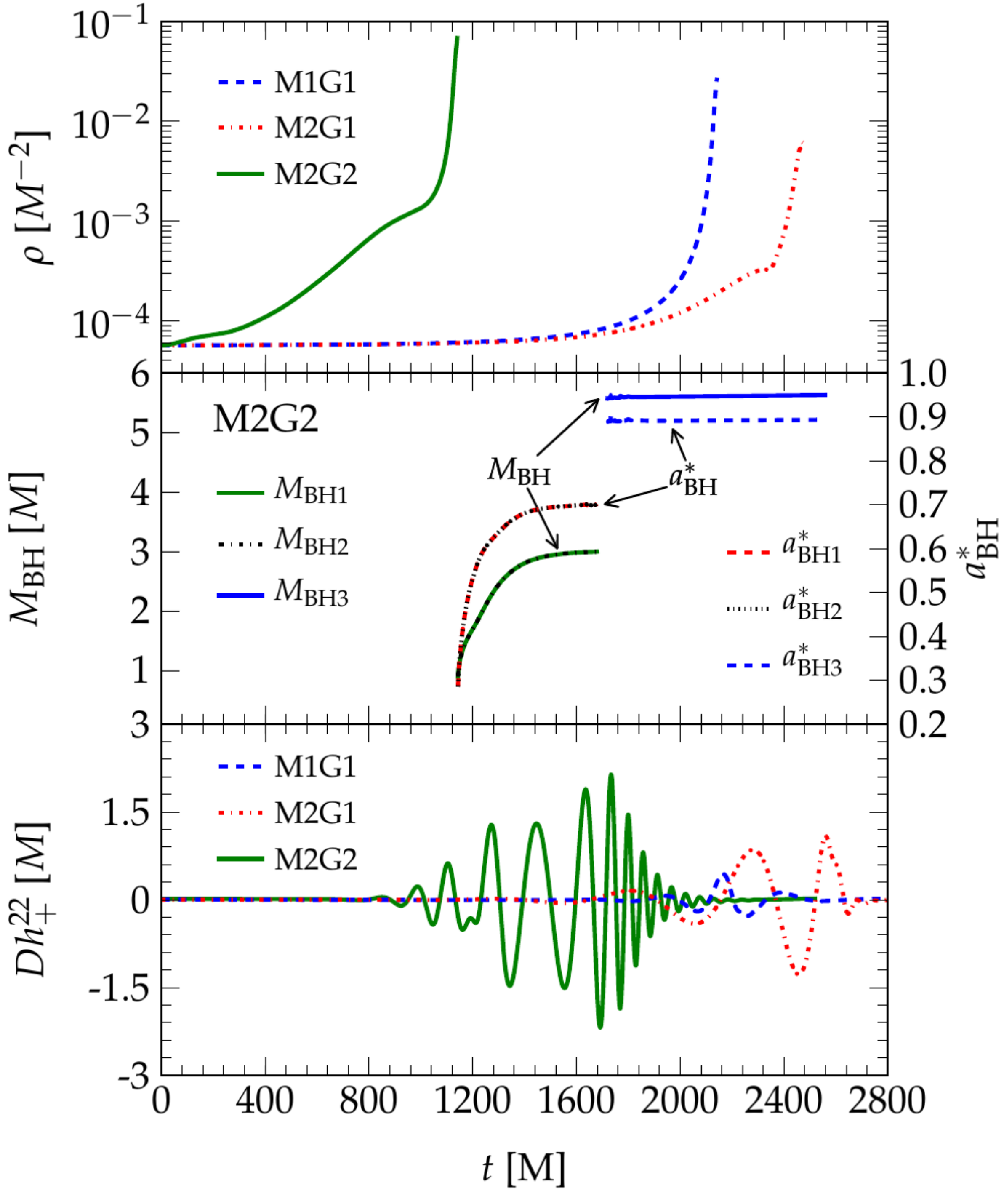
Comparison

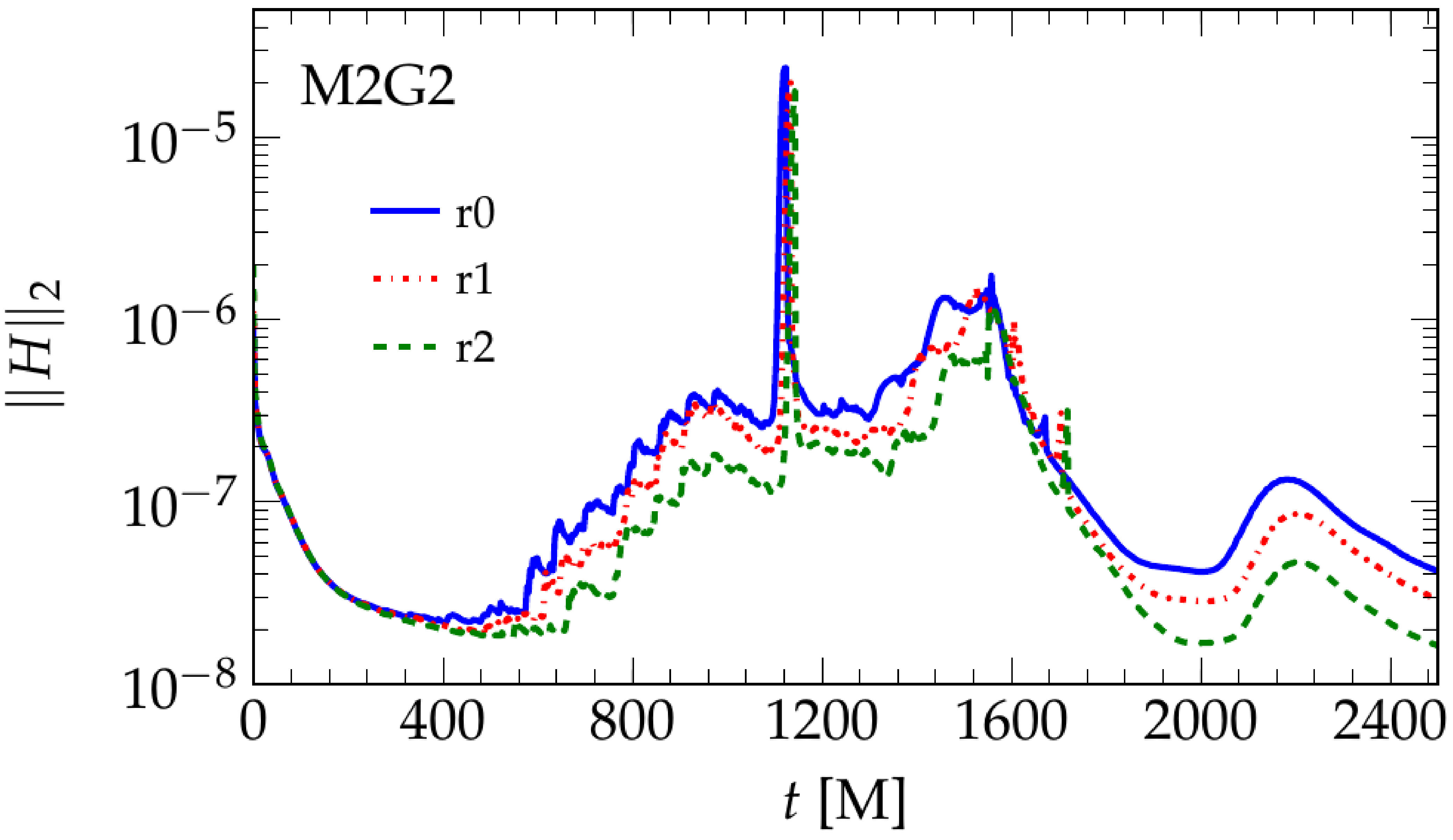


10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\rho\ [M^{-2}]$
M1G1
M2G1
M2G2
M2G2
M_{BH1}
M_{BH2}
M_{BH3}
M_{BH}
a^*_{BH}
a^*_{BH1}
a^*_{BH2}
a^*_{BH3}
$M_{BH}\ [M]$
a^*_{BH}
6 5 4 3 2 1
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2
M1G1
M2G1
M2G2
$Dh^{22}_+\ [M]$
3 1.5 0 -1.5 -3
0 400 800 1200 1600 2000 2400 2800
t [M]

