

Numerical Models of Slowly Accreting Black Holes

Charles F. Gammie

H. Shiokawa, J. Dolence, M. Chandra, B. Ryan, M. Mościbrodzka
with Black Hole Accretion TCAN Collaboration (E. Quataert, J. Stone)



I L L I N O I S

Numerical Models of Event Horizon Telescope Targets

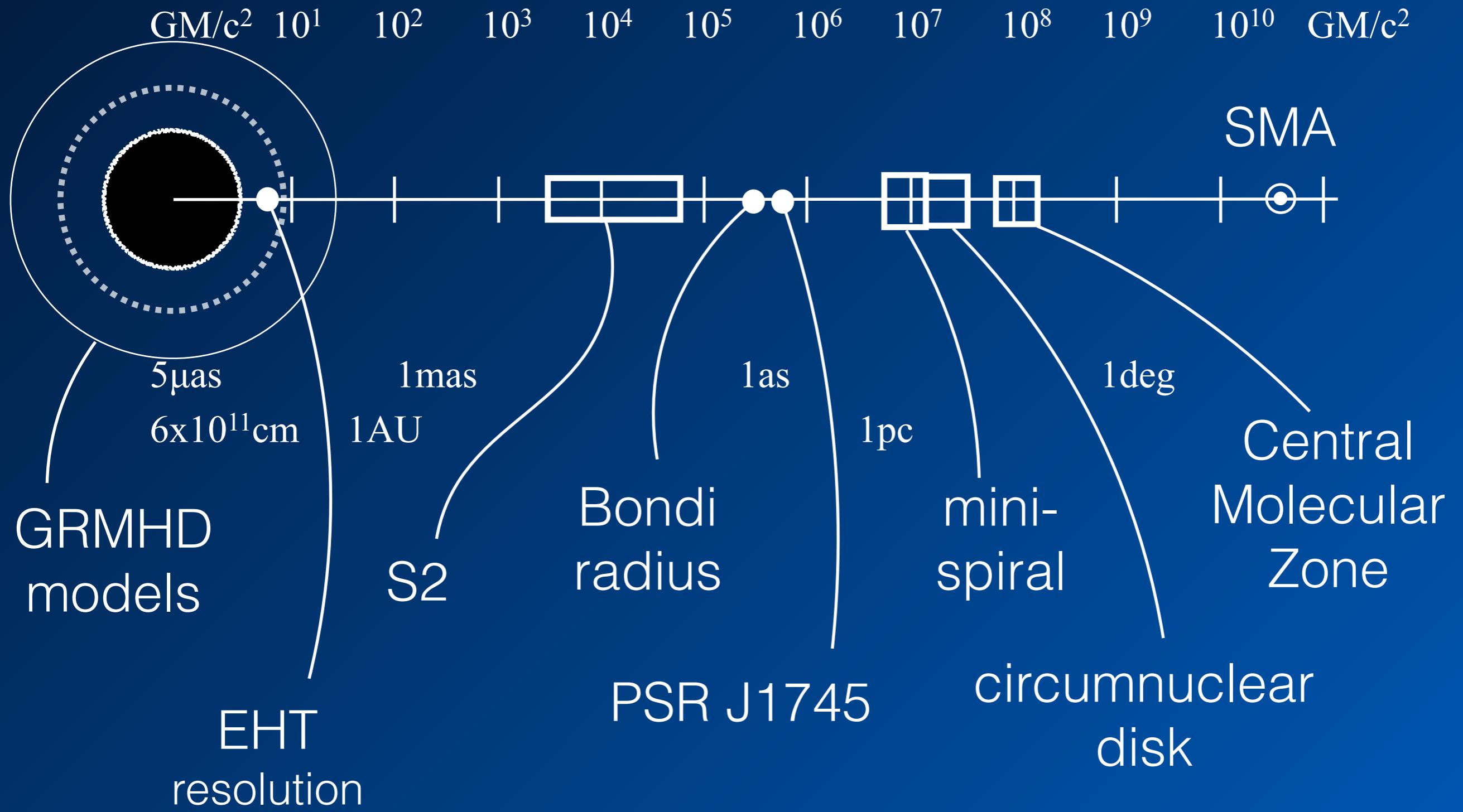
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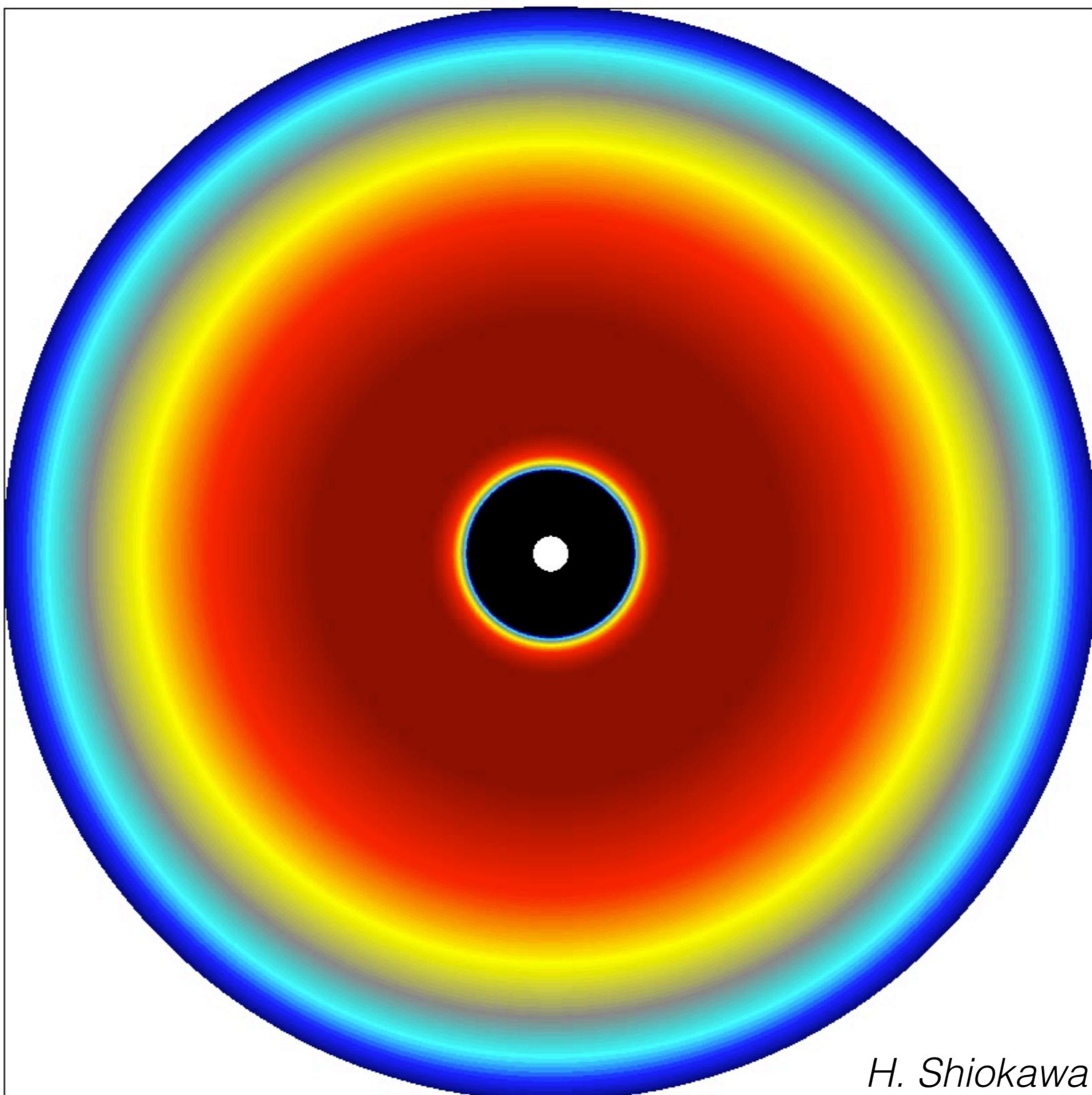


