

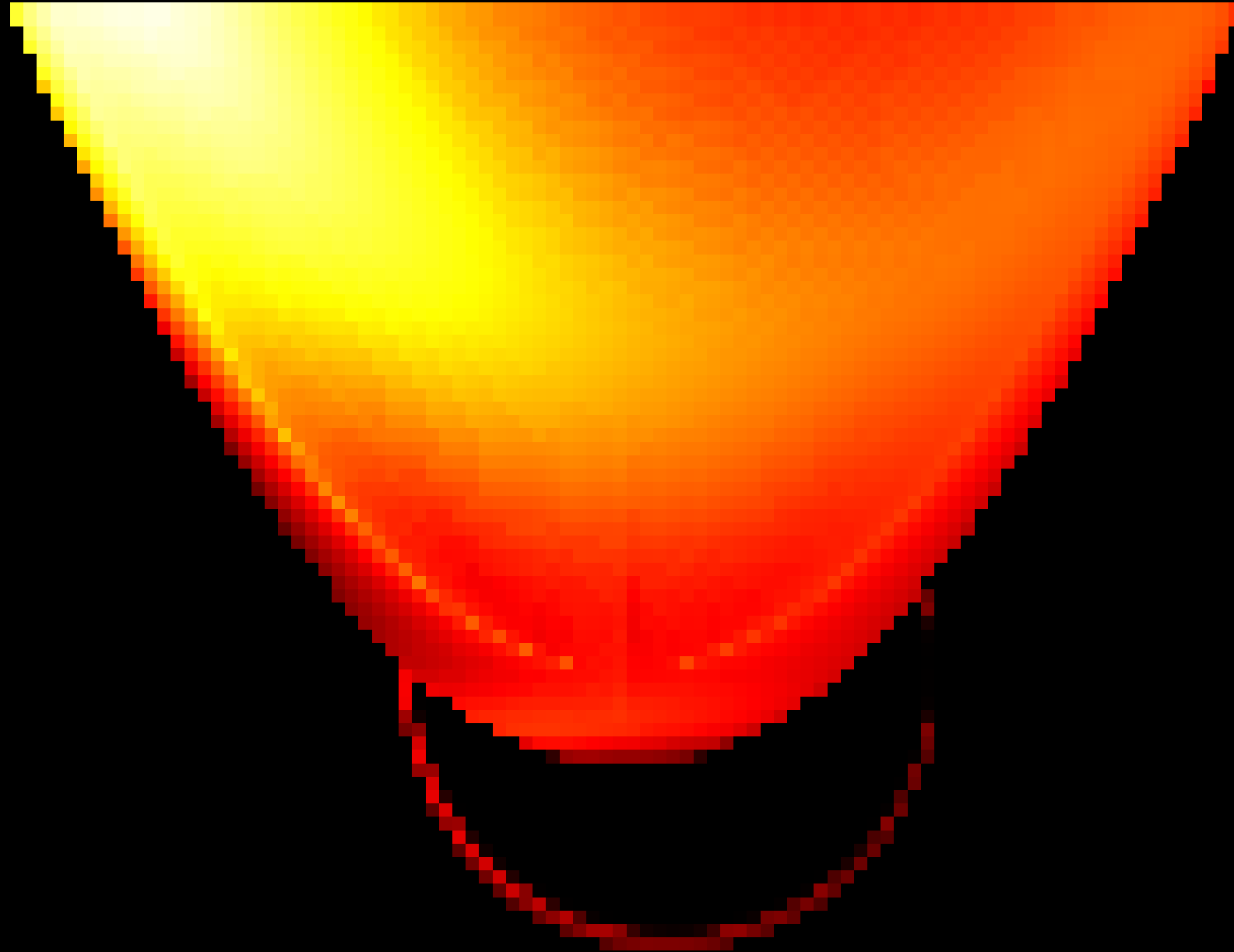
Semi-analytical GRMHD Jet Model and its Synchrotron Radiation Image on Horizon Scale



Hung-Yi Pu 卜宏毅 (ASIAA) &

Masanori Nakamura (ASIAA), Kouichi Hirotani (ASIAA), Ziri Younsi (ITP),
Yosuke Mizuno (ITP), Kinwah Wu (UCL), Keiichi Asada (ASIAA)

Feb. 8 EAYAM 2015

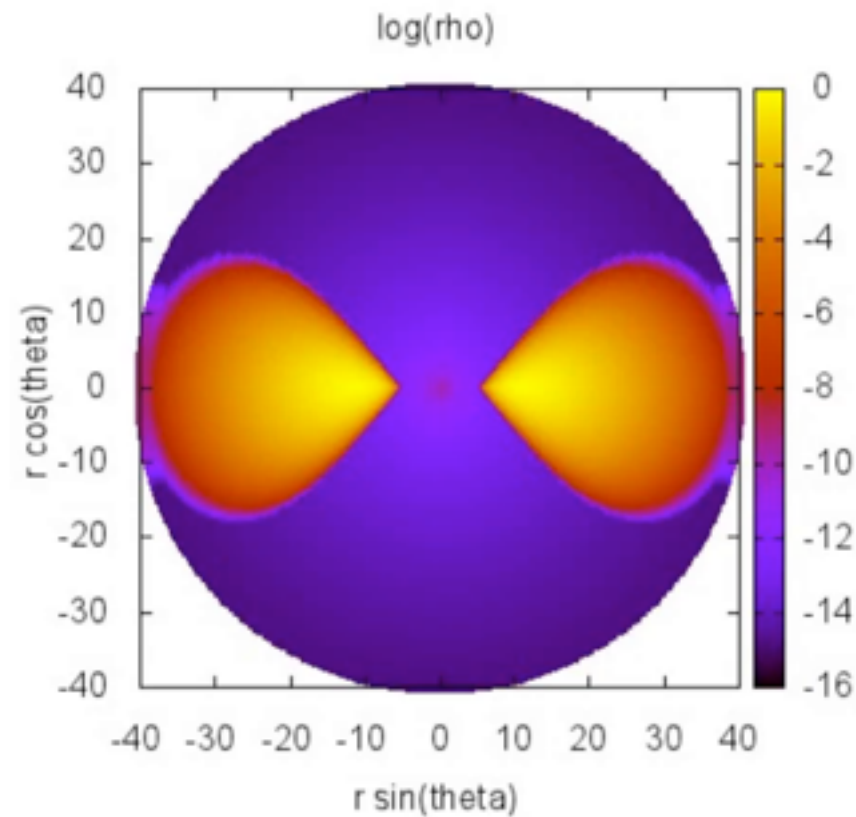


- why GRMHD ?