Properties

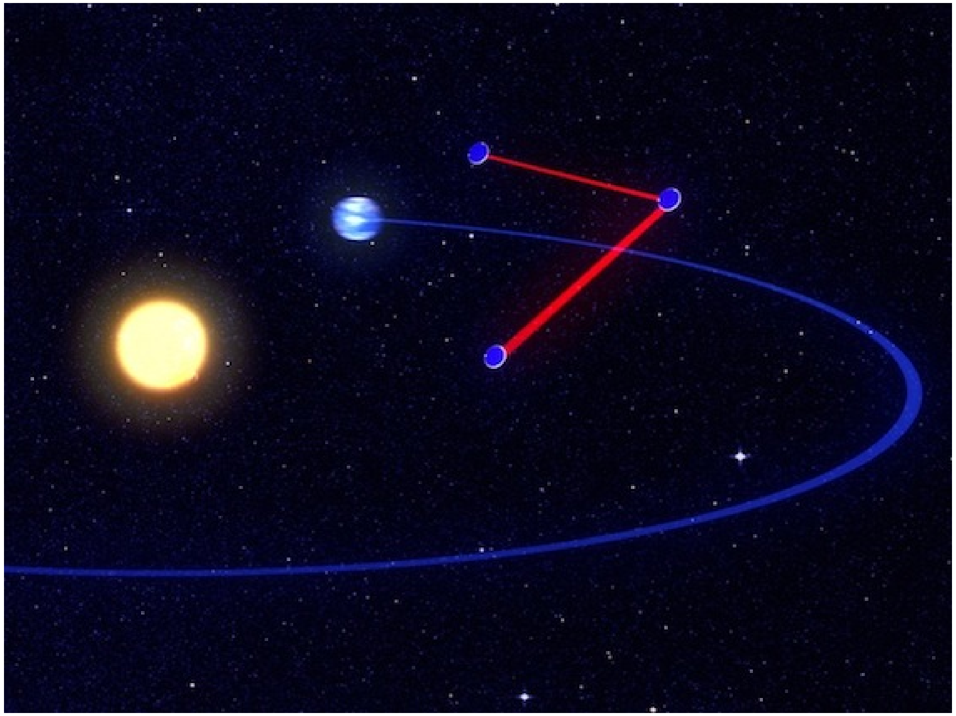
	M1G1	M2G1	M2G2
BH mass $M_{\rm BH}$ $[M]$	5.5	5.8	3.0 ± 0.1
	-	-	3.0 ± 0.1
	-	-	5.8 ± 0.2
BH spin $a^*_{\rm BH}$	0.9	0.9	0.7 ± 0.02
	-	-	0.7 ± 0.02
	-	-	0.9 ± 0.01
bar. disk mass $M_{\rm disk}$ $[M]$	1.3	1	0.7 ± 0.2
accretion rate $\dot{M}$	1.2×10^{-3}	2×10^{-4}	6.7×10^{-5}
rad. GW energy $E_{\rm GW}$ [%]	0.02	0.16	3.71

Convergence

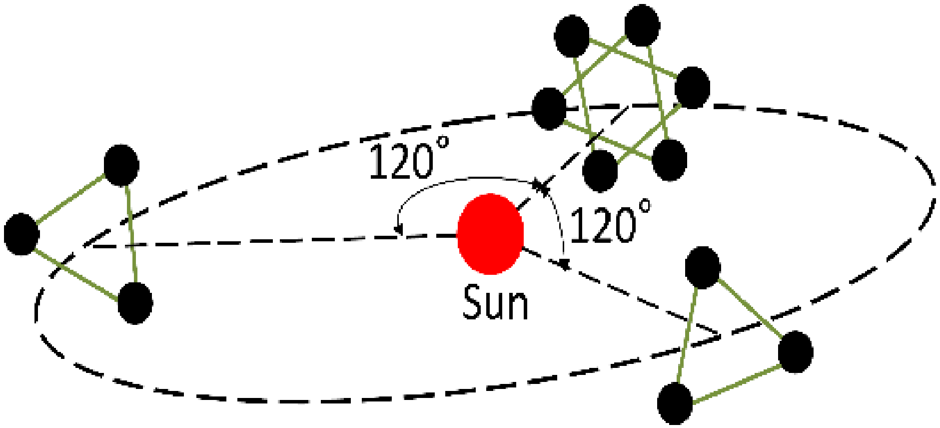


GW detectability
Can we see anything?