I L L I N O I S

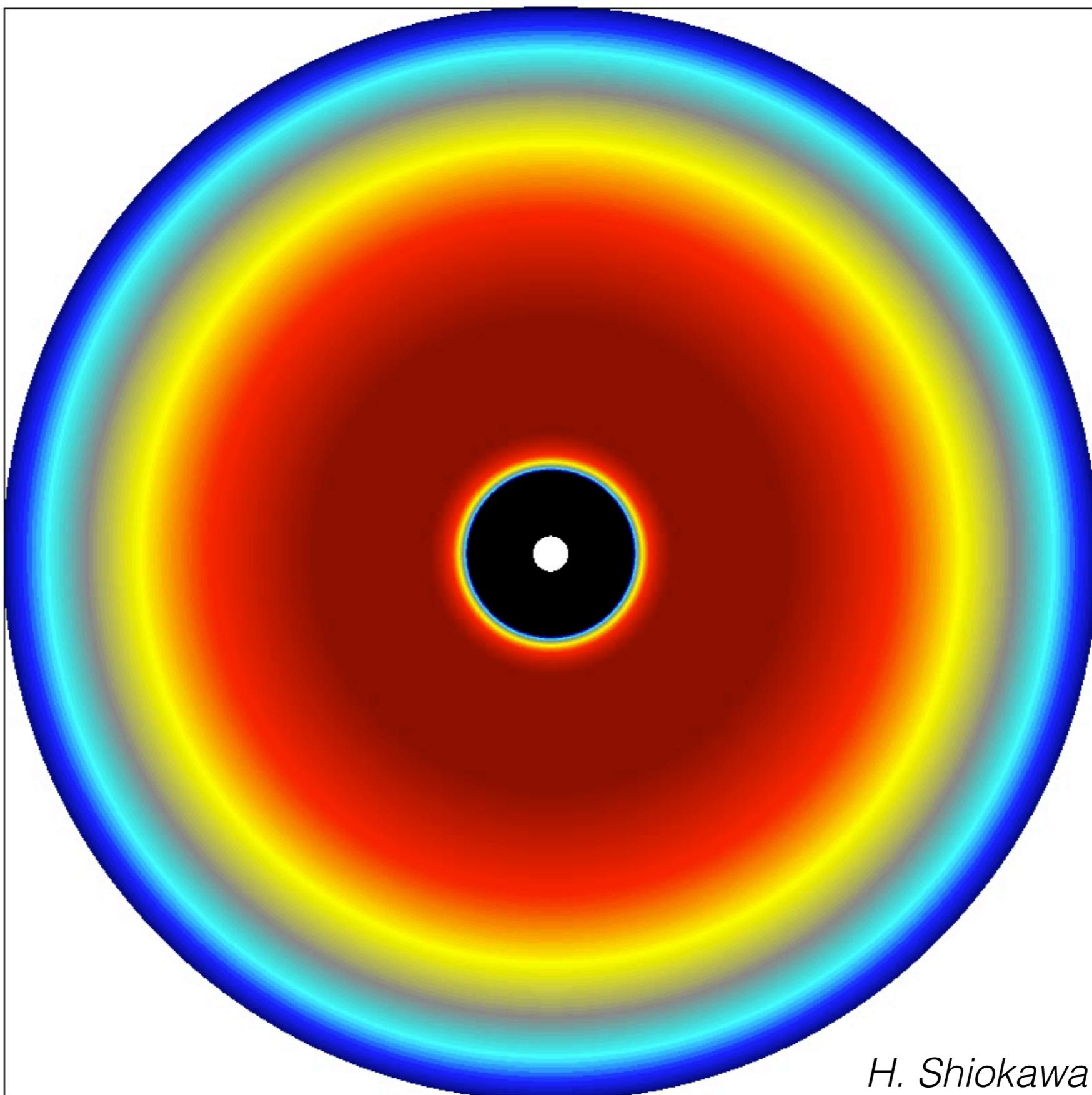
Galactic Center Overview



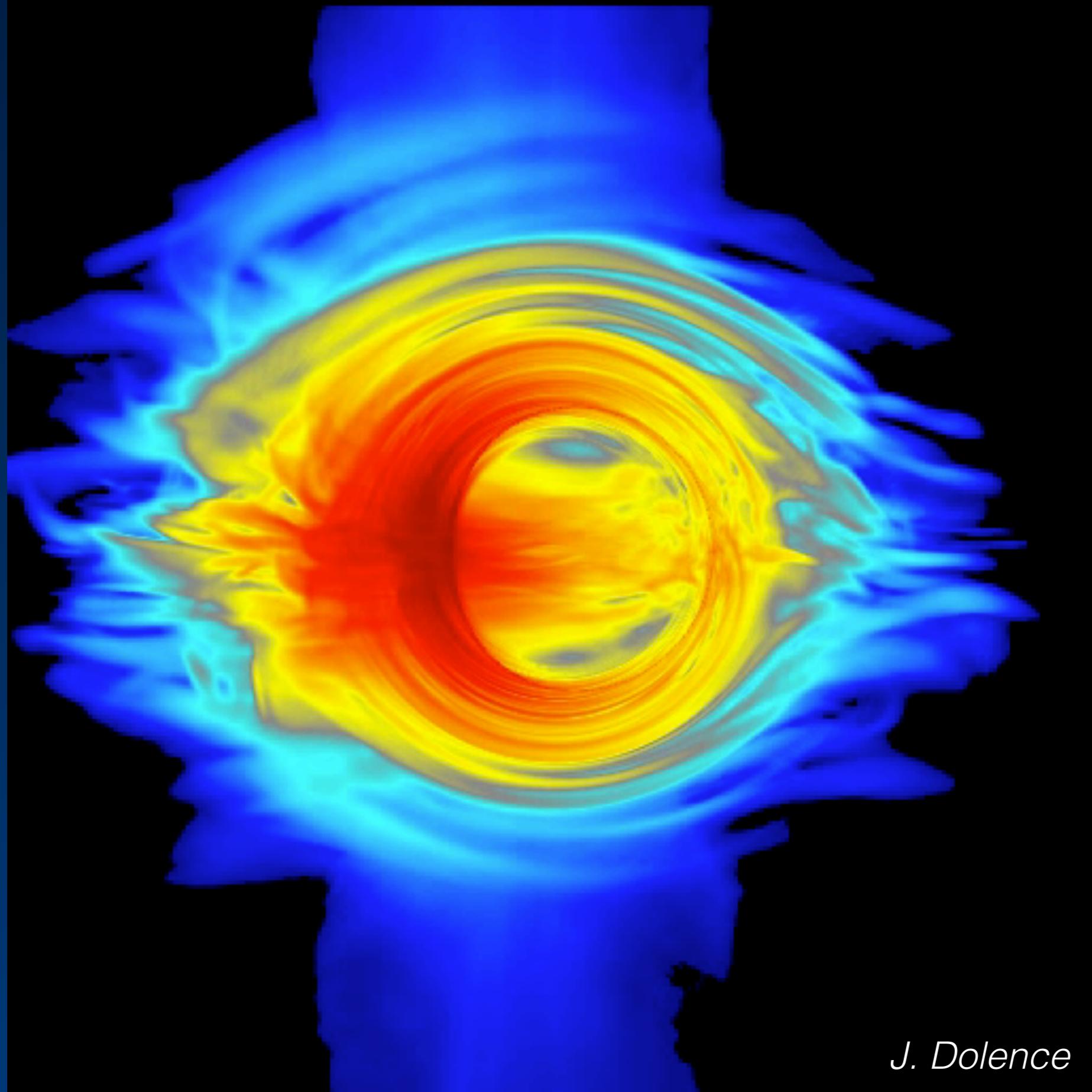
Time=0



Time=0



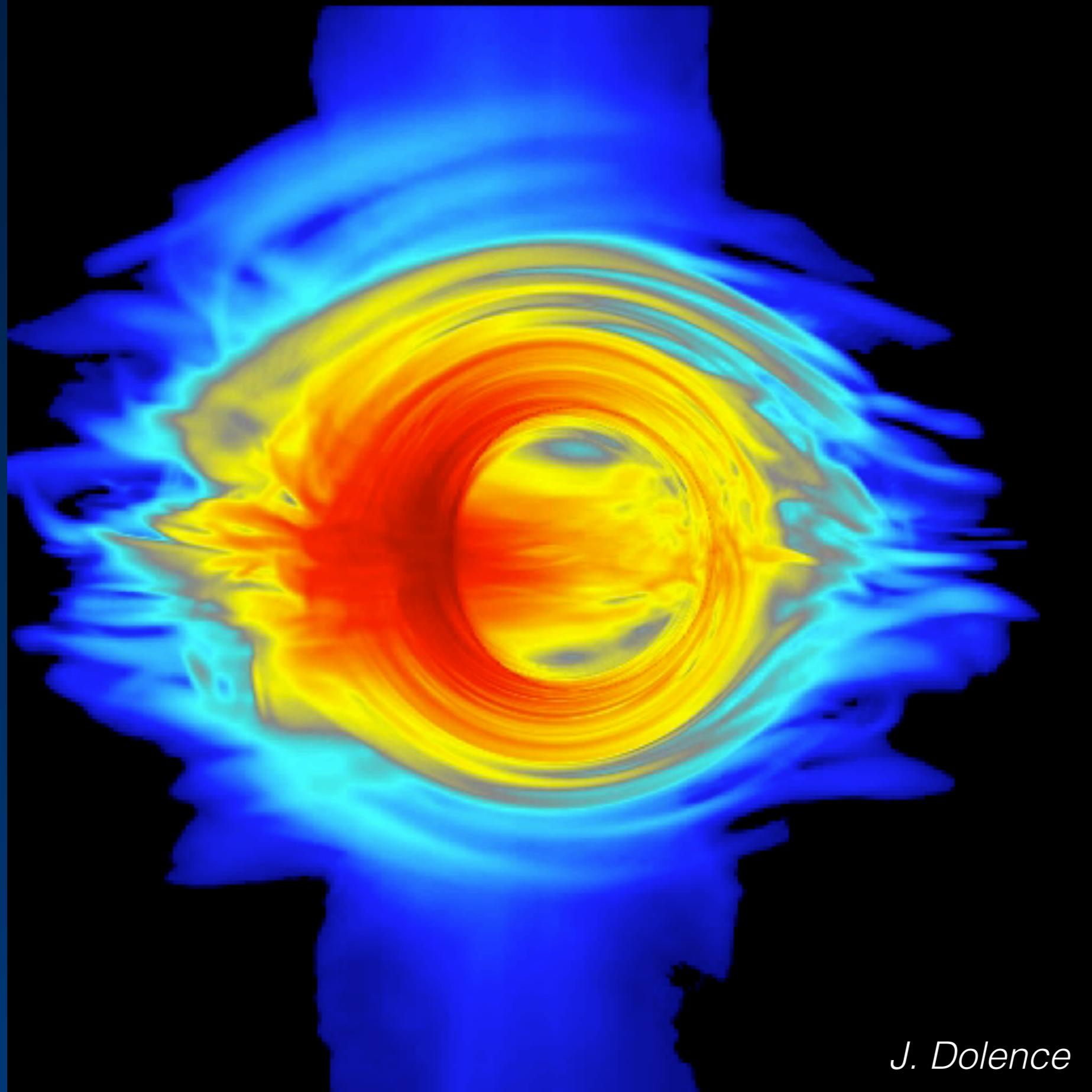
Time in hours: 0.000



Sgr A* model
230 GHz
color shows
 $\log(I_v)$

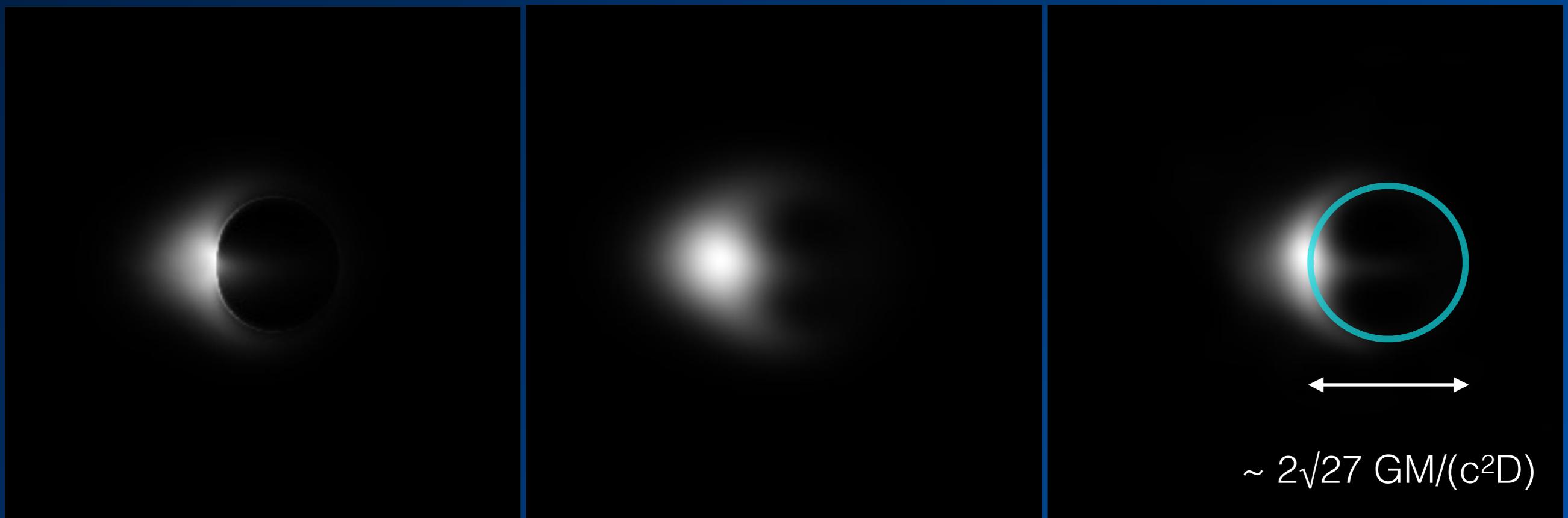
J. Dolence

Time in hours: 0.000



Sgr A* model
230 GHz
color shows
 $\log(I_v)$

J. Dolence



measure apparent size of photon orbit

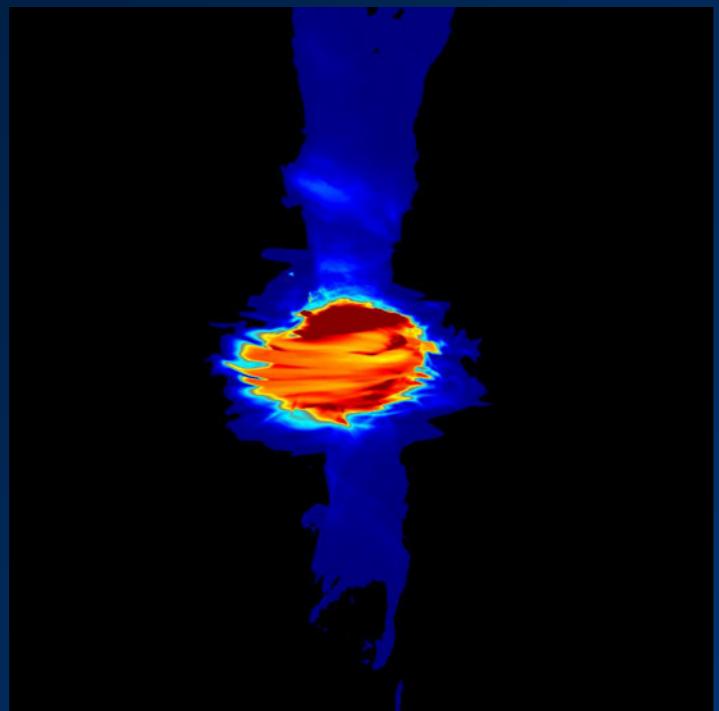
How good are the models?

How bad are the models?

