Novel Challenges of Radiation Physics
- General Relativistic & Quantum-Mechanical -

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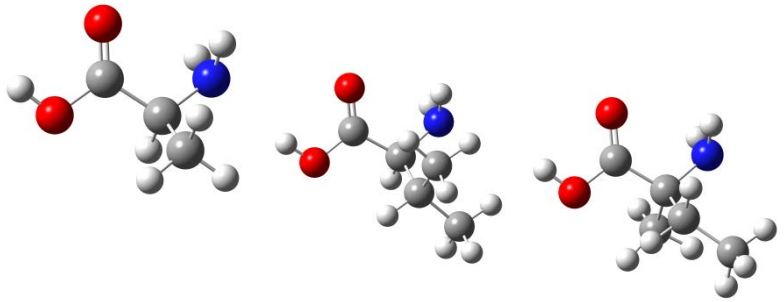


Radiation Hydrodynamics

Radiative Transfer

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\cdot\nabla I_\nu(\mathbf{n}) = -\kappa_\nu I_\nu(\mathbf{n}) + \eta_\nu \,/\, 4\pi - \sigma_\nu I_\nu(\mathbf{n}) + \sigma_\nu \int \phi(\mathbf{n};\mathbf{n}') I_\nu(\mathbf{n}') d\Omega'$$

Lorenz-transformed Boltzmann Equation for Photon Distribution Function

Freedom: 3D in space, 2D in directions, 1D in frequency = 6D problem

Radiation Hydrodynamic Equation of Motion

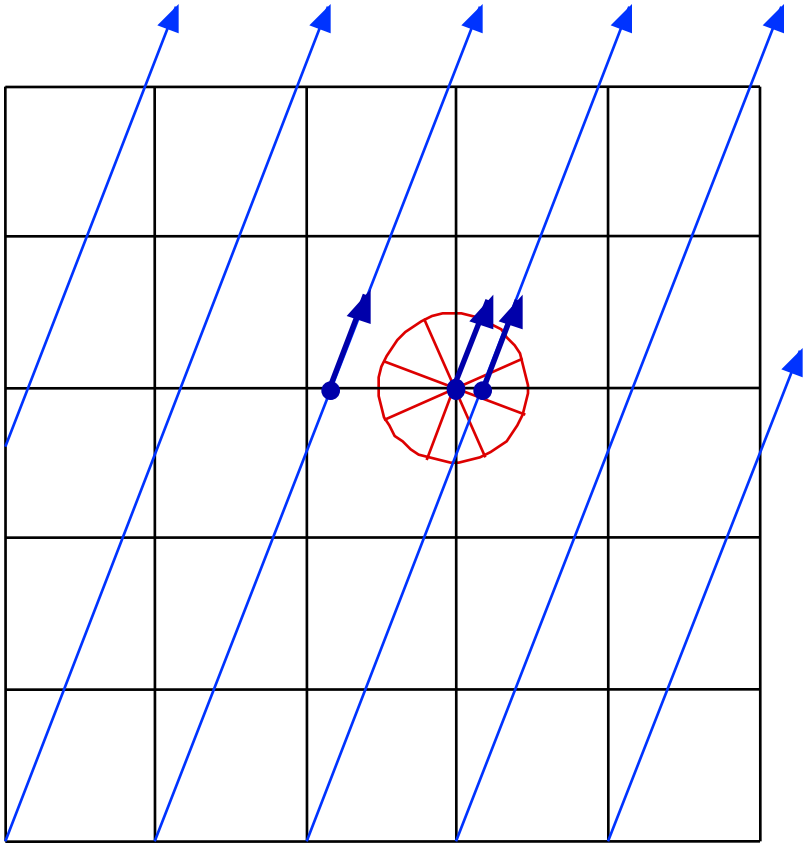
$$\gamma\rho_m \frac{d\mathbf{v}}{dt} = \boldsymbol{f} - \nabla p + \frac{\mathbf{v}}{c^2}\left(\frac{\partial p}{\partial t} + \boldsymbol{f}\cdot\mathbf{v}\right) + \frac{\gamma}{c}\left(\kappa_0 + \sigma_0\right)\left[\mathbf{F} - (E + \mathbf{P})\mathbf{v} + \frac{\mathbf{v}}{c^2}(\mathbf{v}\cdot\mathbf{F})\right]$$