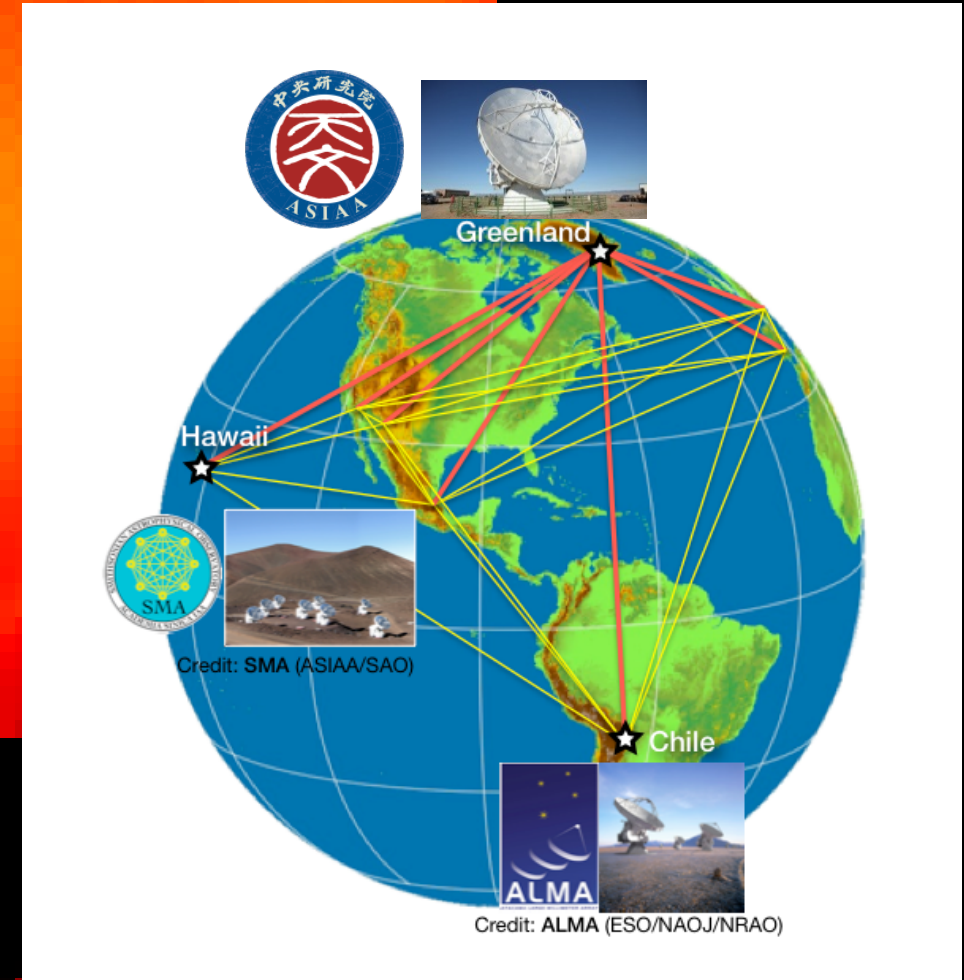
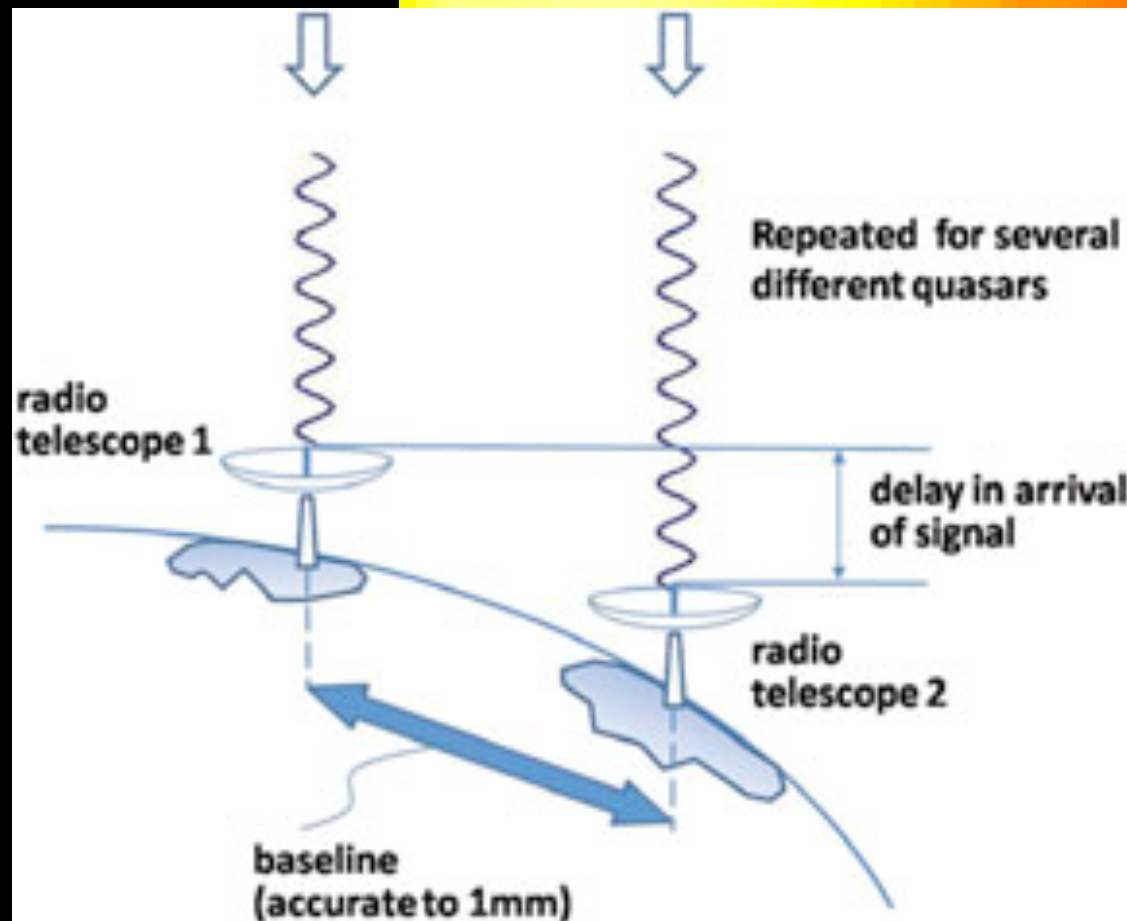
(general relativistic magnetohydrodynamics)