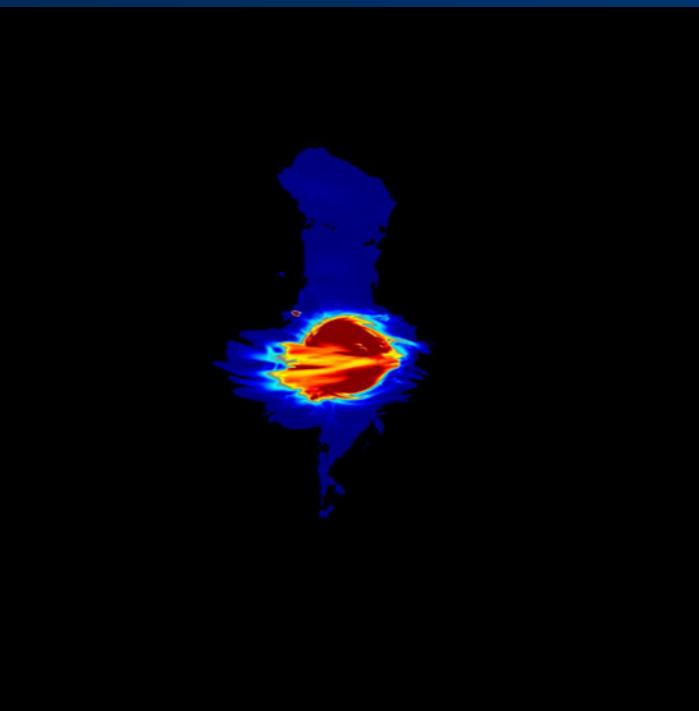
Model Limitations

- Fluid model: resolution
- Fluid model: boundary conditions, net B flux (MAD vs SANE), disk tilt
- Fluid model \Rightarrow collisionless plasma model
- Radiation model: electron distribution function
- Radiation model: coupling to radiation (e.g. M87)

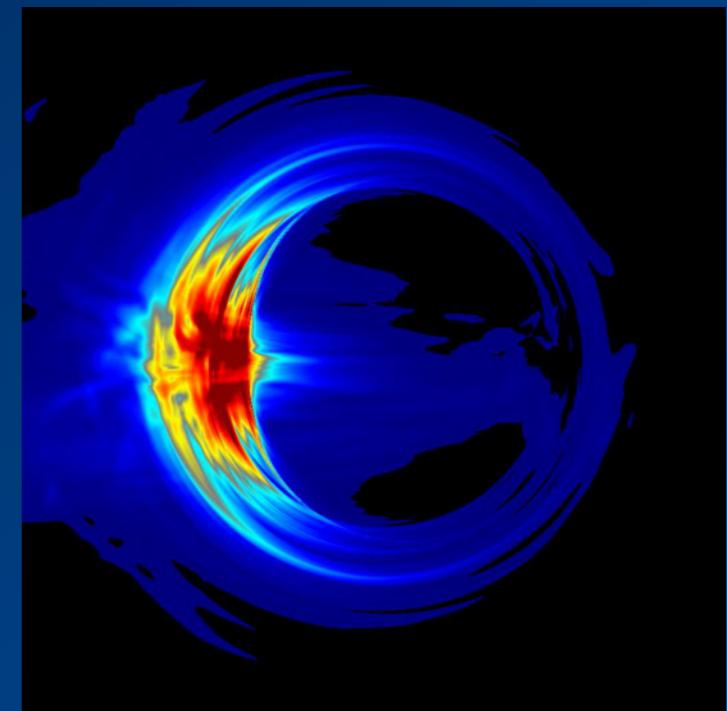
hot disk,
cold jet



$\lambda = 13\text{mm}$

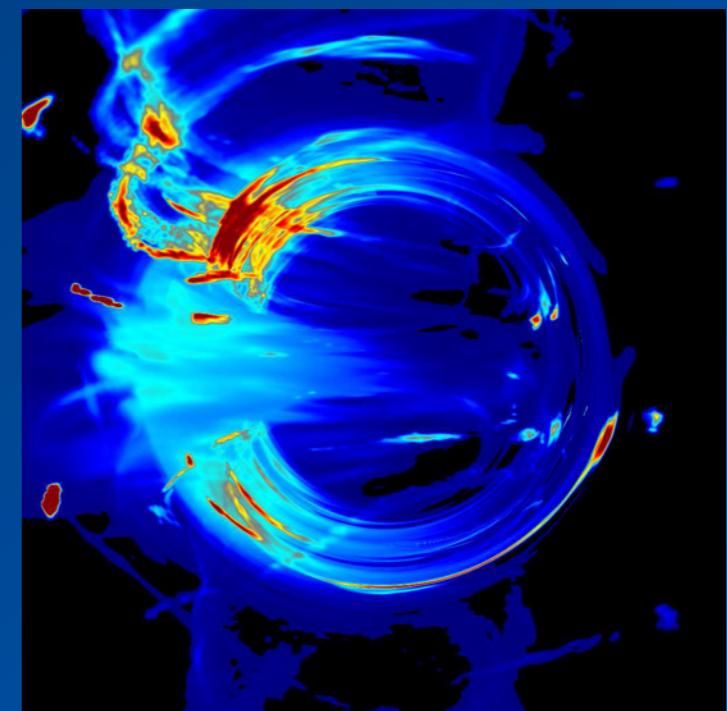
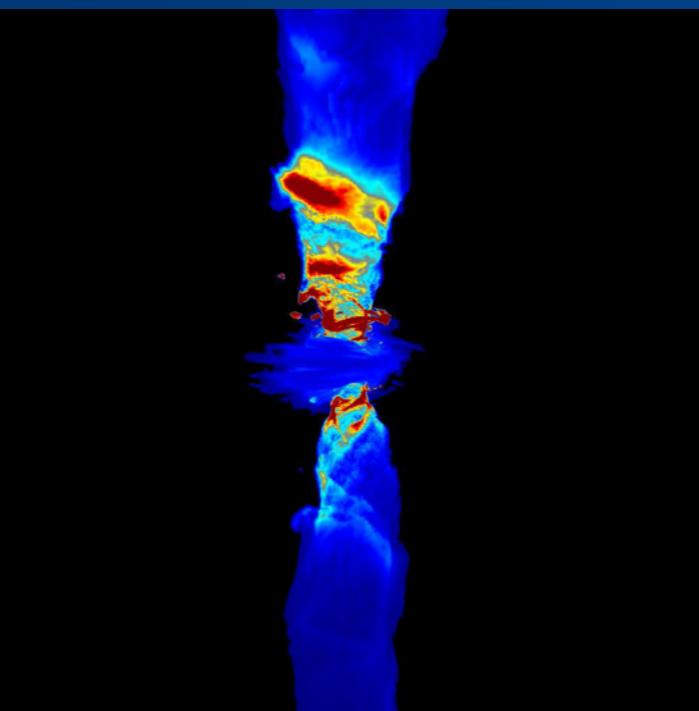
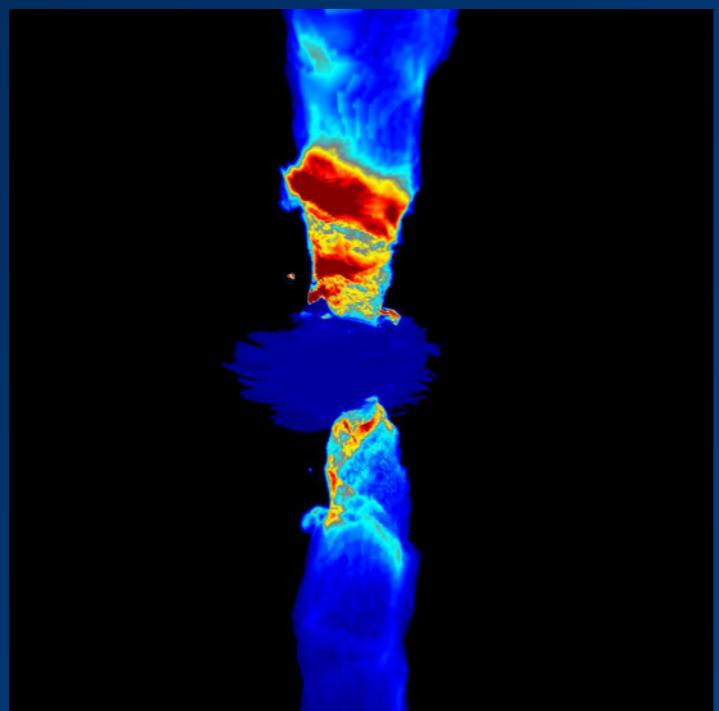