Energy Equation

$$\frac{p}{\Gamma - 1}\frac{d}{dt}\ln\left(\frac{T}{(\rho/\gamma)^{\Gamma-1}}\right) = -\frac{\eta_0}{\gamma} + \gamma c\kappa_0 E - \frac{2\gamma\kappa_0}{c}\mathbf{v}\cdot\mathbf{F} + \frac{\gamma\kappa_0}{c}\mathbf{v}\cdot\mathbf{v}\mathbf{P}$$

ART
(Authentic Radiative Transfer)

Transfer is solved along a long ray across the domain



- Physical quantities are interpolated at each grid
- A bit complex coding
- No numerical diffusion (accuracy equivalent to long char.)
- Operations (same as short char.)

$$\sim N_x N_y N_z \cdot N_\theta N_\varphi N_\nu$$

START

SPH with Tree-based Accelerated Radiative Transfer

Full 6-Dimensional Radiation Hydrodynamics

- no on-the-spot (Case B) approximation
- diffuse radiation is solved completely

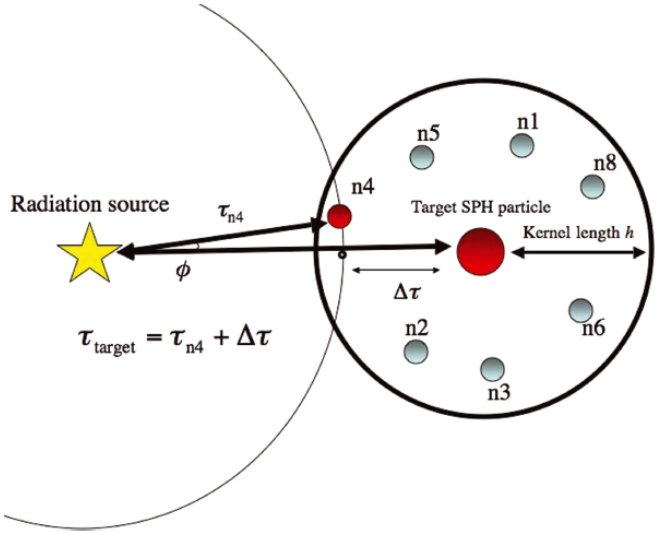


Figure 1. The method for the ray-tracing adopted in RSPH scheme is schematically shown. The large filled circle indicates the target particle to which the optical depth from the radiation source is evaluated. Smaller filled circles around the target particle indicate particles in the neighbour list of the target particle.

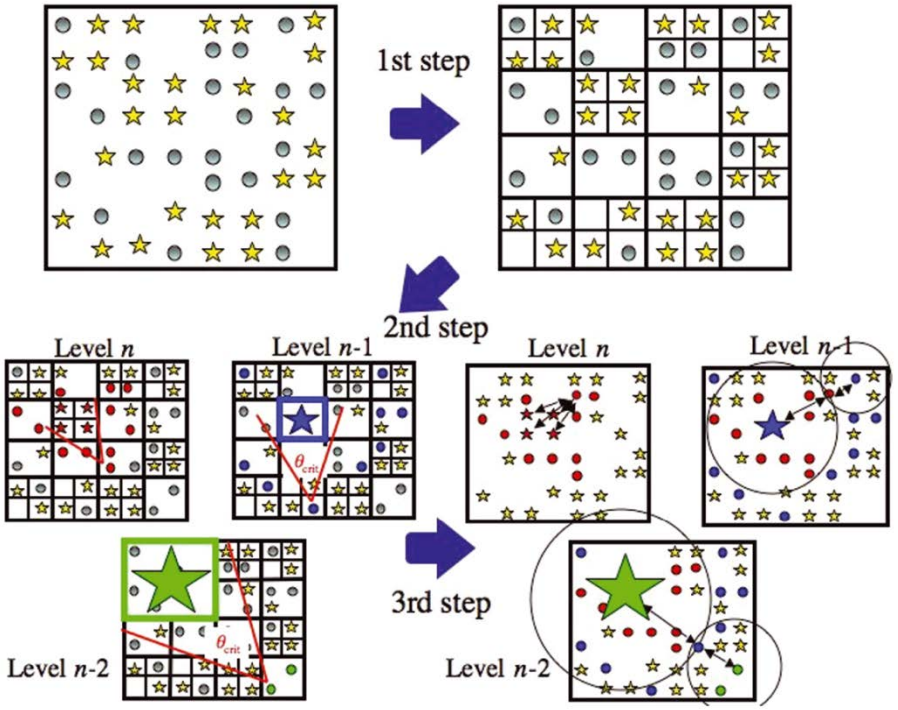


Figure 2. The new ray-tracing method based on oct-tree structure is schematically shown. Each star and circle, respectively, indicates a radiation source and an SPH particle. In the first step, the tree structure for the distributions of radiation sources is constructed. In the second step, a list of SPH particles satisfying the same level of conditions (12) and (13) is produced for each virtual radiation source. In the lower right panel, particles in a list of a virtual radiation source are indicated by circles filled with the same colour as the owner source of the list. In the third step, optical depths from virtual sources to particles in the lists are evaluated in the same manner as Fig. 1.