strong gravity + magnetic field + fluid

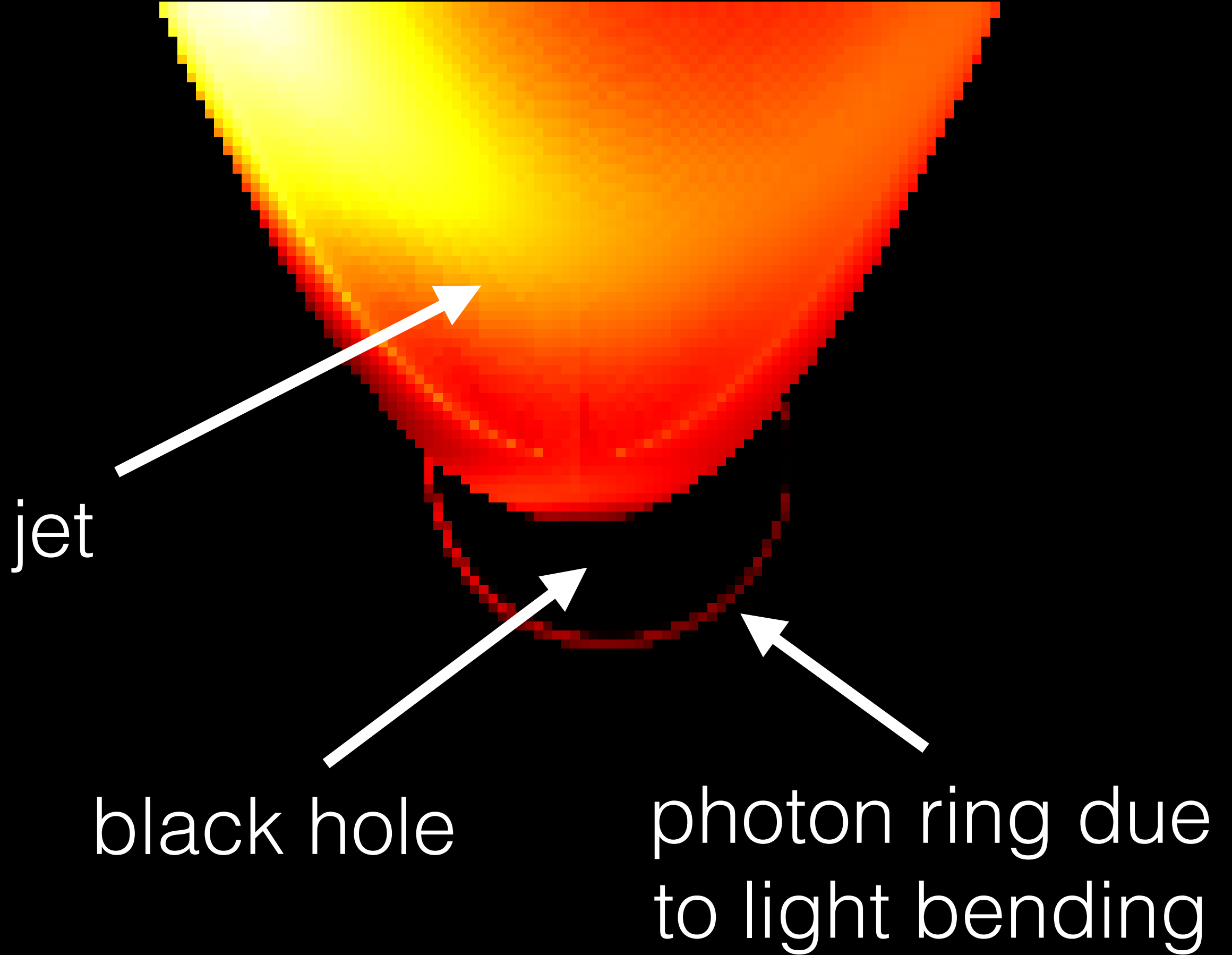
GRMHD simulation example



- why **semi-analytical** approach?
 - to provide a **complementary** understanding of the relativistic jets, compared to GRMHD **numerical simulations**

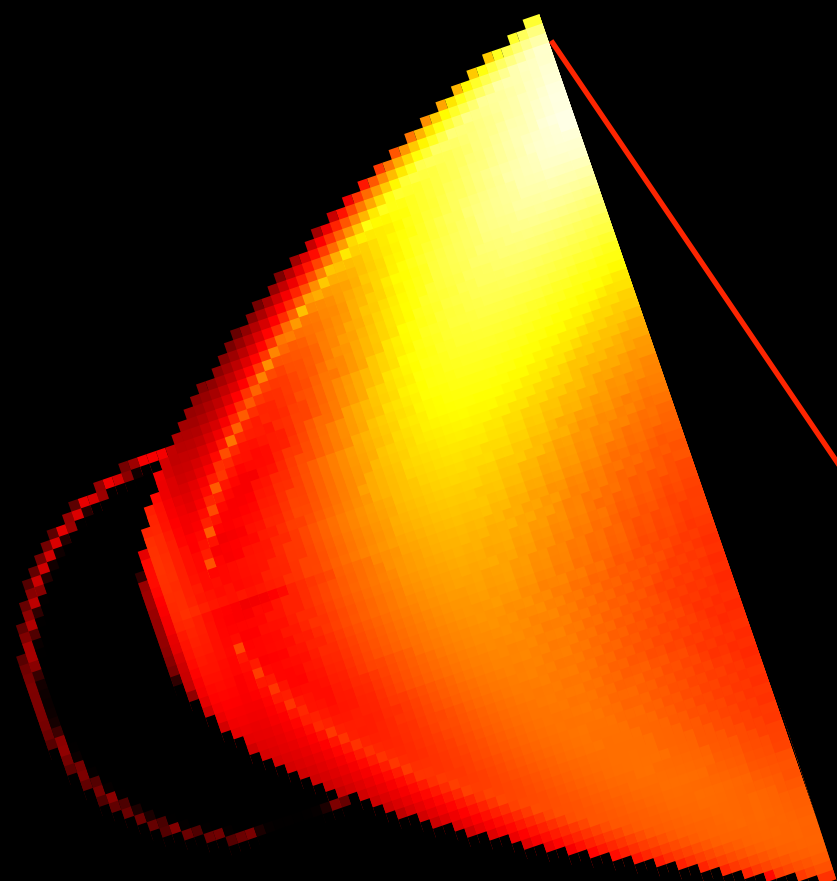


- why Radiation Image **on horizon scale?**
important for upcoming **sub-mm VLBI observation** (Very Long Baseline Interferometry) with micro-arcsec resolution