$\lambda = 7\text{mm}$

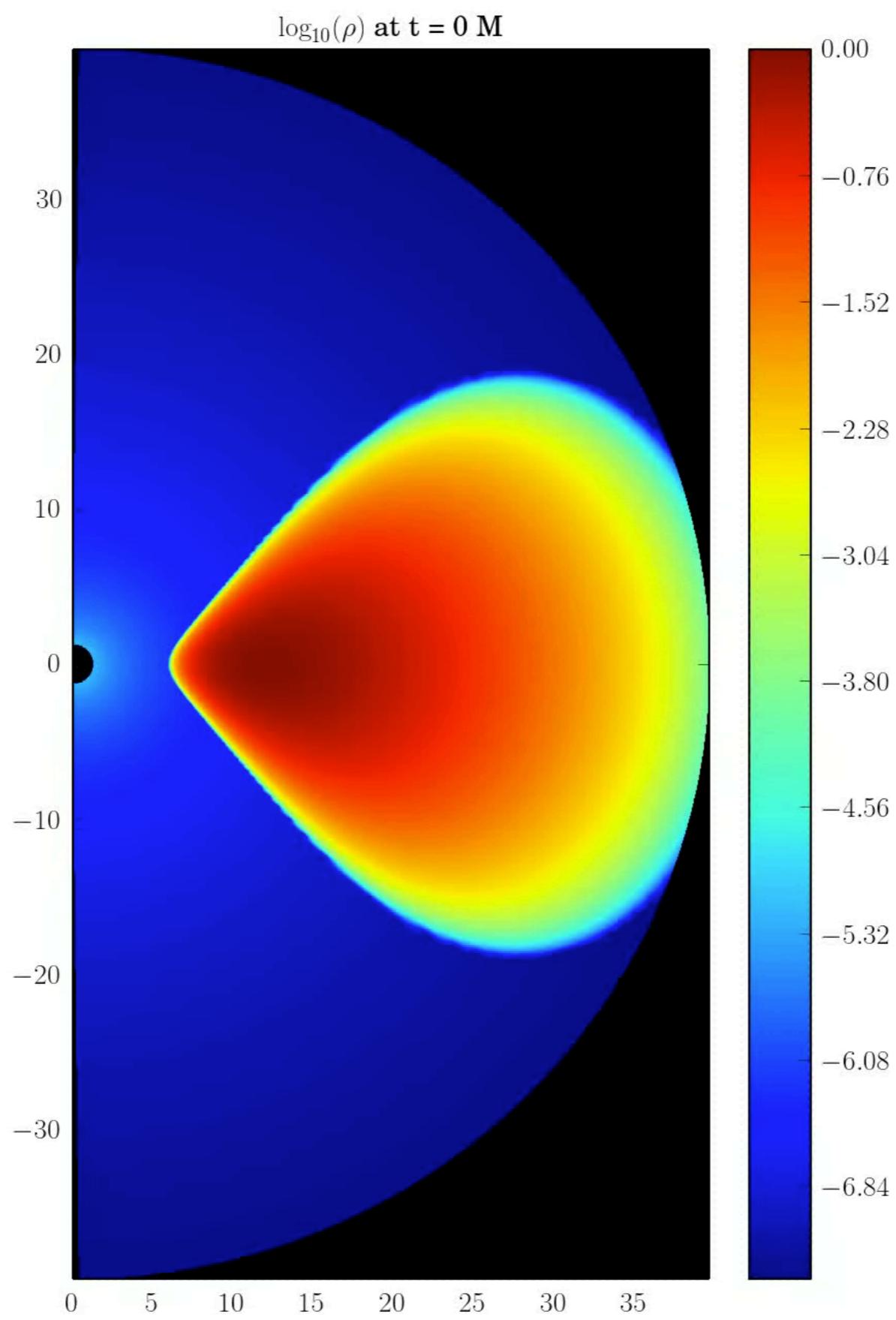


$\lambda = 1.3\text{mm}$

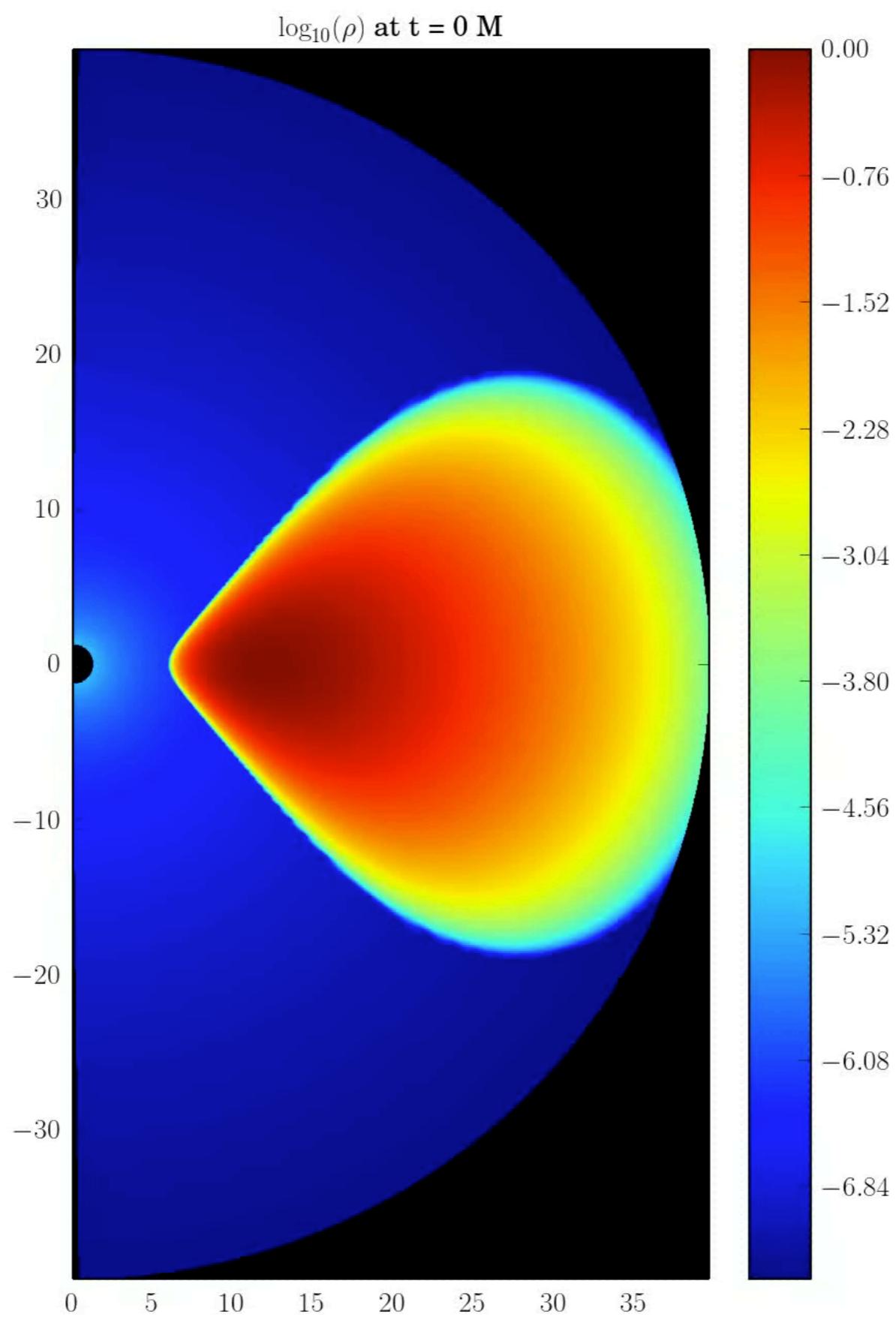
cold disk,
hot jet



grim
GR
implicit
MHD



grim
GR
implicit
MHD



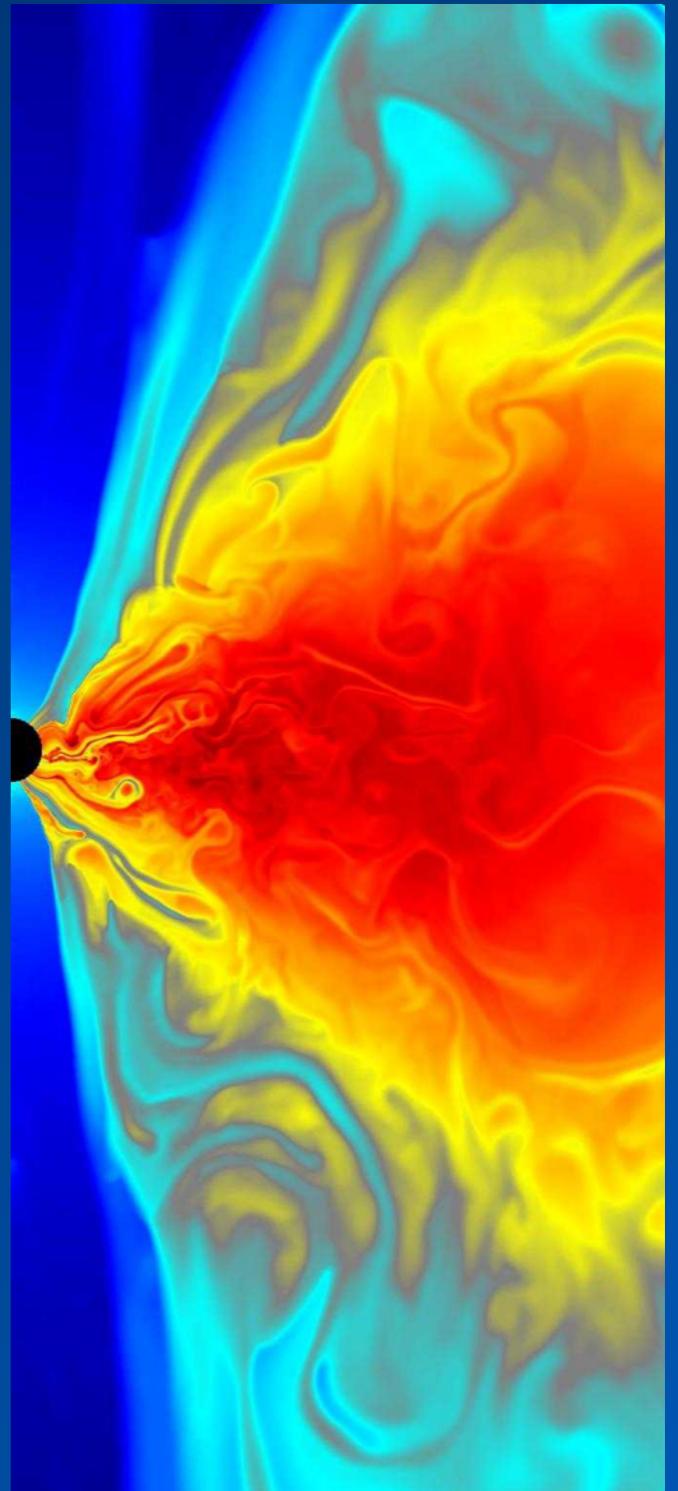
Conclusion

- Dynamical and radiative models for slowly accreting black holes
- Result depends on electron DF
- EHT motivates more accurate models
- Extended MHD models, with PIC inspired closure schemes, on the way.

What is in the model?

Dynamical Model

- *ideal* MHD (fluid)
- fully relativistic
- Kerr-Schild coordinates
- nonradiative
- gamma-law gas
- harm code



Radiative Model

- Fully relativistic (fast light, slow light)
- synchrotron emission, absorption
 j_ν, κ_ν depends on electron DF
 $v_s \sim \gamma^2(eB/m_e c)$
- DF assumed *thermal*, $T_i/T_e = \text{const.}$
- Compton scattering
- grmonty, bothros codes

Time=6,060.0M

Time=6,060.0M

Collisionless Plasma

- Coulomb mfp $\sim (GM/c^2) \tau_T^{-1} \sim 10^5 GM/c^2$ (Sgr A*)
- ion and electron DF not relaxed
- ***dynamics:*** ideal fluid incomplete
- ***radiation:*** emission dependent on electron DF
 $v_{\text{syn}} \sim \gamma^2(eB/m_e c)$

Extended MHD models

Ideal MHD + corrections

- electron, ion energy equations
- electron, ion conduction
- electron, ion dissipation model
- anisotropic pressure tensors (viscosity)
- coupling electrons to radiation

Example: conduction

- Is it important? Saturated conduction:
 $q \sim Q c_s^3$
 $du/dt \sim \nabla_\mu q^\mu \sim u c_s/r \sim u (c/r)$
- Eckart model (unstable: Lindblom & Hiscock)
 $q^\mu = -\kappa h^{\mu\nu} (\nabla_\nu T + T a_\nu)$
 $T^{\mu\nu}[\text{cond}] = u^\mu q^\nu + q^\mu u^\nu$
numerical complexity: $T^{\mu\nu} \sim \partial T, \partial u^\mu$
- Numerical implementation: implicit code **grim**,
PIC inspired closure schemes.

DB: plot-000.vts

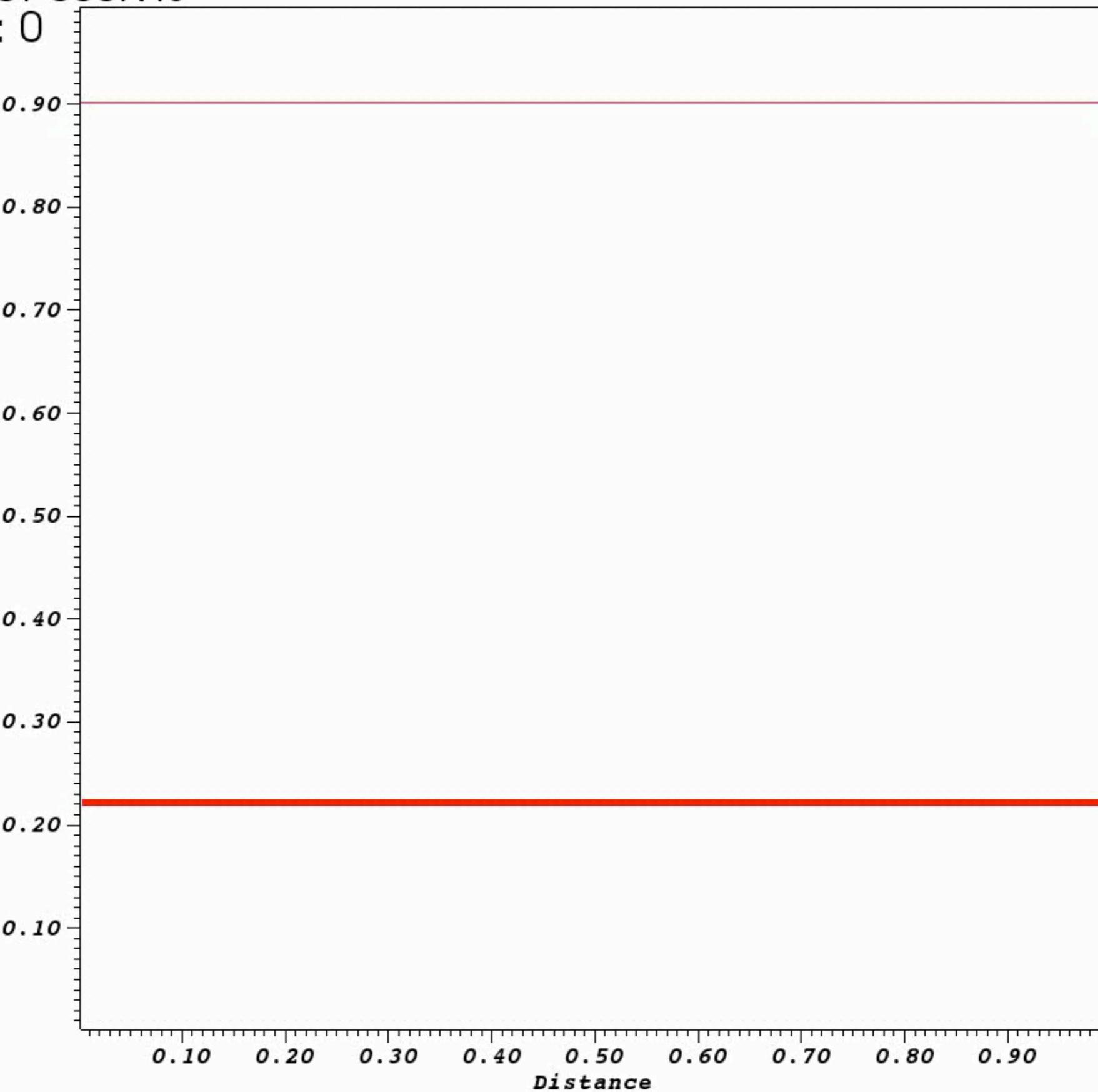
Cycle: 0

Pseudocolor
Var: varrho
Constant.