Frequency band: dHz – mHz (mass-dependent)



eLISA (mHz)



DECIGO, Big Bang Observer (dHz)

Supermassive stars have possibly existed beyond z>7

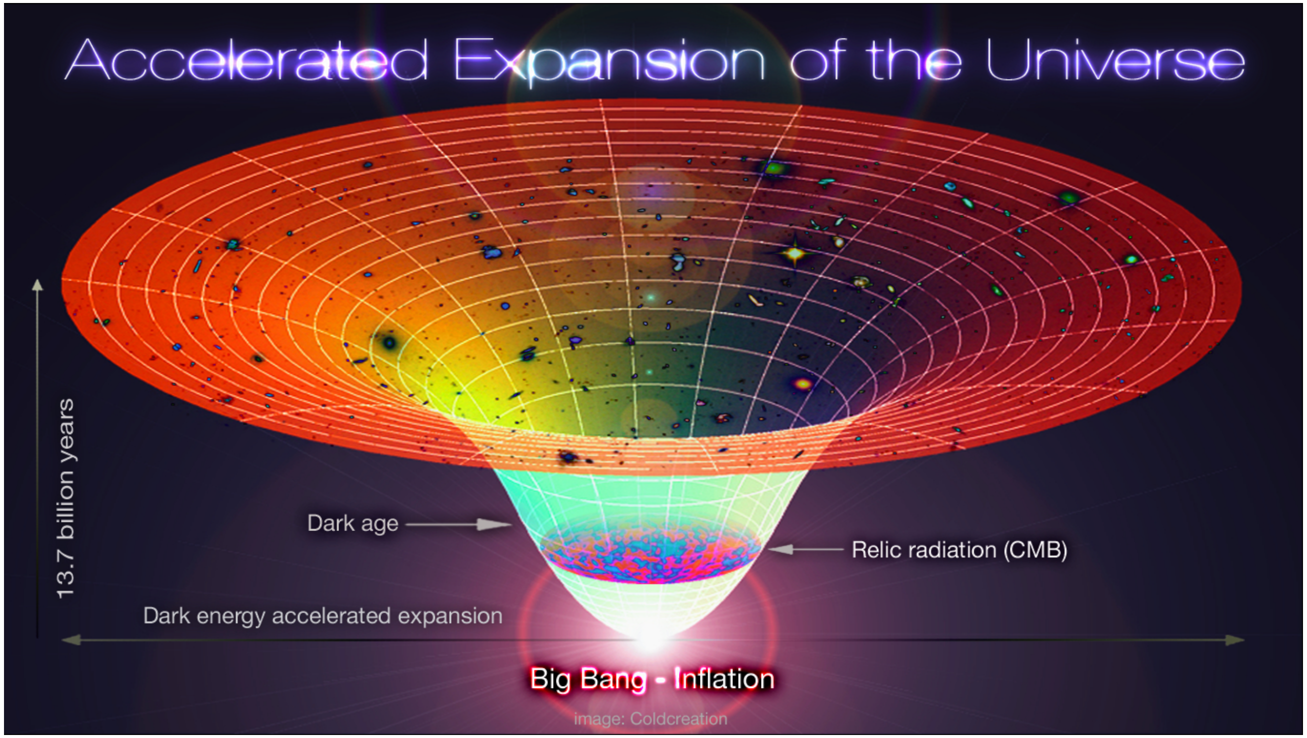
GW detectability

Supermassive stars have possibly existed beyond z>7

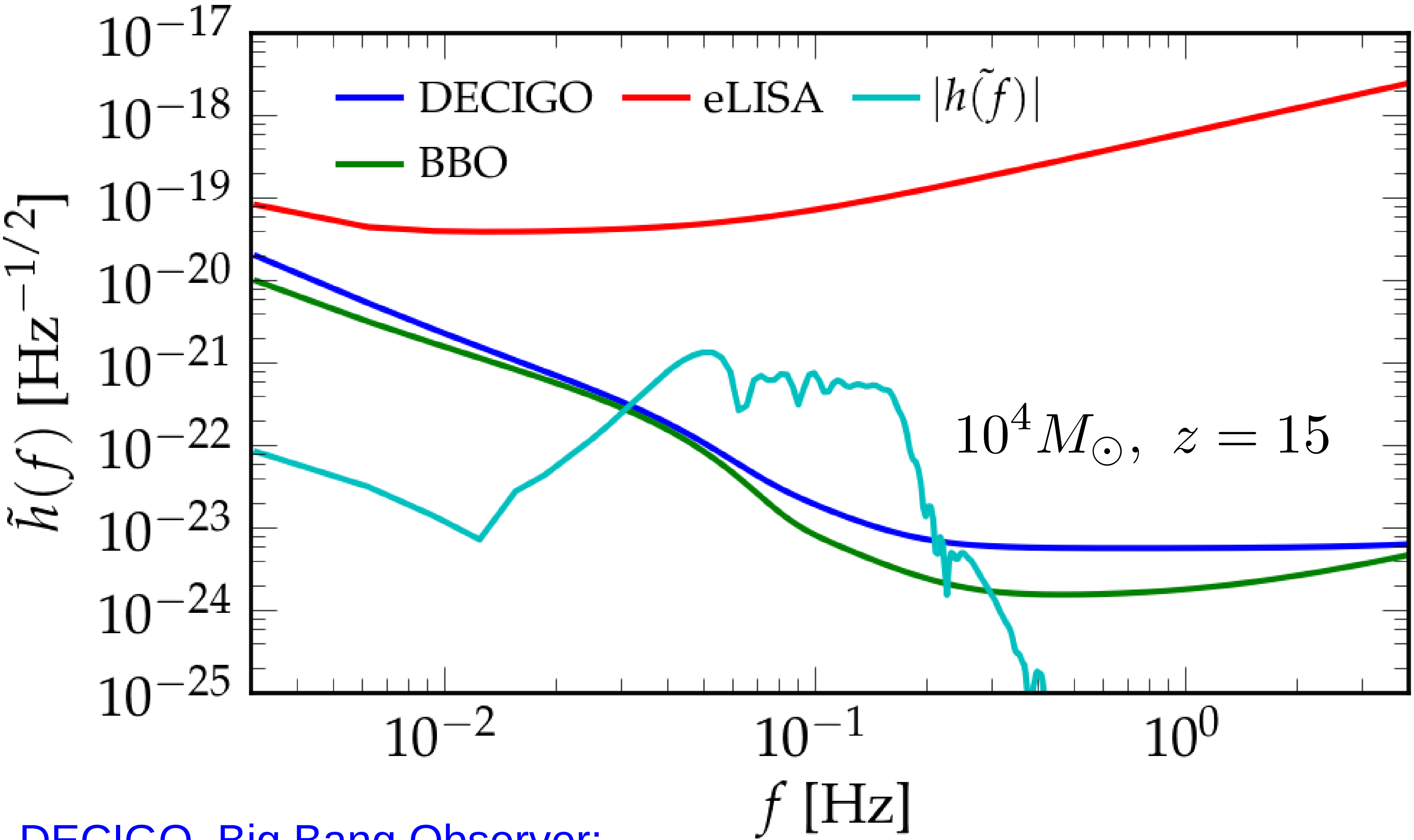
Need to compute luminosity distance $D(z)$

ΛCDM-Cosmology (using latest Planck data):

Matter density $\Omega_m = 0.3175$
Dark energy density $\Omega_\Lambda = 0.6825$
Hubble constant $\mathrm{H}_0 = 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$



GW detectability



DECIGO, Big Bang Observer:

Max detectability: $z = 25\,(10^4 M_\odot),\ z = 16\,(10^6 M_\odot)$

Mean detectability: $z = 23\,(10^4 M_\odot),\ z = 13\,(10^6 M_\odot)$

How likely is it?

We require...

- (i) Rapid differential rotation
- (ii) Pressure reduction
- (iii) M=2 perturbation

- → (i) primordial gas clouds usually carry substantial angular momentum
- → (ii) At $T>10^9$ K, electron-positron pair production sets in
- → (iii) perturbations are likely present, primordial cloud might develop M=2 structure
- → (iii) M=1, M=2 grow at same speed and are fastest modes

Summary

- Supermassive stars give a viable pathway for seeding supermassive black holes at z>7
- Rapid differential rotation, reduced pressure, and m=2 perturbation lead to formation of a supermassive black hole binary system
- GWs can be seen up to z=25 (DECIGO, BBO)
- We have used a new multiblock scheme for more efficient 3D general relativistic hydro simulations
- Codes are publicly available as part of the EinsteinToolkit

Reisswig et al 2013, arXiv:1304.7787
Reisswig et al 2013, PRD
Moesta et al 2013, arXiv:1304.5544