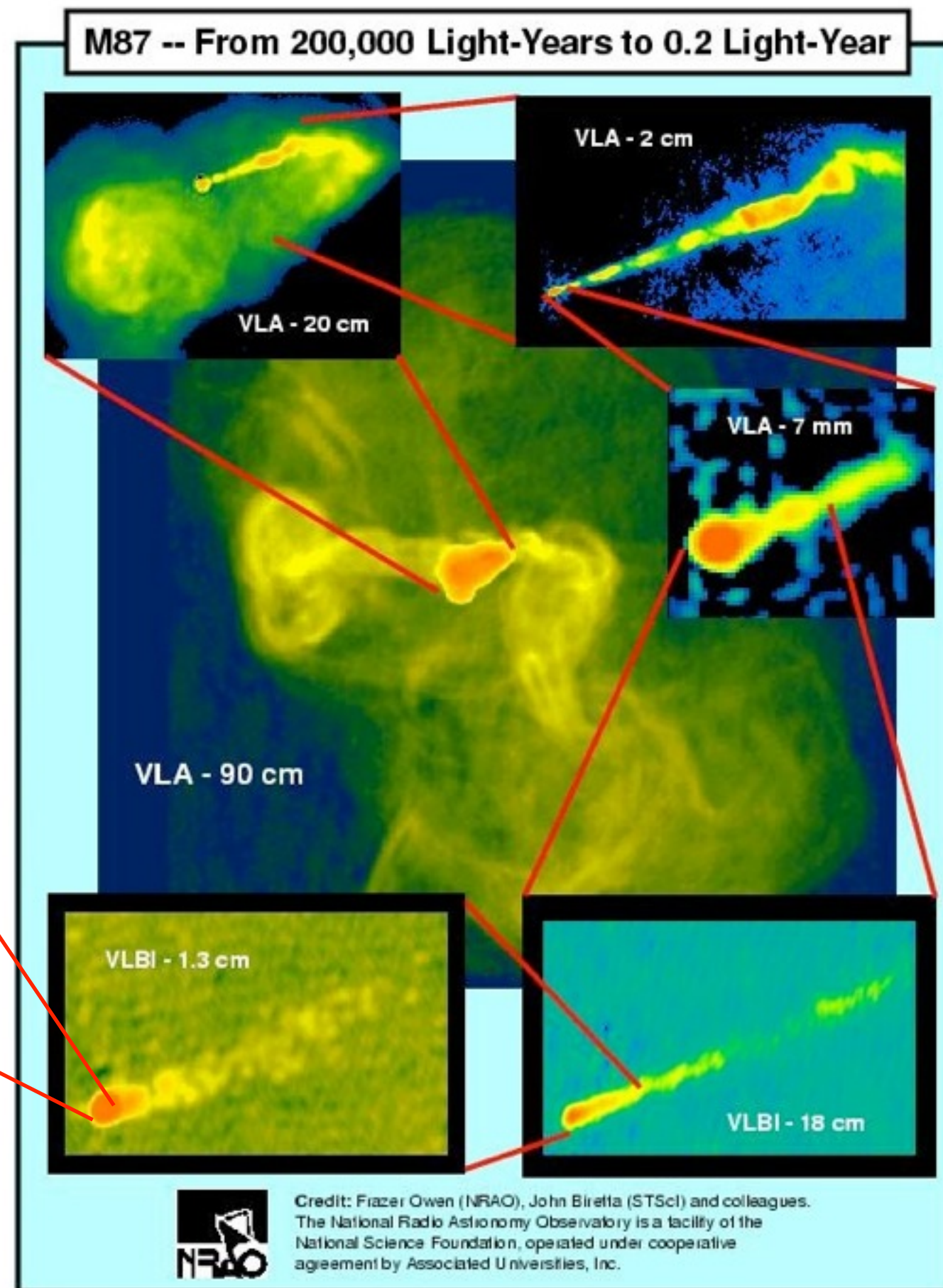


(theoretical computation; consider only jet component)

future sub-mm VLBI
observation
(micro-arcsec scale)!!



?

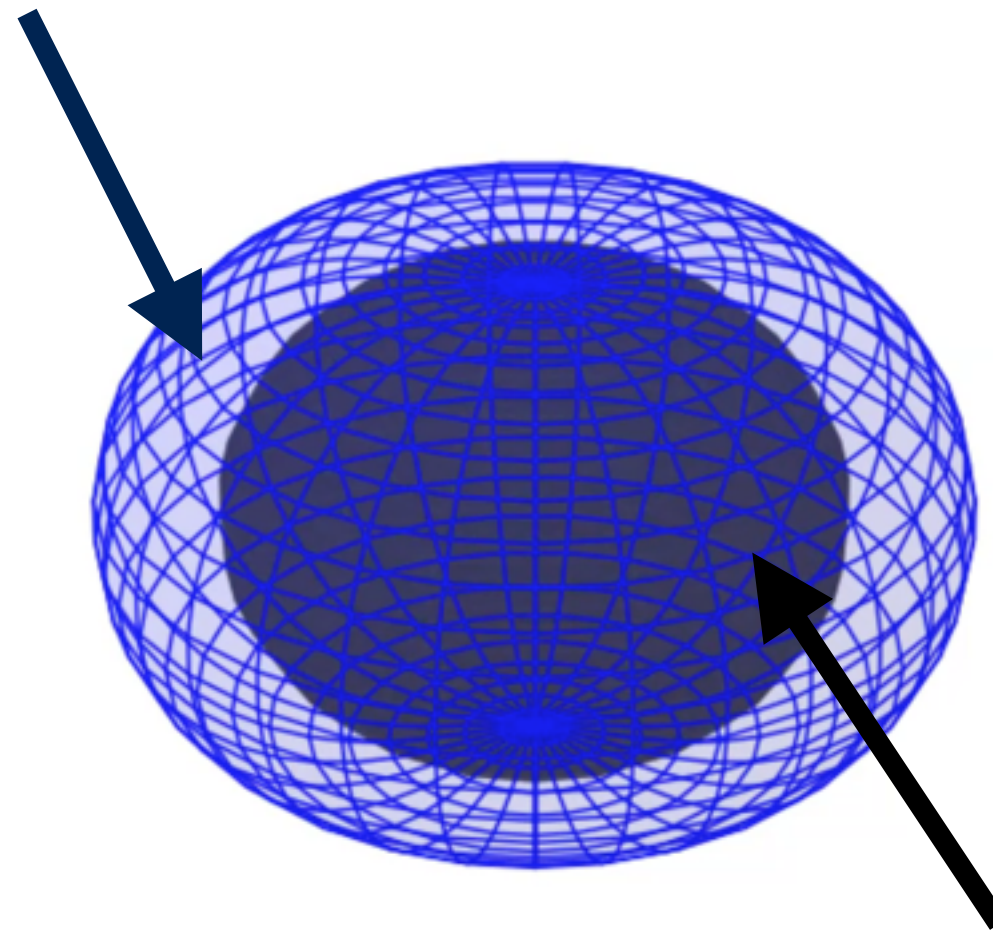


Outline

- GRMHD jet model
 - jet launching at the expense of black hole rotational energy
 - semi-analytical approach
- Synchrotron Radiation Image
 - ray-tracing and GR relativistic transfer
 - challenge
- Summary