Max: 0.2210
Min: 0.2210

Value



DB: plot-000.vts

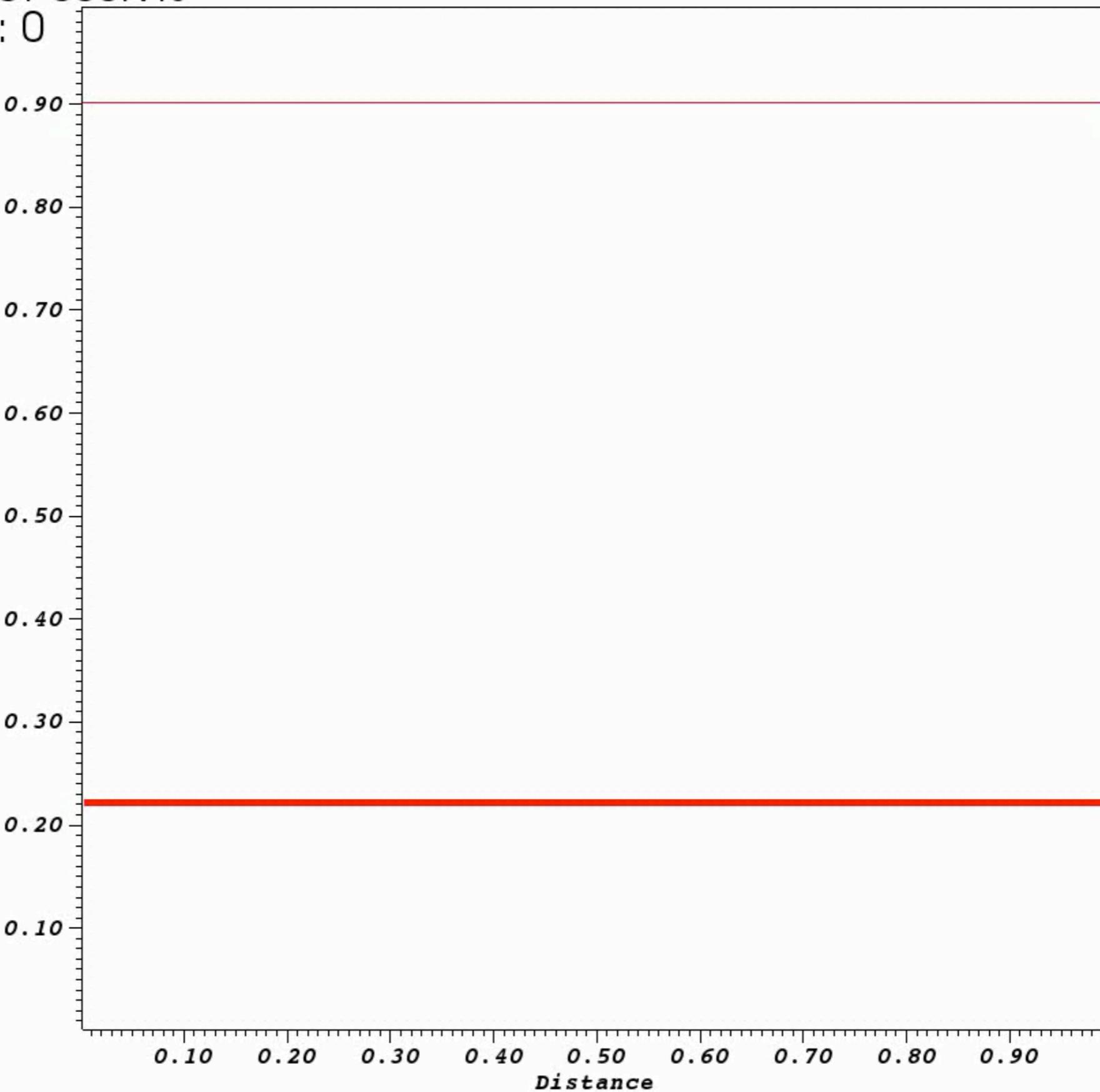
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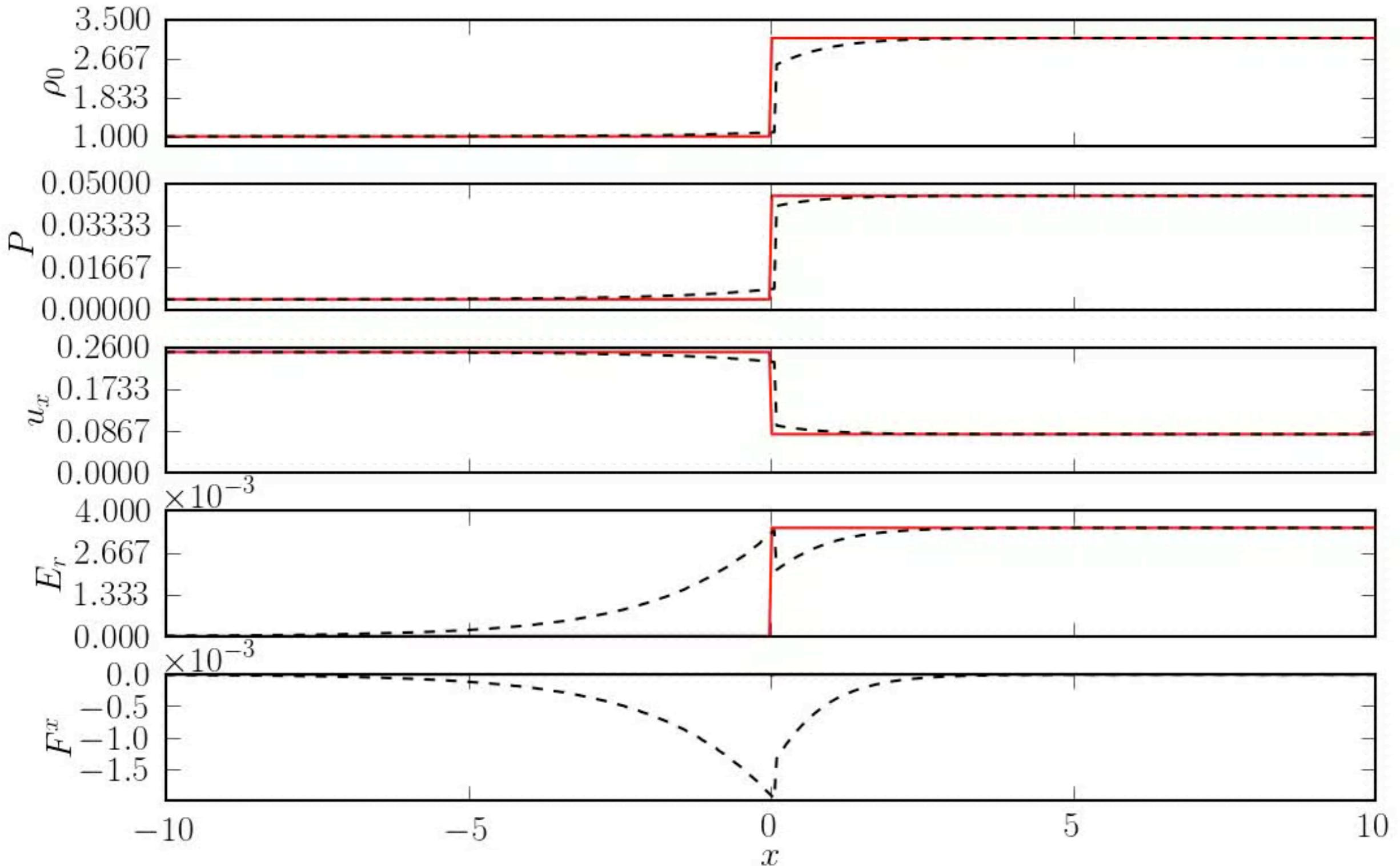
Value



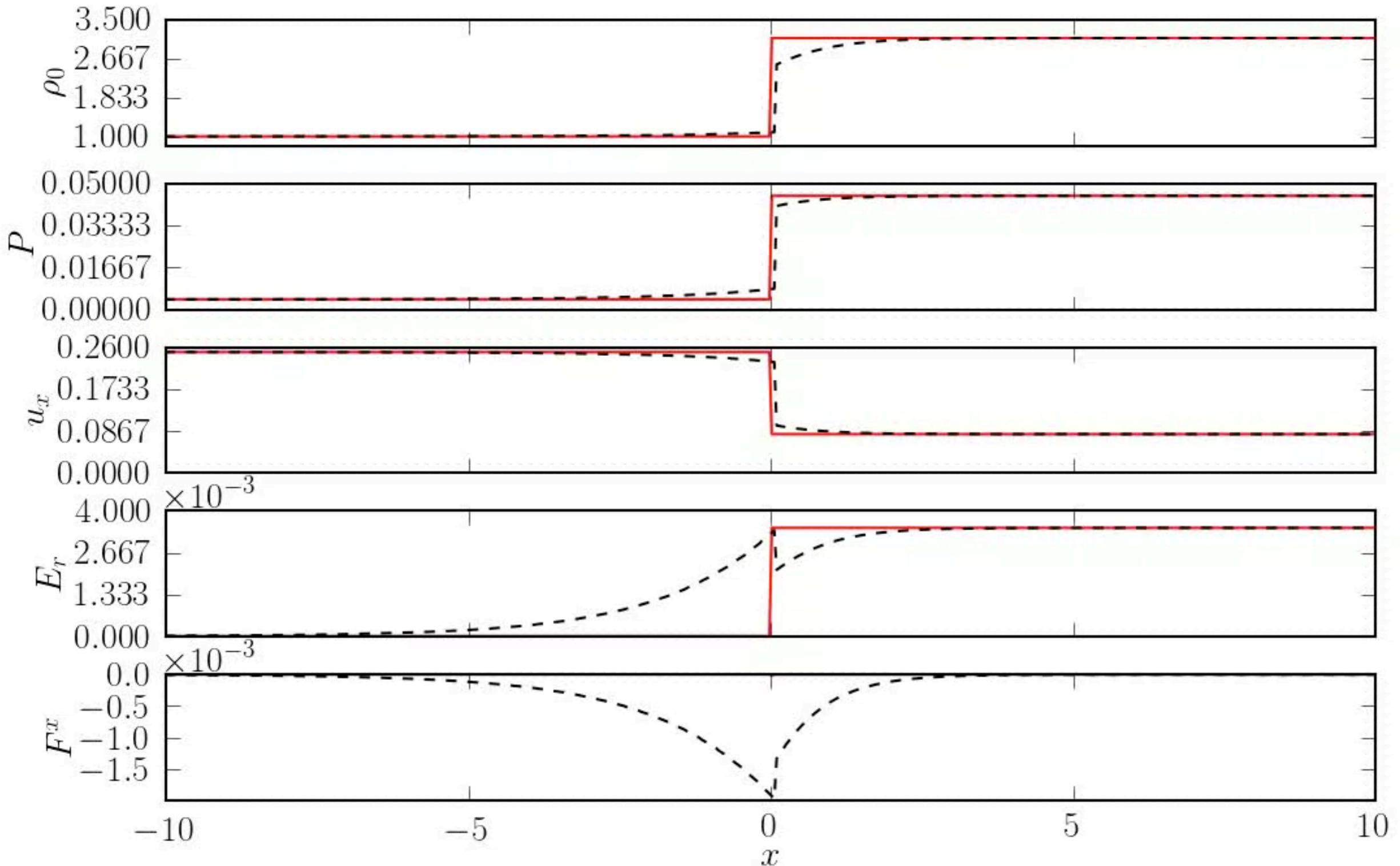
Example: radiative coupling

- Cooling increases as \dot{M} increases
- synchrotron, Compton cooling
- Numerical implementation: Monte Carlo radiation
GRMHD code **bhlight**