FIRST Project

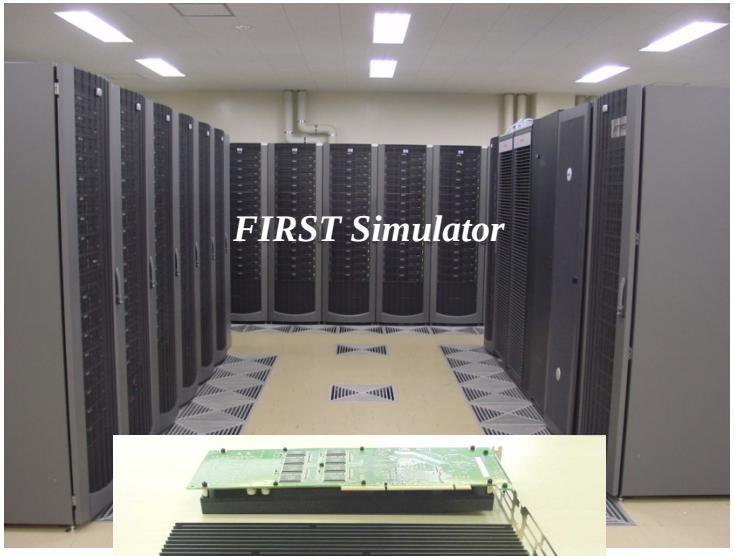
The Origin of FIRST Generation Objects

Fusional Integrator for Radiation-hydrodynamic Systems in Tsukuba University for elucidating the origin of FIRST generation objects

Grants-in-Aid for Specially Promoted Research by MEXT in Japan (2004-2007)
Total budget is 428 million yen (US$4.2 million)
Grant-in-Aid for Scientific Research (S) by JSPS (2008-2012)
Total budget is 100 million yen (US$1 million)

Division of Computational Astrophysics — **Division of High Performance Computing Systems**

"FIRST" Simulator



256（16×16）nodes
496 CPU ＋ 240 Blade-GRAPE

Total Performance = 36.1 Tflops
- **Host 3.1 Tflops**
- **Blade-GRAPE 33 Tflops**

Total Memory = 1.6TB

Total storage = 89.2TB (Gfarm)

Cosmic Time

10^{-44}sec

Big Bang

Radiation

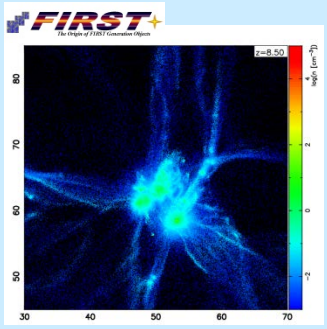
Matter (dark matter+baryons)

0.4Myr

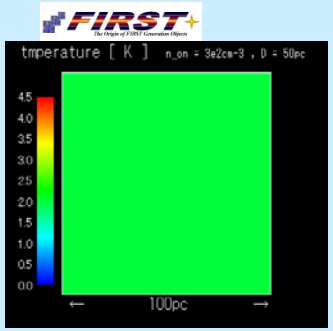
Cosmic Recombination

Dark Age

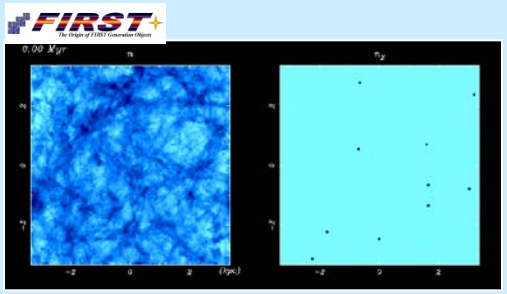
First generation stars
(Pop III)