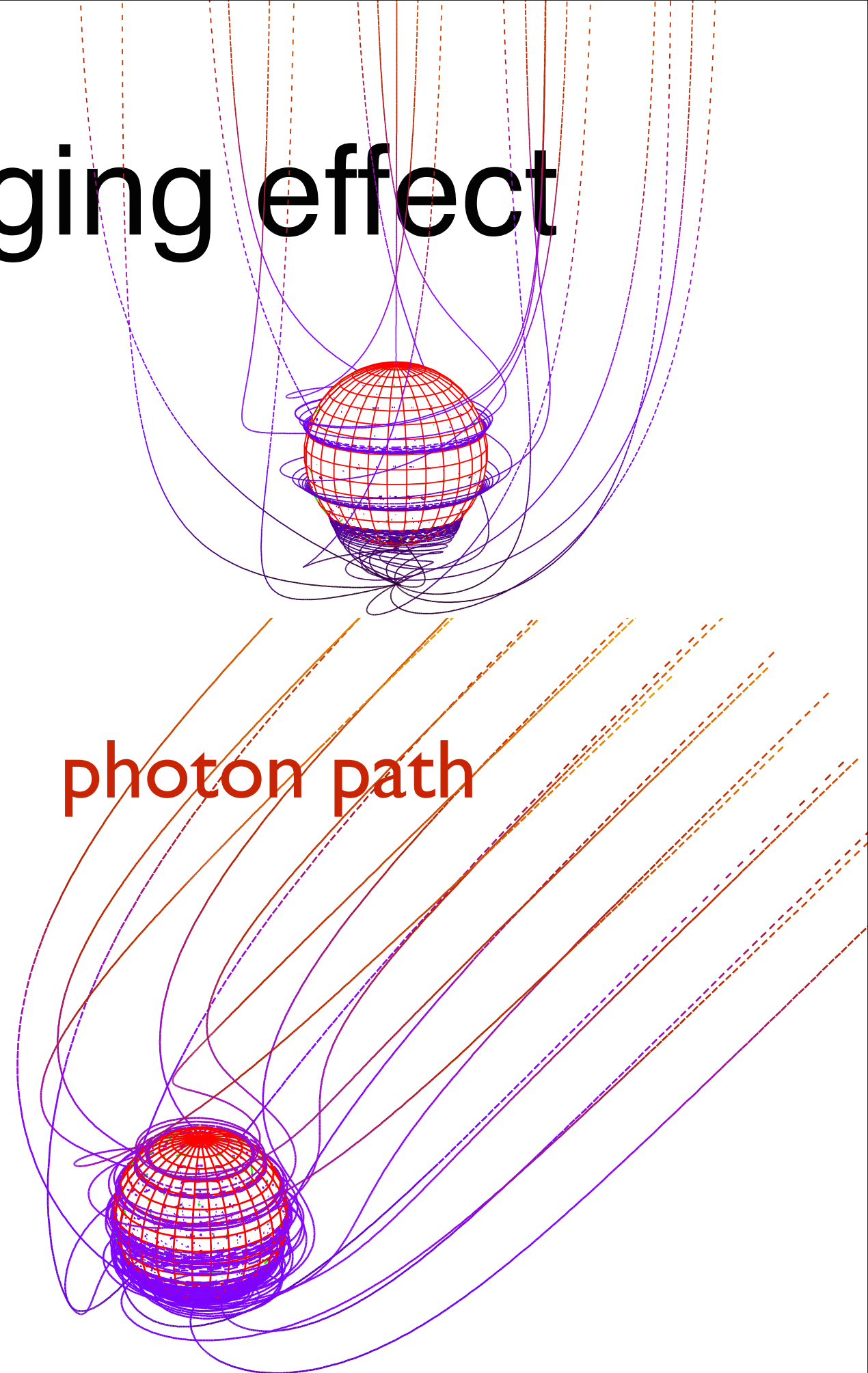
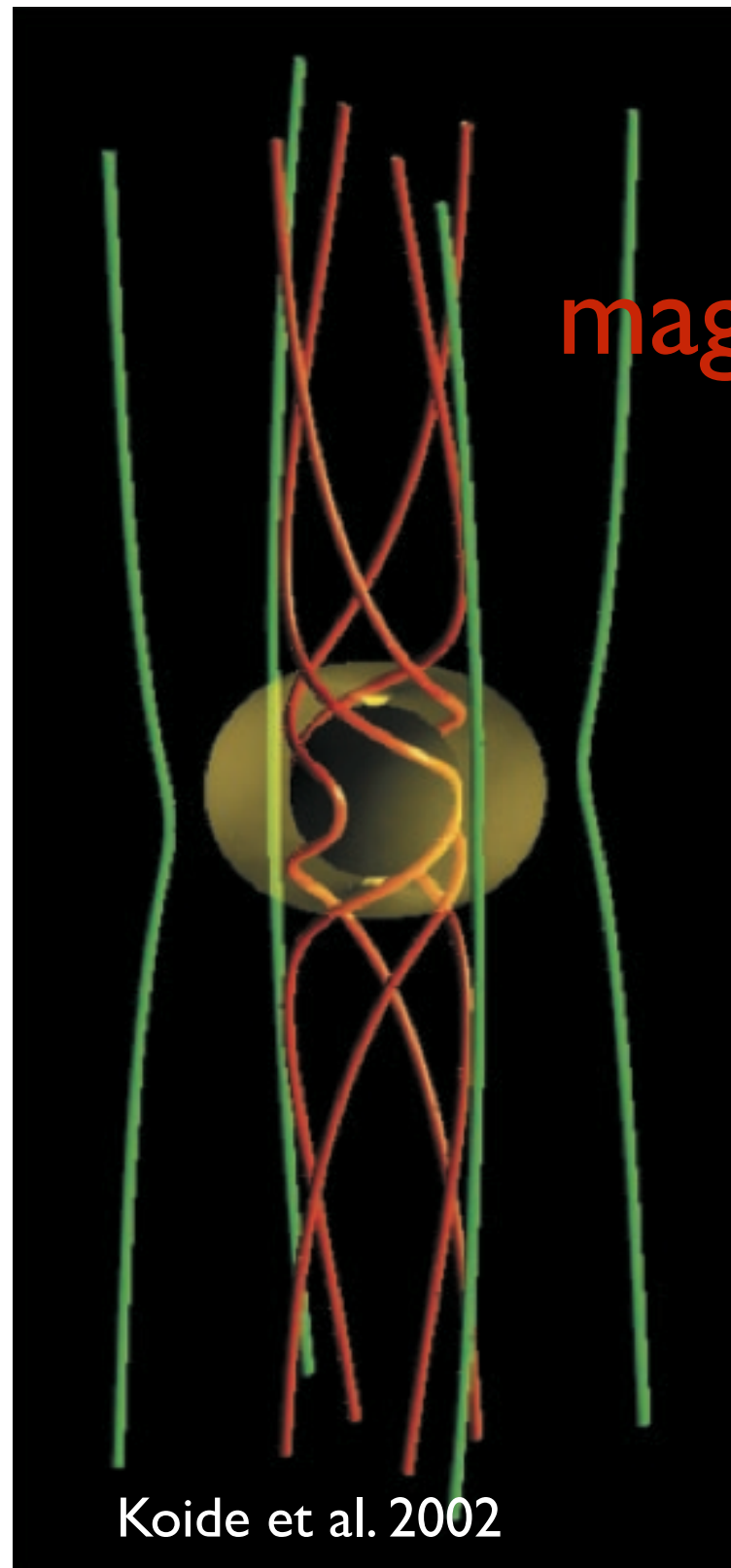
ergosphere

(the outer boundary is called “static limit”)