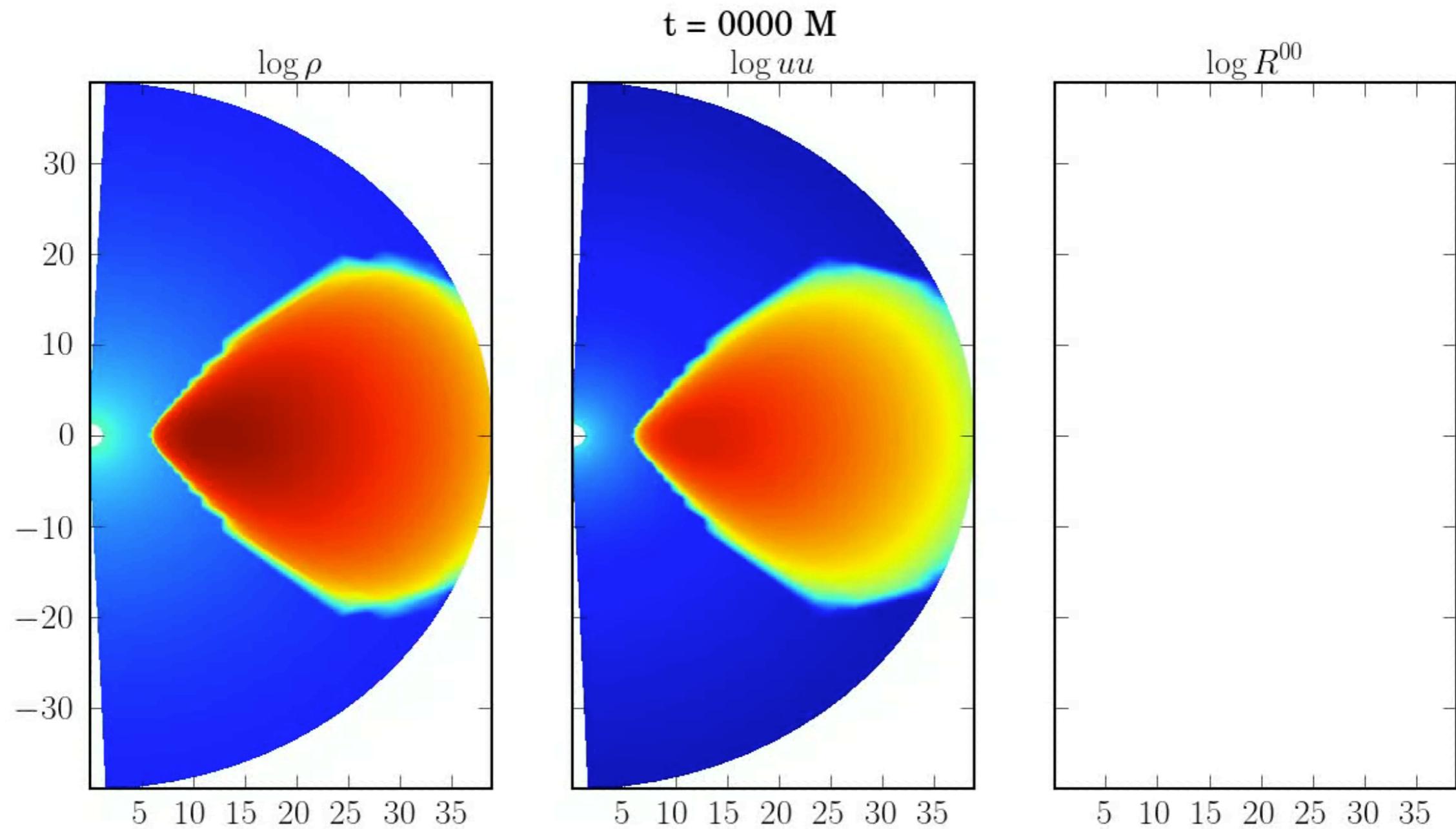
bhlight: Monte Carlo radiation hydrodynamics



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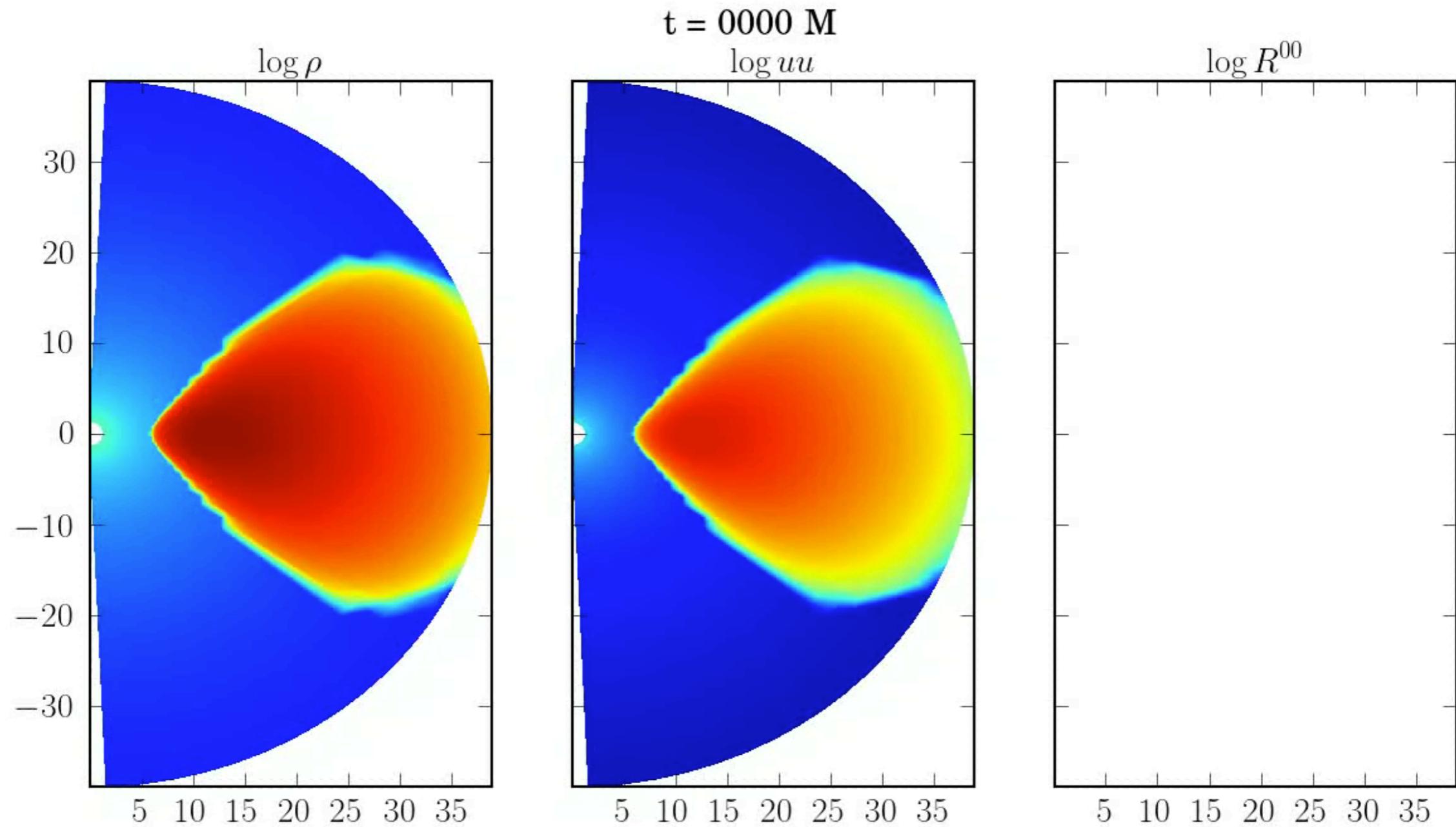