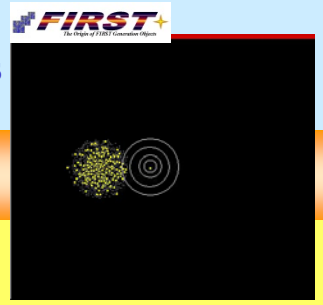
2nd generation stars



First chemical enrichment



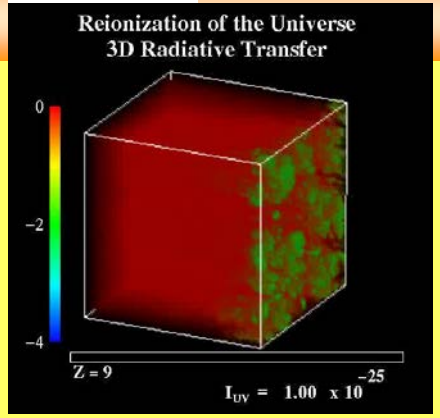
Globular clusters
(Pop II)



Gyr

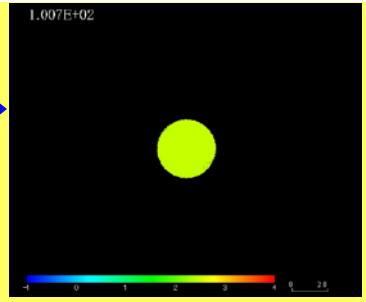
Cosmic Reionization

CP-PACS



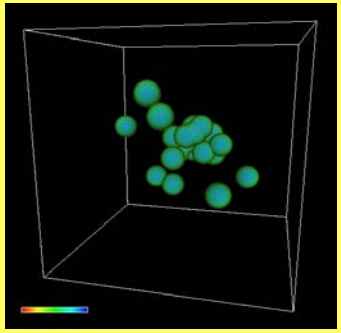
Dwarf galaxy formation

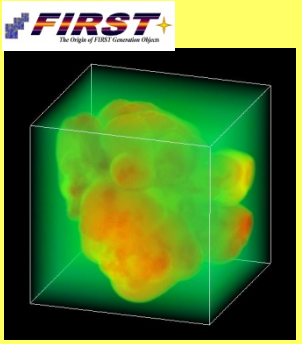
HMCS (CP-PACS+GRAPE)



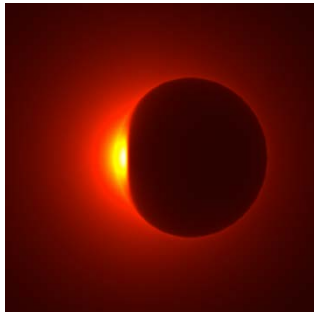
Primordial galaxies
(Pop I)

Earth-simulator





13.7Gyr
(present)



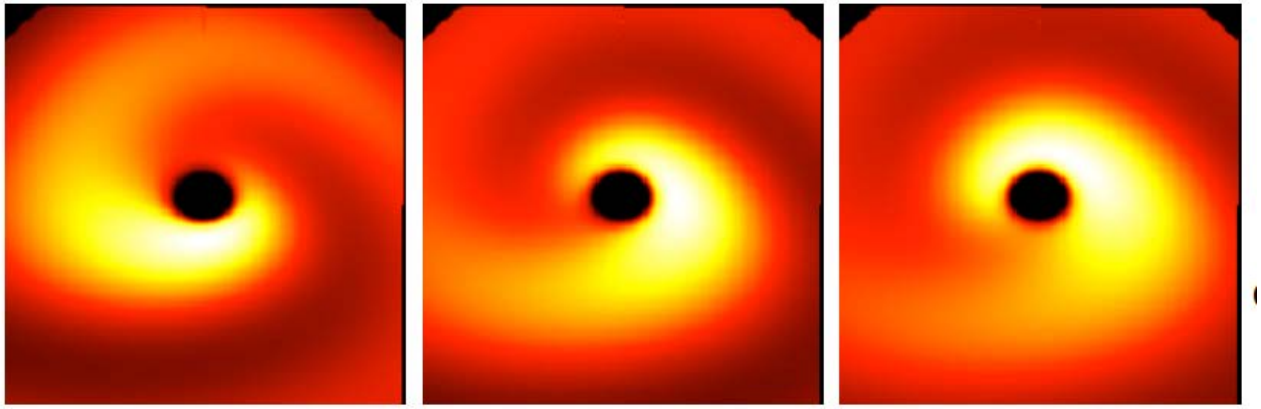
Vermeer

Master of light

Variable Eddington-tensor Radation-hydrodynamics with Metric Enchained Ray-tracing

Collaboration with **Rota Takahashi** in Tomakomai National Collage of Technology

General Relativistic Radiation Transfer
Radiation Hydrodynamics in Curved Space



General Relativistic Simulations

GR MHD simulation [no radiation]
Koide + 1999, Hawley + 2000, Gammie + 2003,
Komissarov 2005, Duez+2005, Shibata & Sekiguchi 2005,
Nagataki 2009 etc.