event horizon

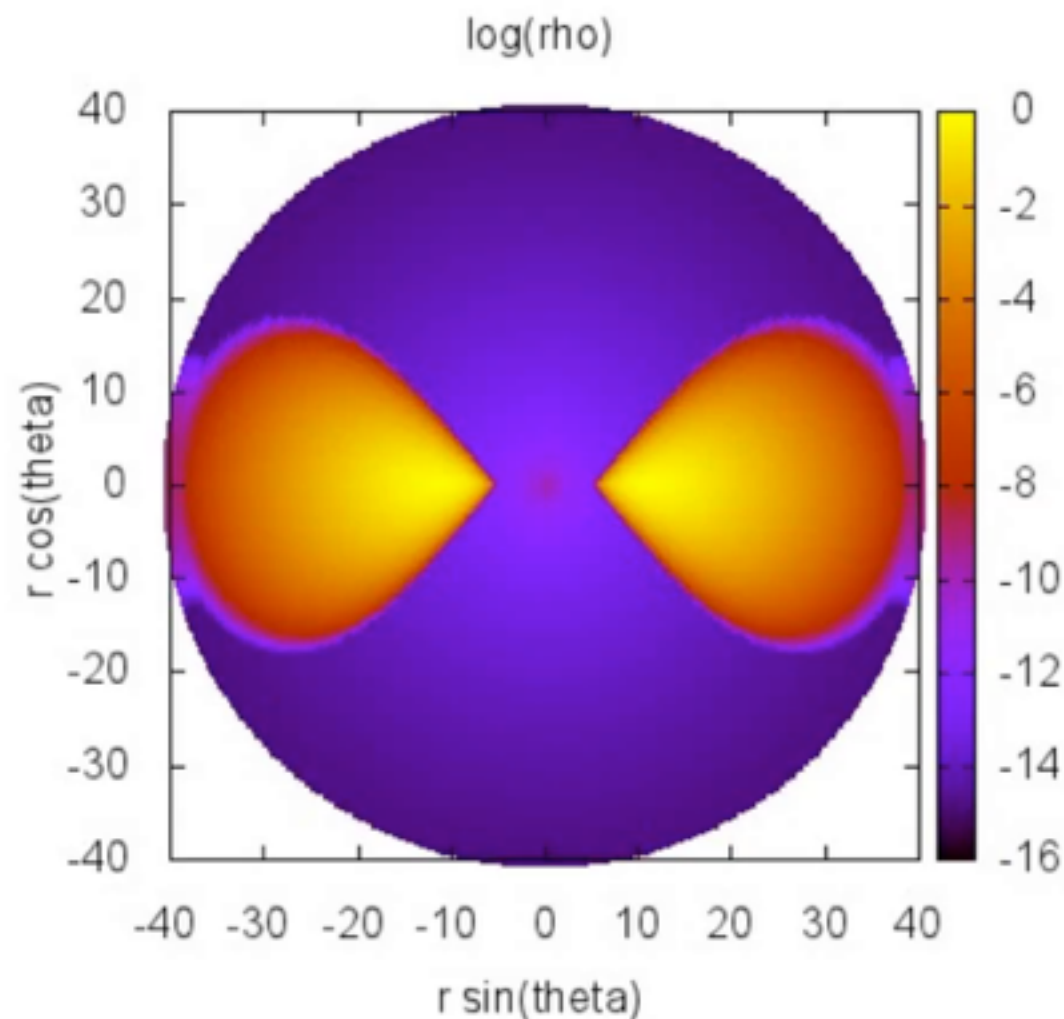
Frame Dragging effect



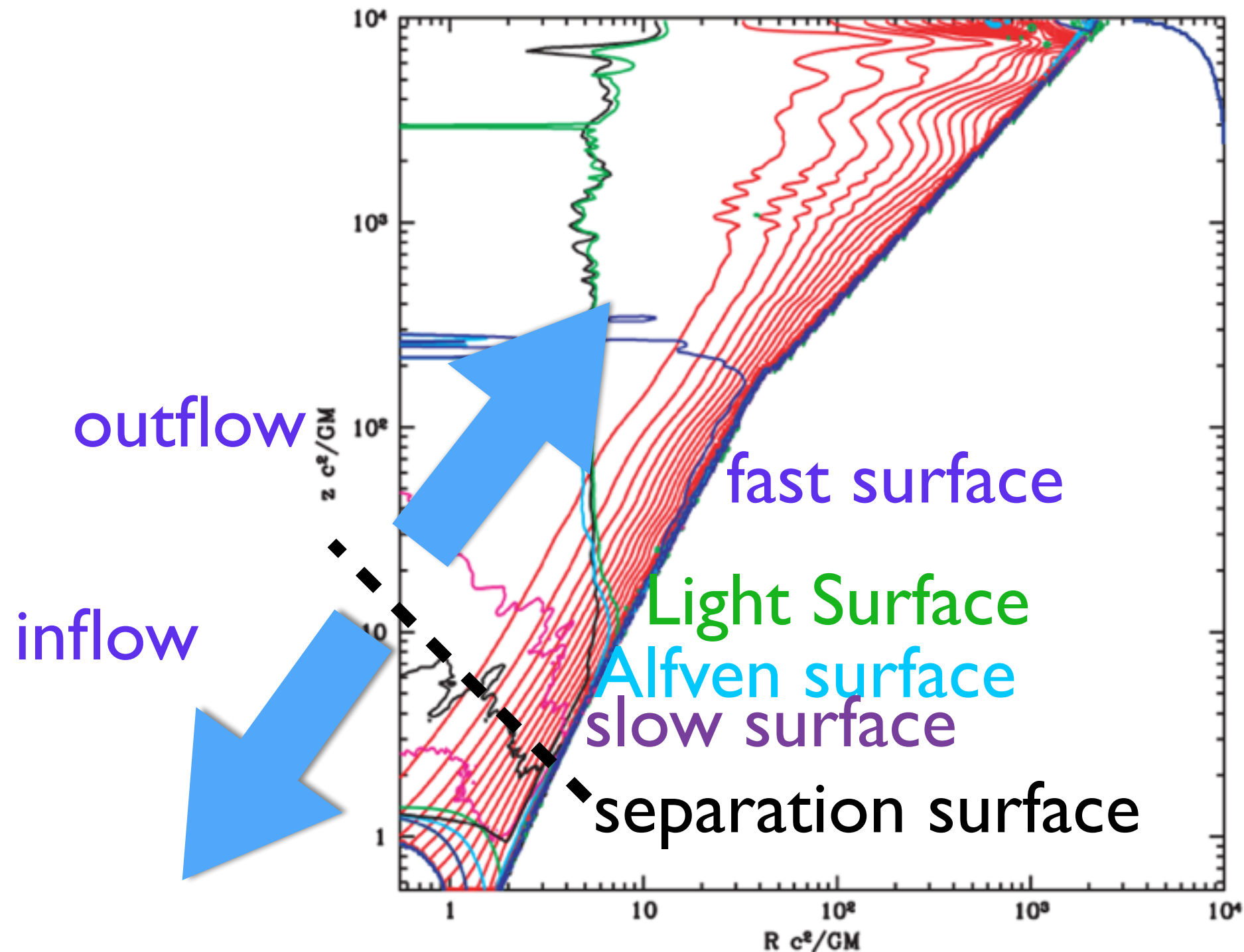
Extraction of Black hole Energy:

by large scale magnetic field (Blandford & Znajek 1977)
by GRMHD flow (Takahashi et al. 1990)