bhlight: Monte Carlo radiation hydrodynamics



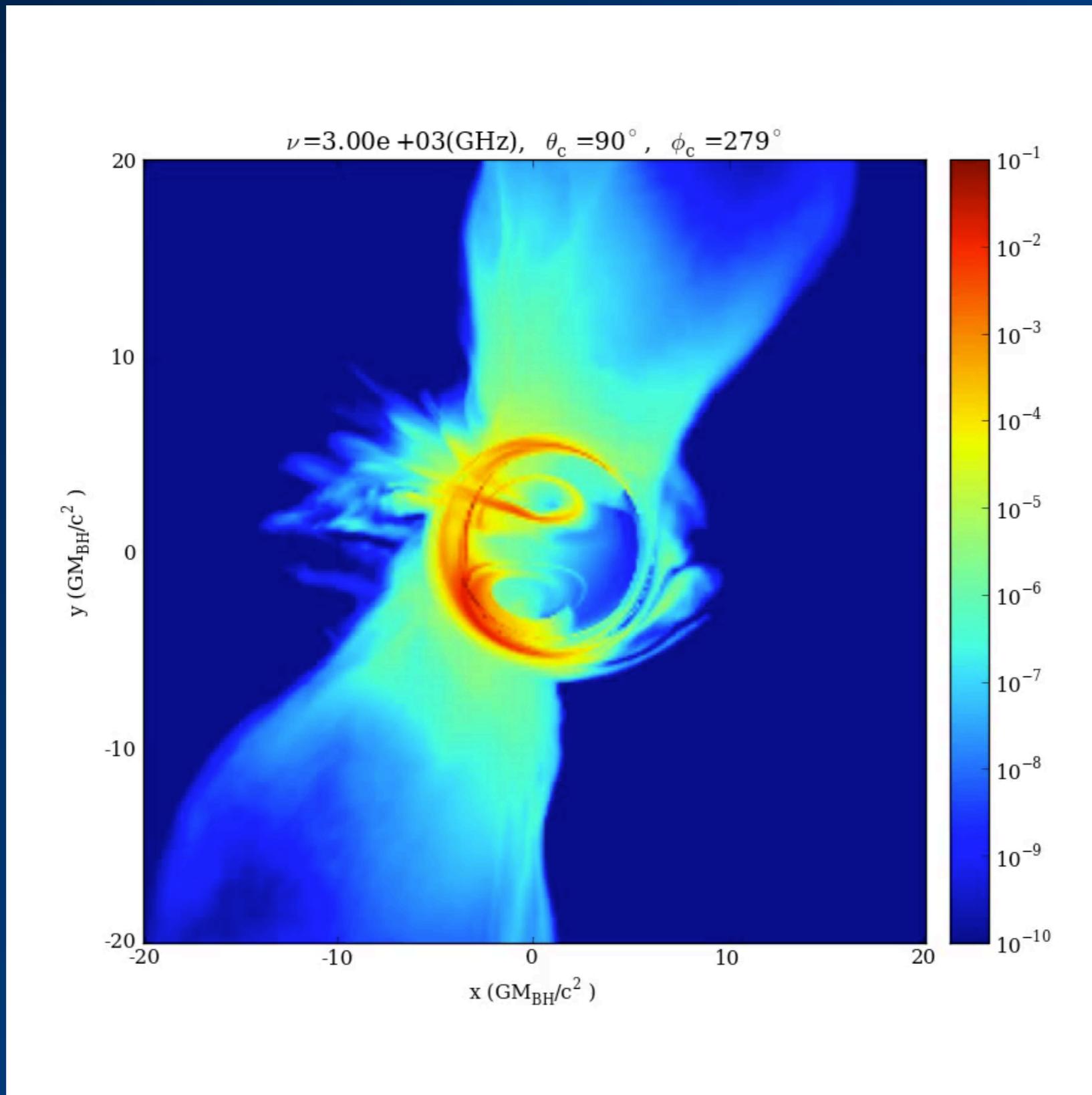
B. Ryan, J. Dolence

bhlight: Monte Carlo radiation hydrodynamics

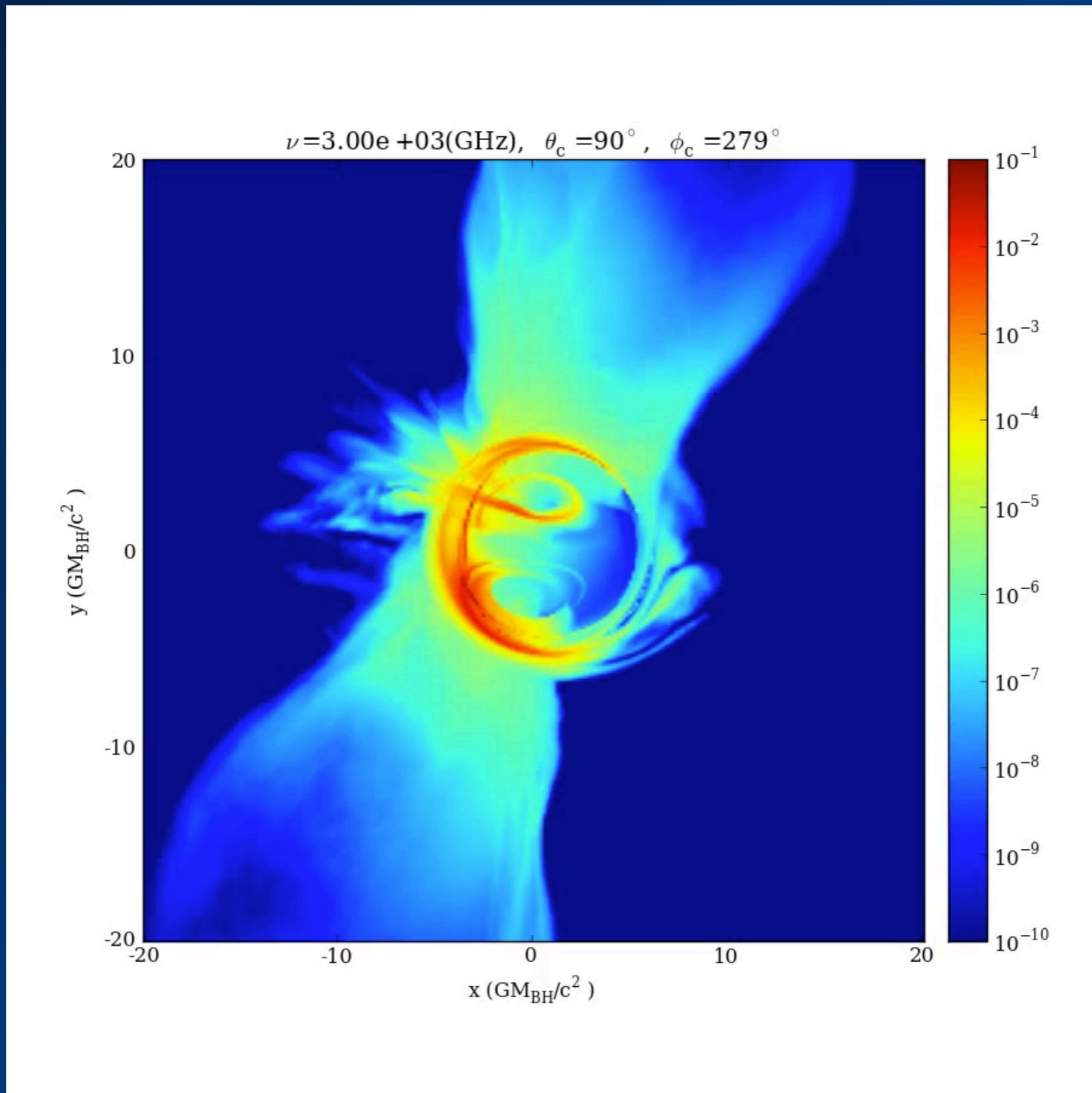


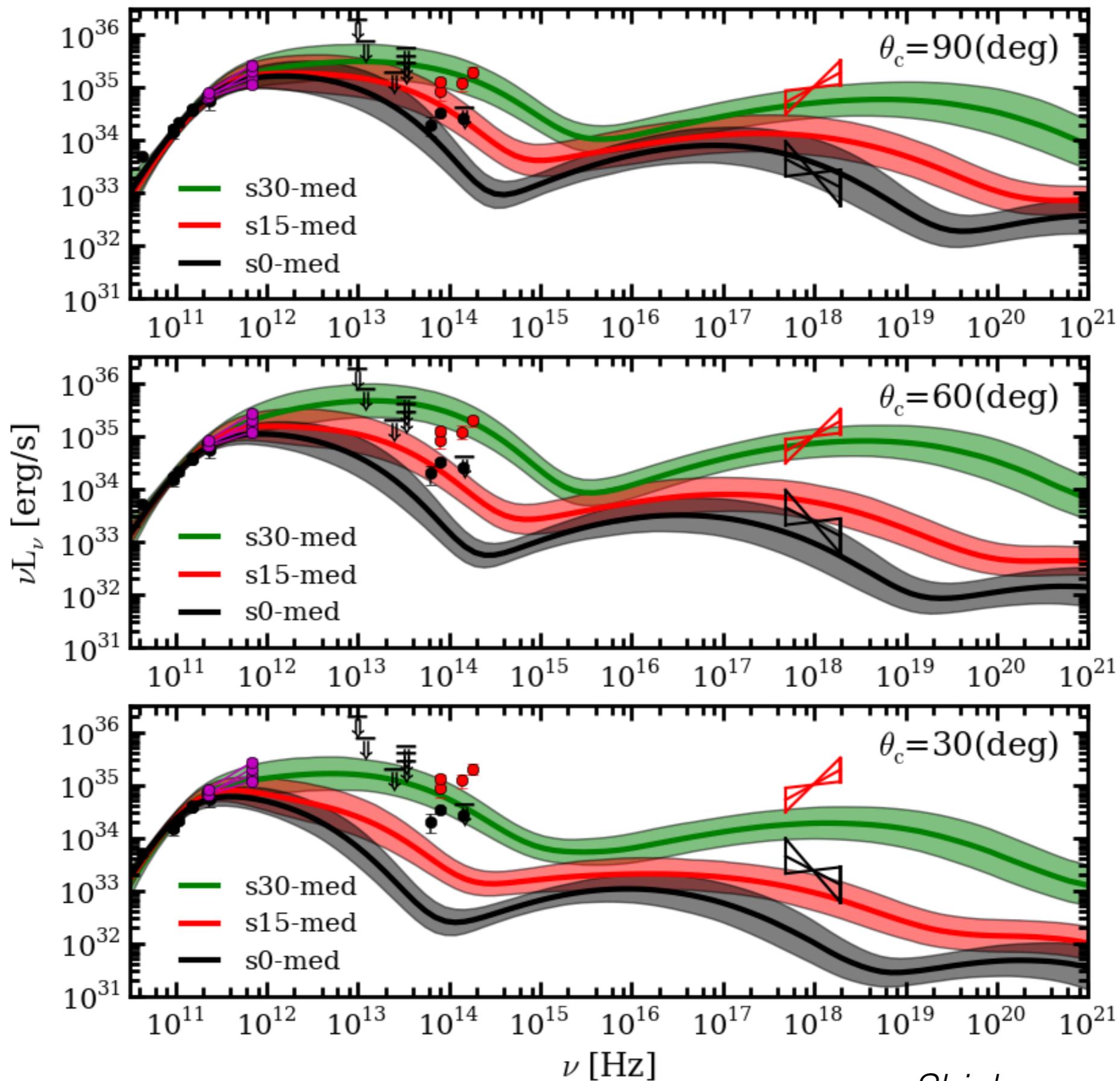
B. Ryan, J. Dolence

Example: disk tilt



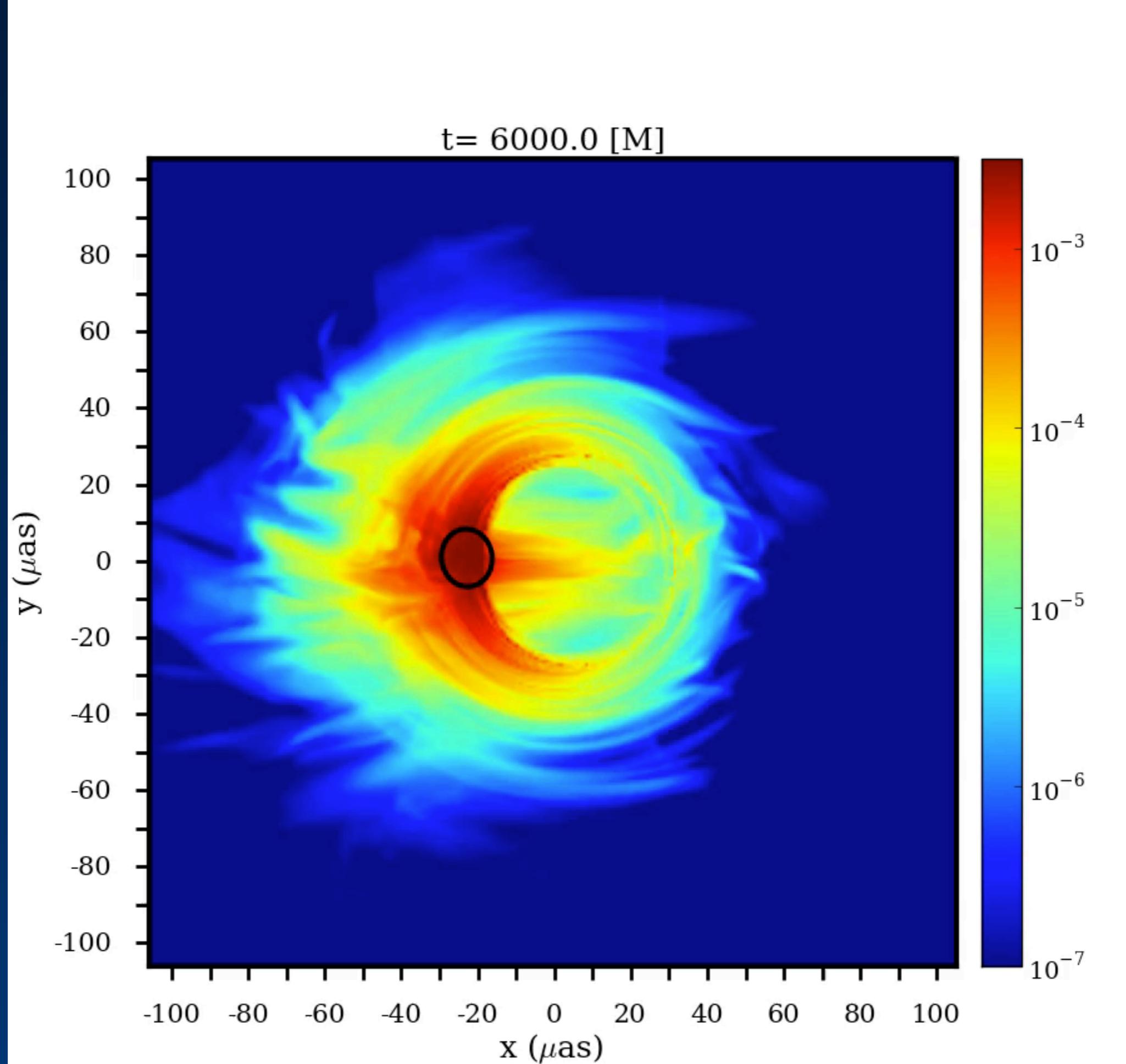
Example: disk tilt



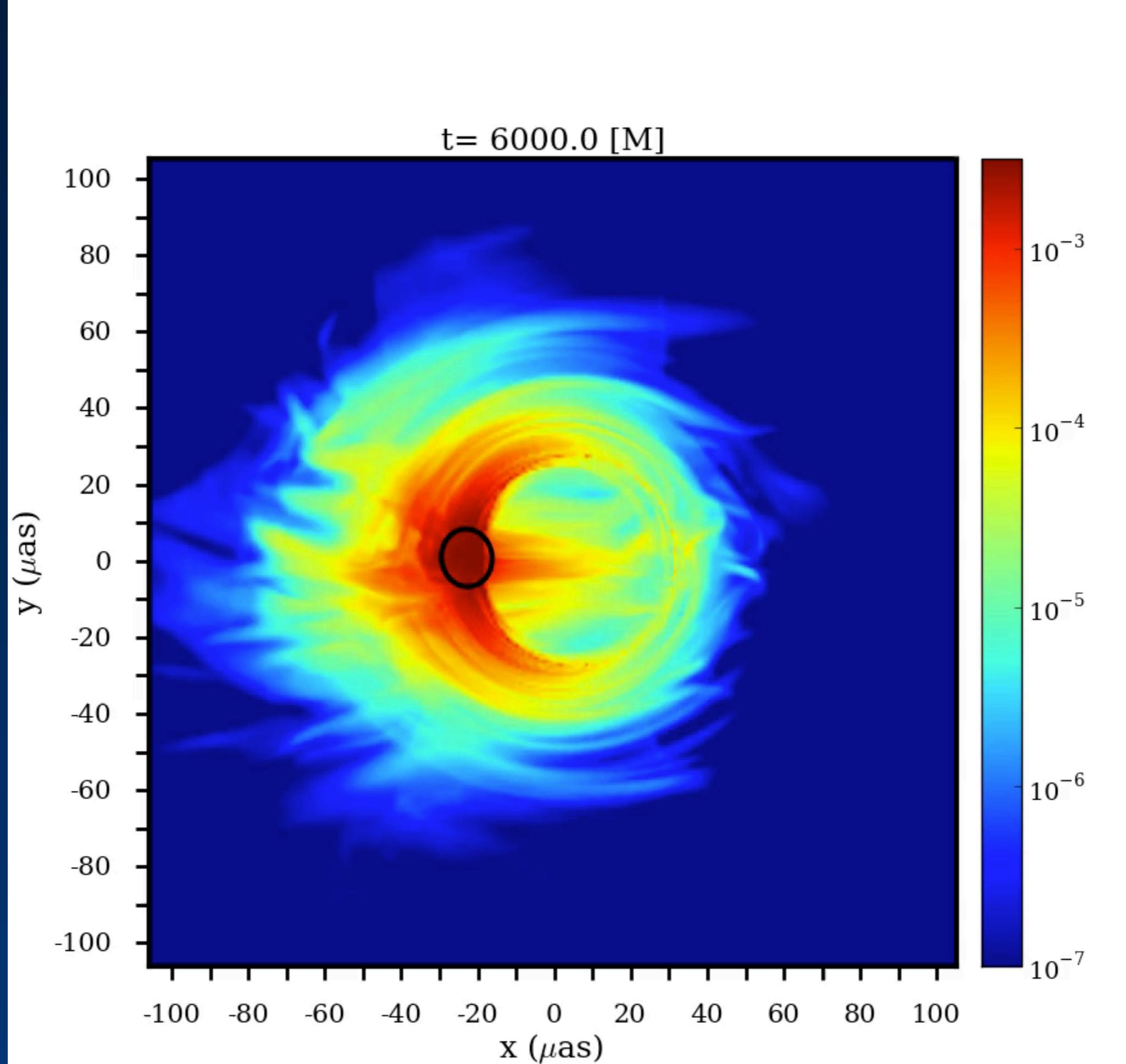
$\phi_c=0(\text{deg})$ 