GR radiation MHD simulation [no radiative transfer]
Farris+ 2008 (FLD), Zanotti+2011(FLD),
Shibata+ 2012 (M1 closure), Fragile+2012(FLD),
Sadowski+ 2012 (M1 closure) etc.

Tetrad formalism

Mix-frame approach

Local Minkovski spacetime

Global curved spacetime

$$(T^{\mu\nu} + R^{\mu\nu})_{,\nu} = F^{\mu} \quad \Longleftrightarrow \quad (T^{\alpha\beta} + R^{\alpha\beta})_{;\beta} = F^{\alpha}$$

Conservation Law of RHD

$$R^{\alpha\beta} = \varepsilon^{\alpha}_{\mu}\varepsilon^{\beta}_{\nu}R^{\mu\nu}$$

$$T^{\mu\nu} = (\rho_0 + \rho_0\varepsilon/c^2 + P/c^2)u^{\mu}u^{\nu} - P\eta^{\mu\nu}$$

$$R^{\mu\nu} = \begin{pmatrix} E & \mathbf{F}/c \\ \mathbf{F}/c & \mathbf{P} \end{pmatrix}$$

$E = \frac{1}{c}\int_0^{\infty} d\nu \int I_{\nu} d\Omega$: radiation energy density

$\mathbf{F} = \int_0^{\infty} d\nu \int I_{\nu}\mathbf{n} d\Omega$: radiation flux

$\mathbf{P} = \frac{1}{c}\int_0^{\infty} d\nu \int I_{\nu}\mathbf{n}\mathbf{n} d\Omega$: radiation stress tensor

GR Radiation Transfer

General Relativistic Boltzmann Equation of Photons

$$\frac{d\mathcal{I}_\nu}{d\lambda} = \mathcal{E}_\nu - A_\nu \mathcal{I}_\nu$$

$\mathcal{I}_\nu \equiv \frac{I_\nu}{\nu^3}$: Invariant specific intensity

$\mathcal{E}_\nu \equiv \frac{\eta_\nu}{\nu^3}$: Invariant emissivity

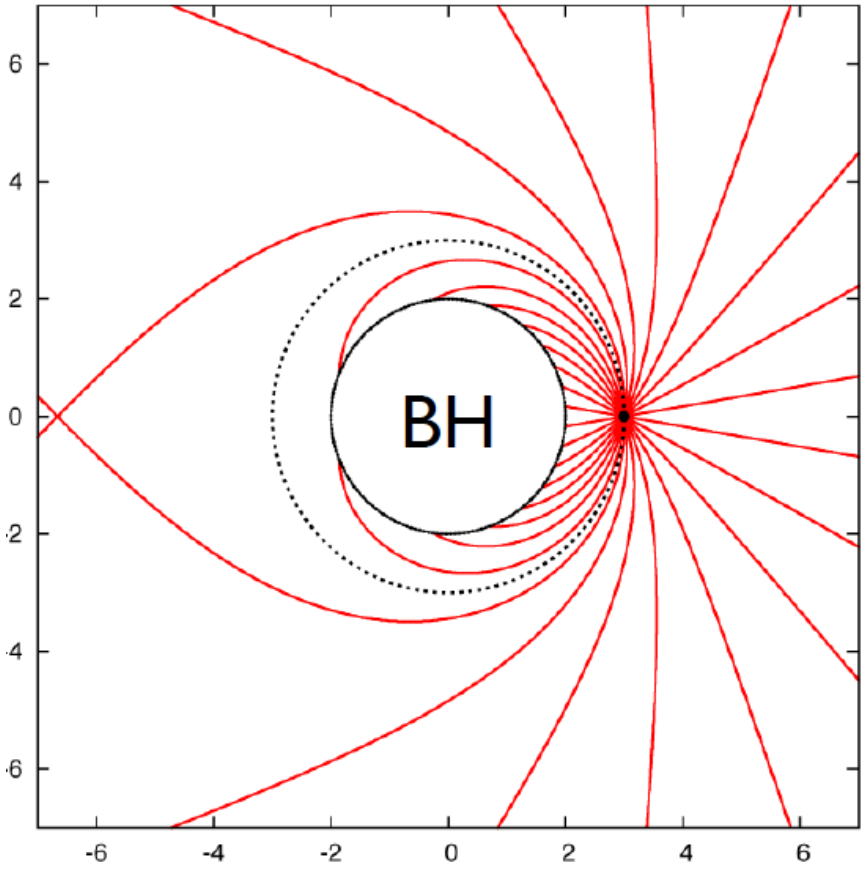
$A_\nu \equiv \nu\chi_\nu$: Invariant extinction