GRMHD simulation example

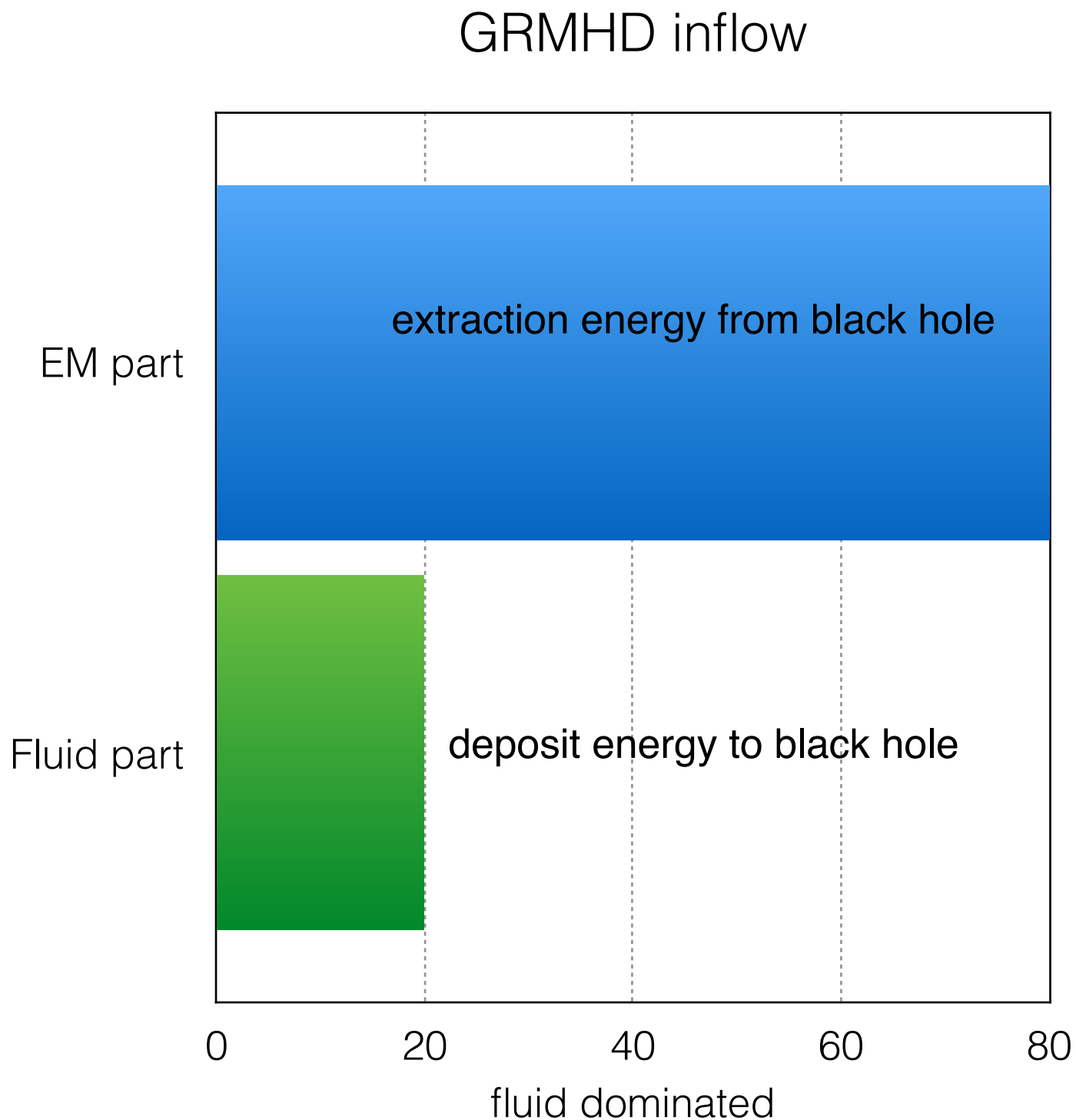


GRMHD flow structure



time-averaged GRMHD simulation result, McKinney 2006

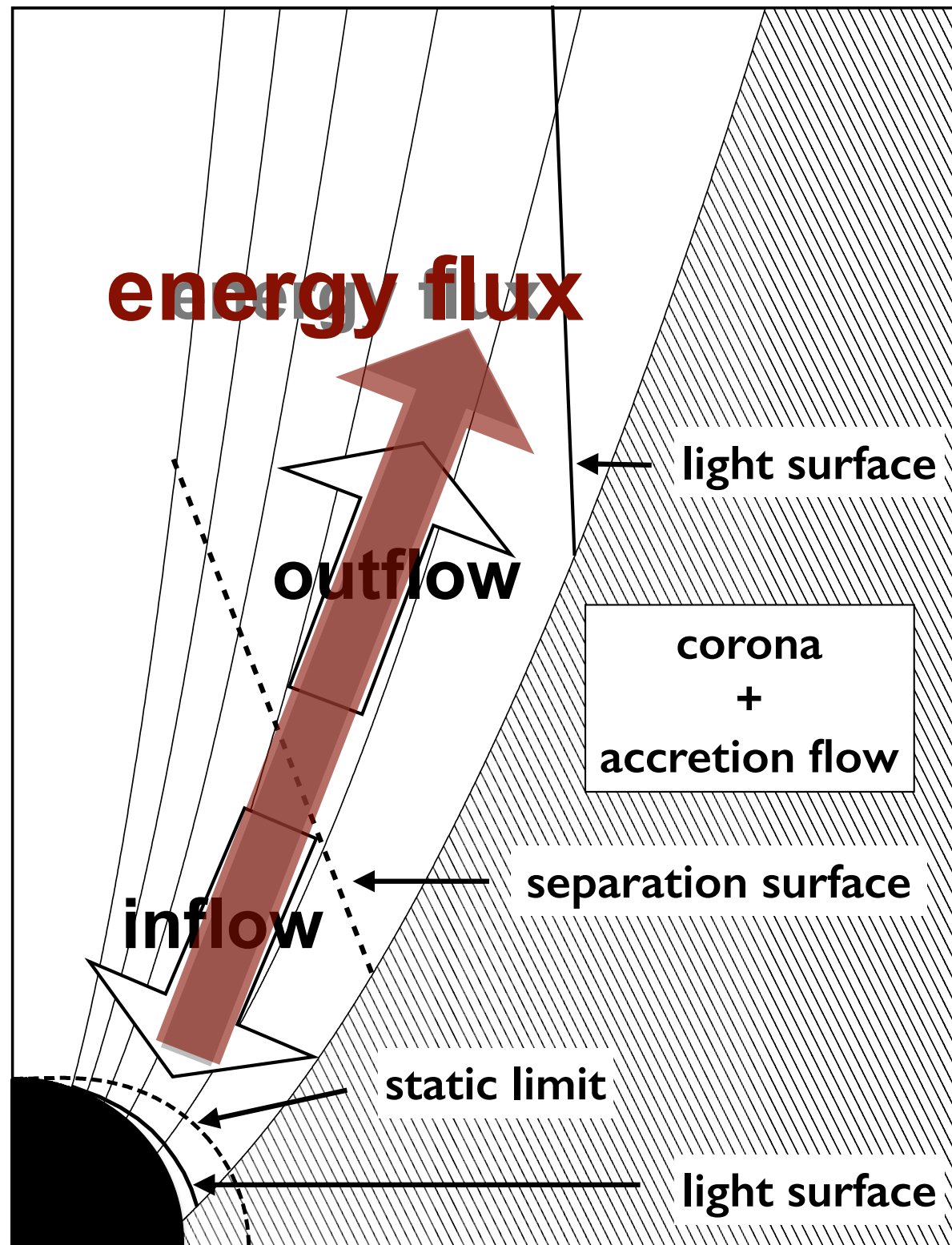
inflow



The black hole rotational energy is extracted outward when the flow become **magnetically dominated**

launching and quenching of relativistic jet can be related to the accretion state
(Pu et al. 2012, Globus & Levinson 2013)