Parameters

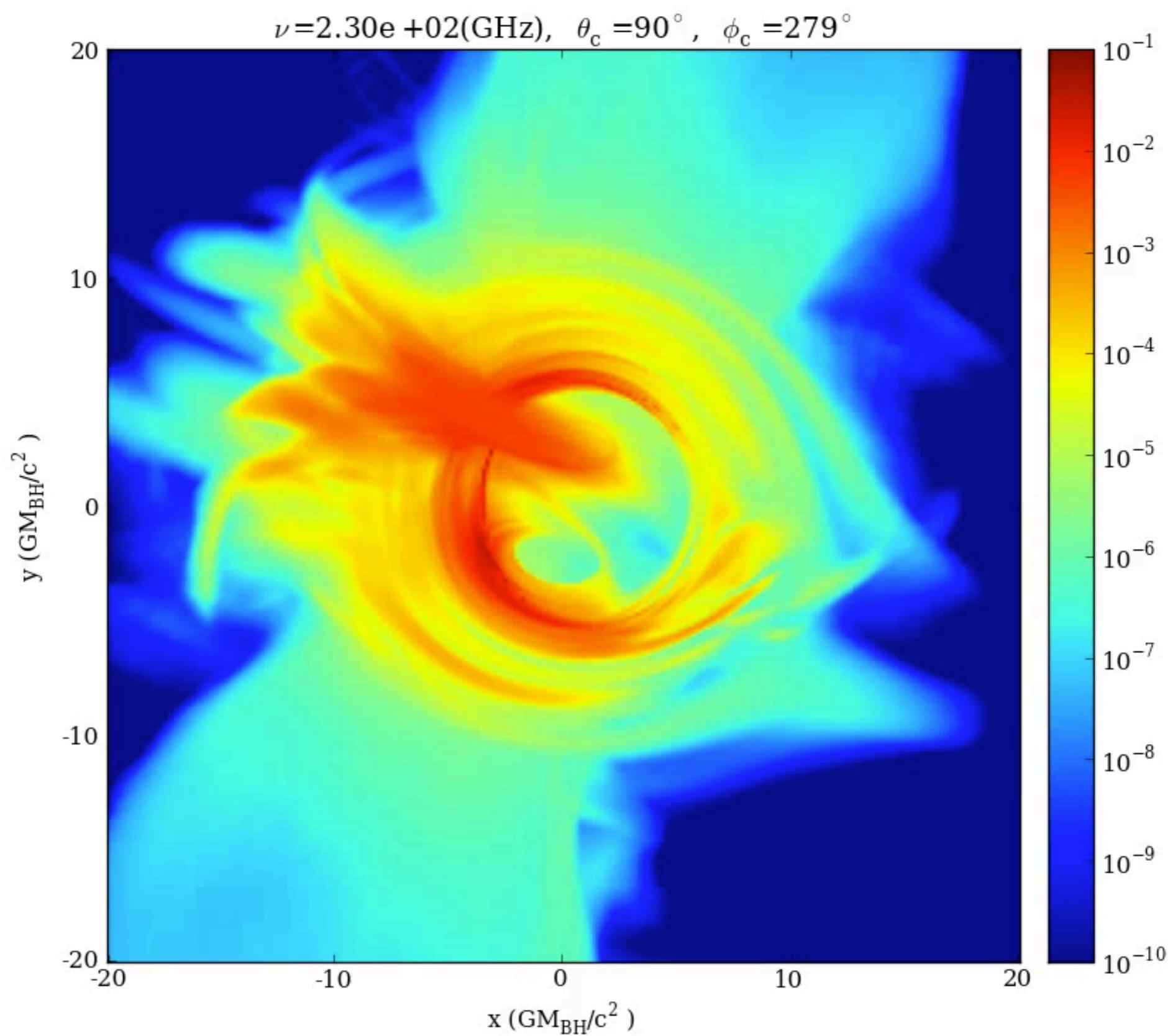
- M_{BH} : black hole mass
- D : distance to source
- \dot{M} : accretion rate
- T_i/T_e : ion/electron temperature ratio
- i : inclination
- ϕ : position angle
- Tilt?



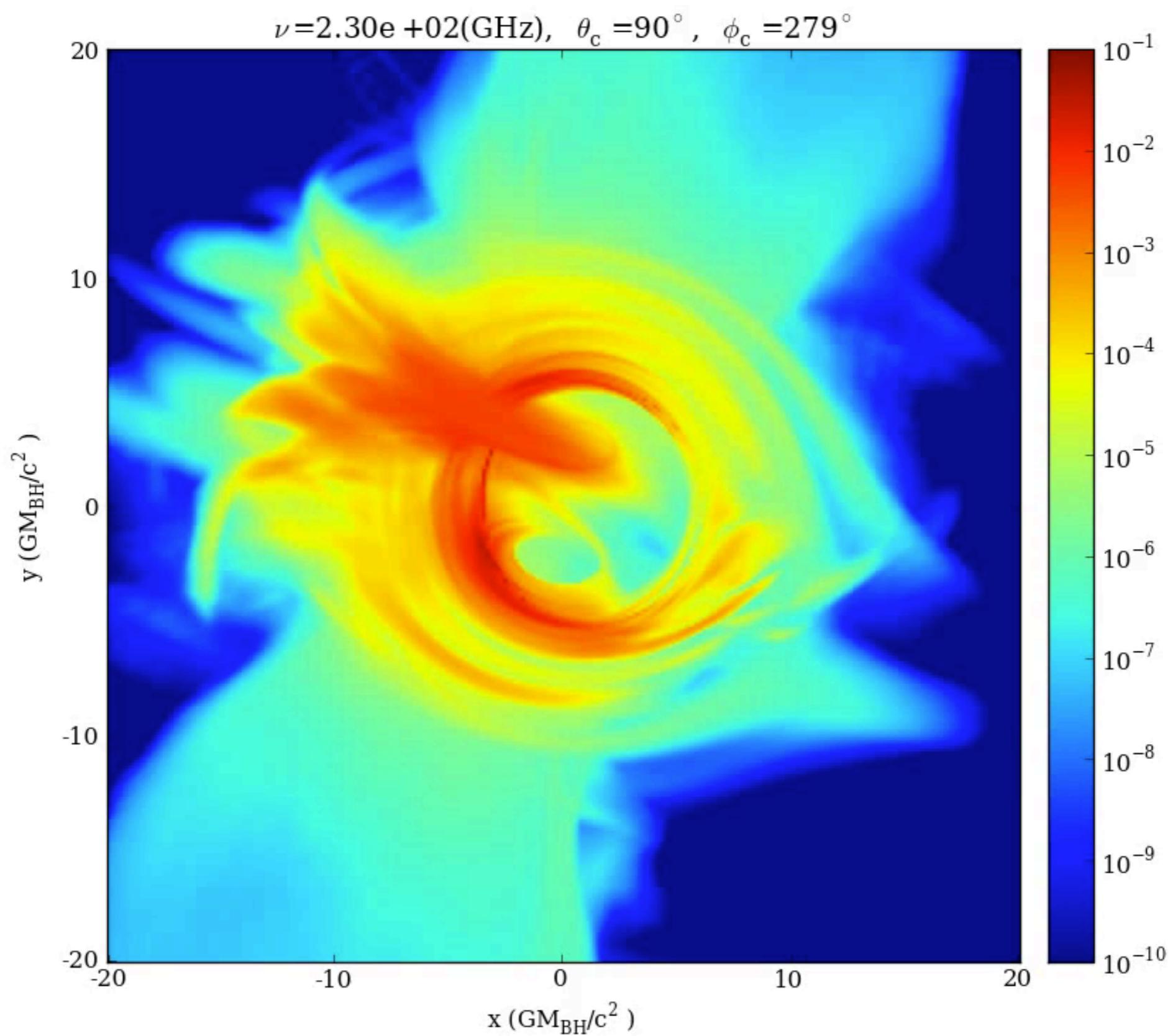
H. Shiokawa



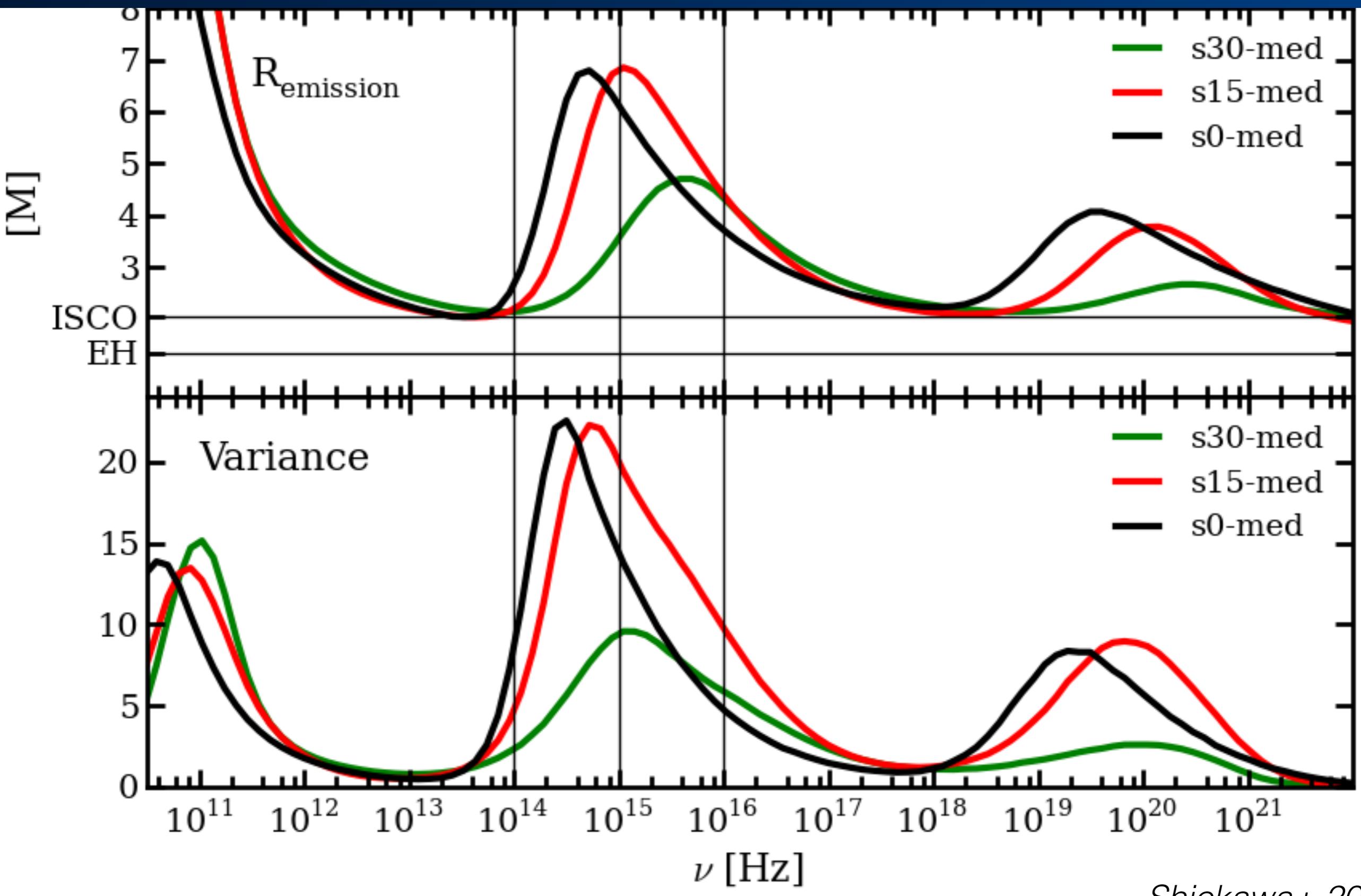
H. Shiokawa



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Shiokawa+ 2014