- **Solve GR radiative transfer along geodesics**
- **Obtain invariant specific intensity in 6D phase space**

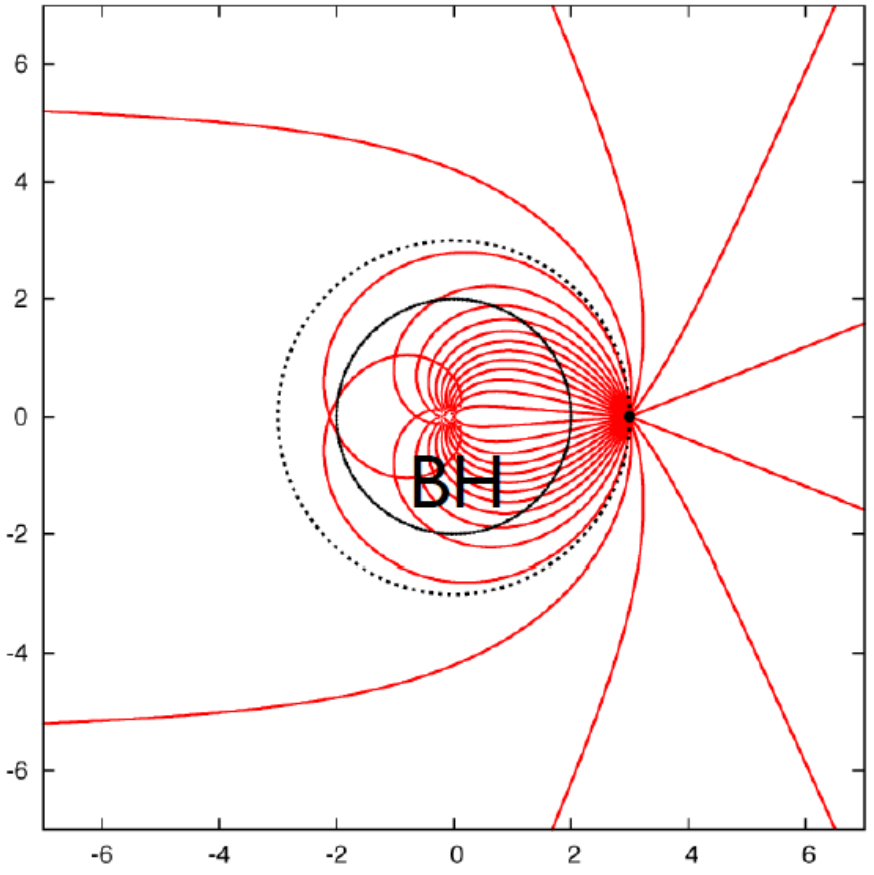
Ray Tracing in Curved Space

Horizon capture

Boyer-Lindquist coordinate

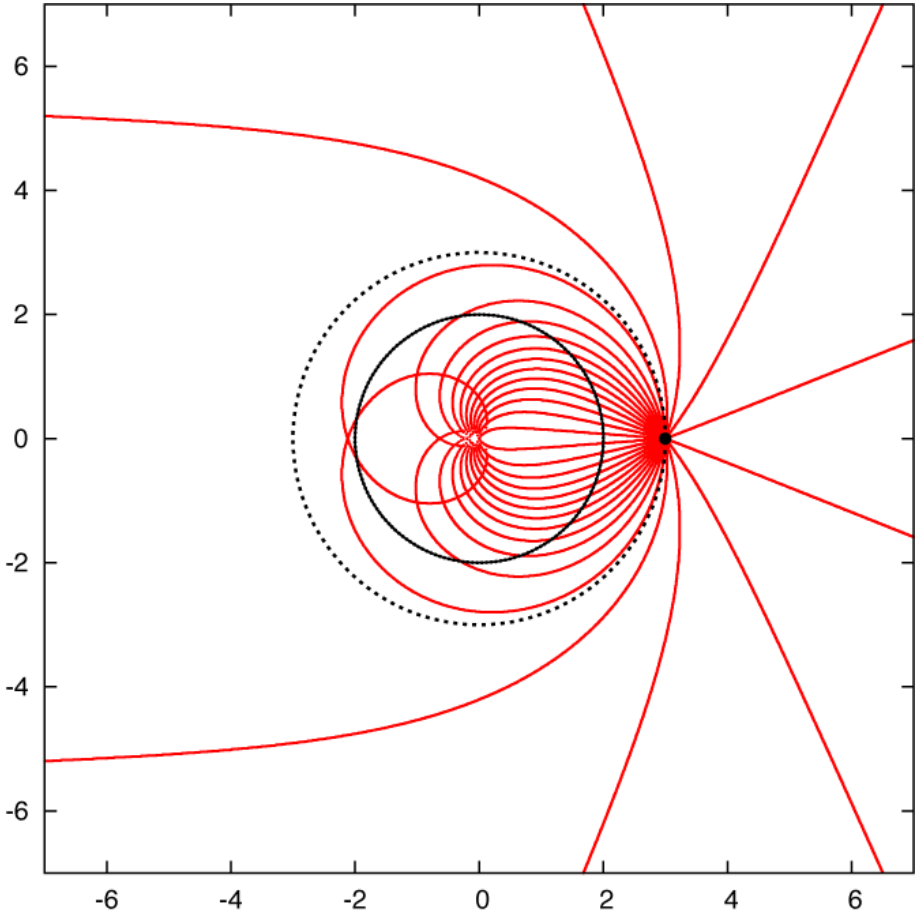


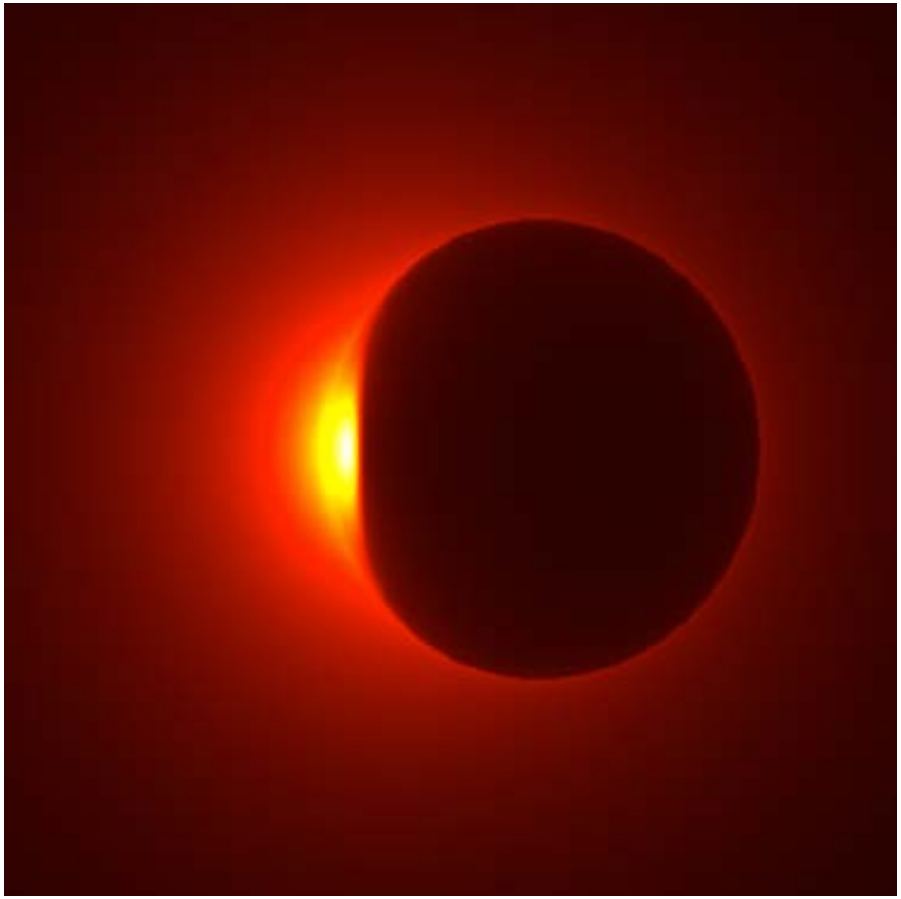
Kerr-Schild coordinate



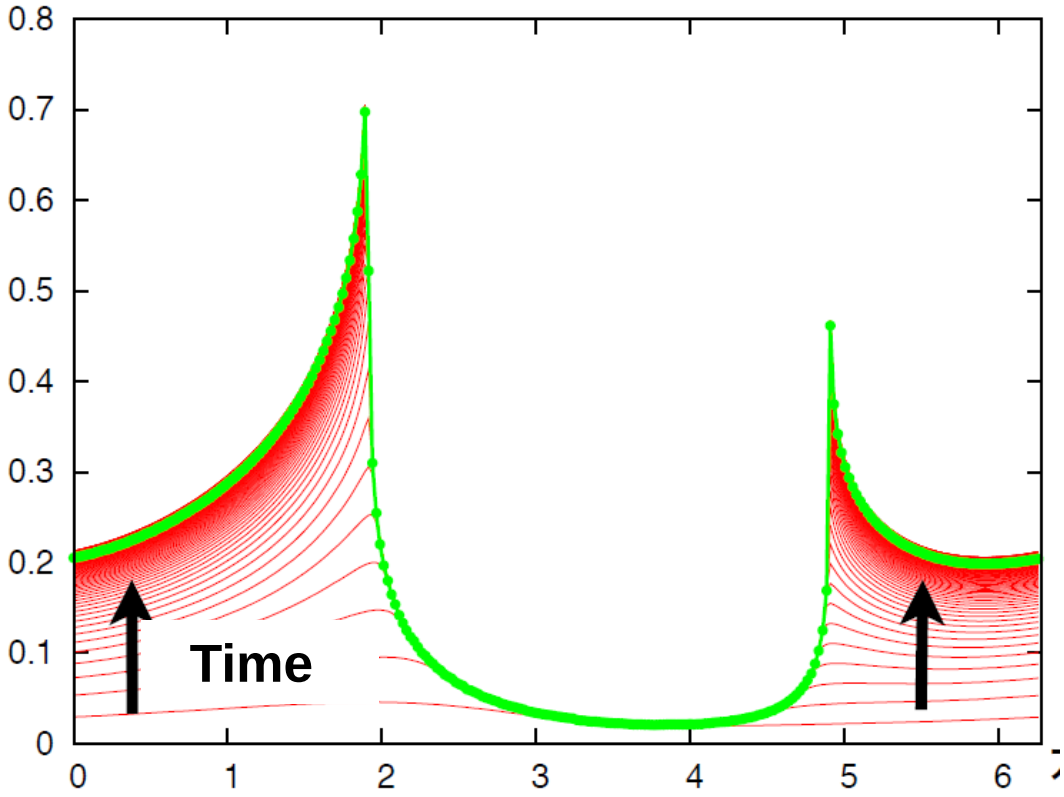
BH shadow formation test

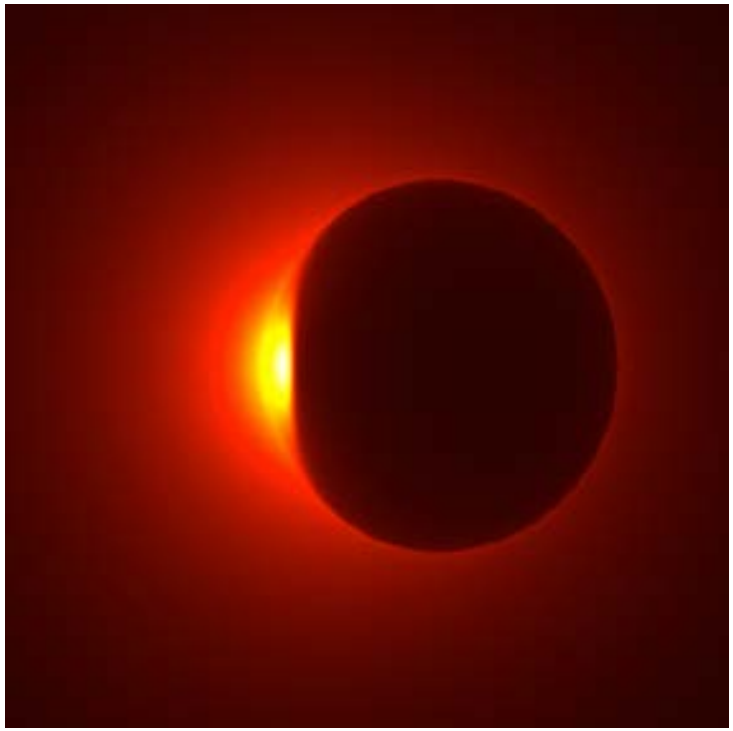
A source is located behind a BH.
A shadow forms by light bending + frame-dragging + gravitational redshift.





Time Evolution of Invariant Brightness





Future Work by *Vermeer*

- **General relativistic RHD calculations on BH accretion disk. Especially, super-Eddington accretion with photon trapping.**

- **Evolution of an aspherical (radiation-dominated) supermassive star.**

Elucidation of the Physics of SMBH Formation