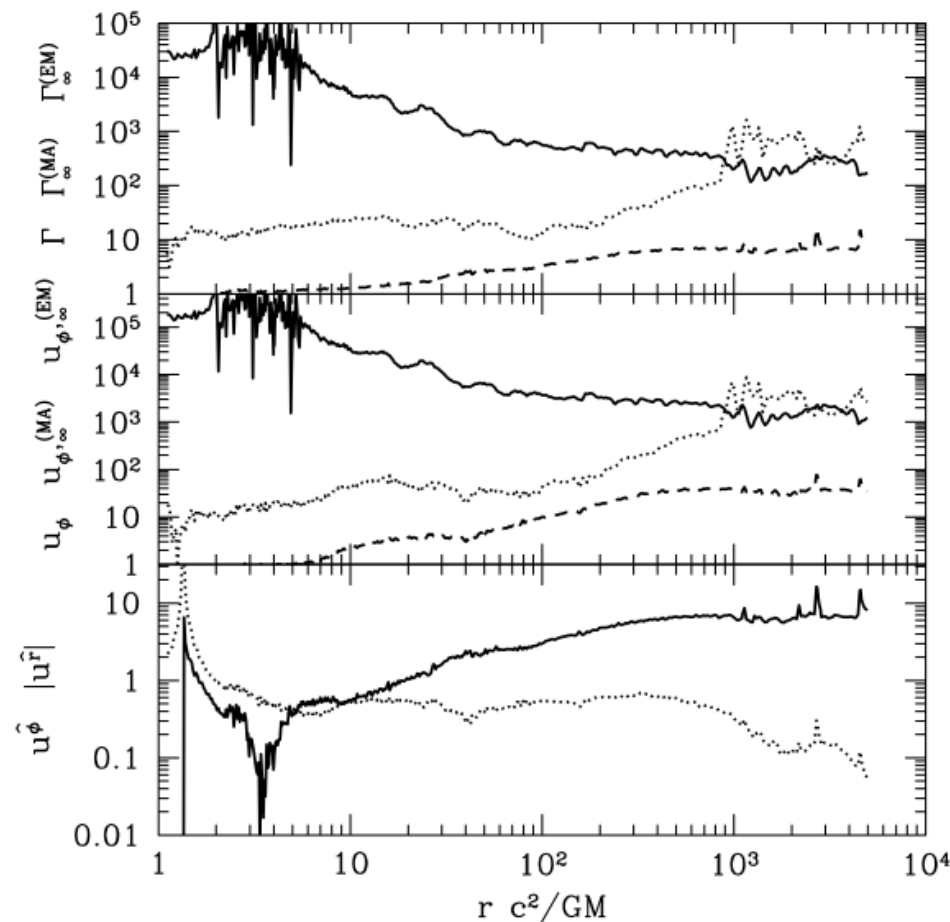
from inflow to outflow



- focus on **magnetically dominated case**
- the develop of the **outflow** is constraint by the **inflow**, assuming **Poynting energy flux is continuously propagate outward**

H.-Y. Pu et al. 2015 in press

semi-analytical jet model



Location of
characteristic
surfaces

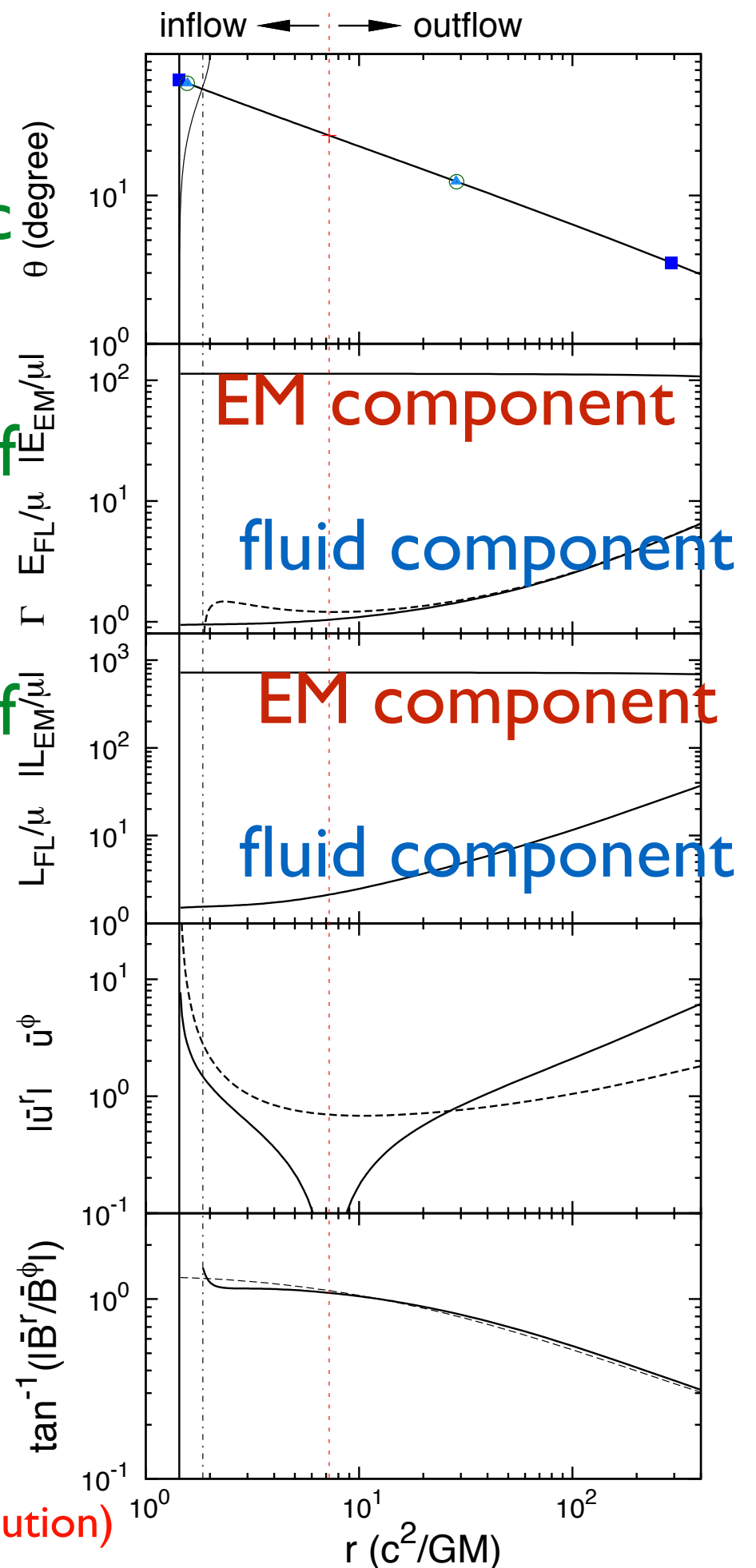
conversion of
energy

conversion of
angular
momentum

dynamical
structure

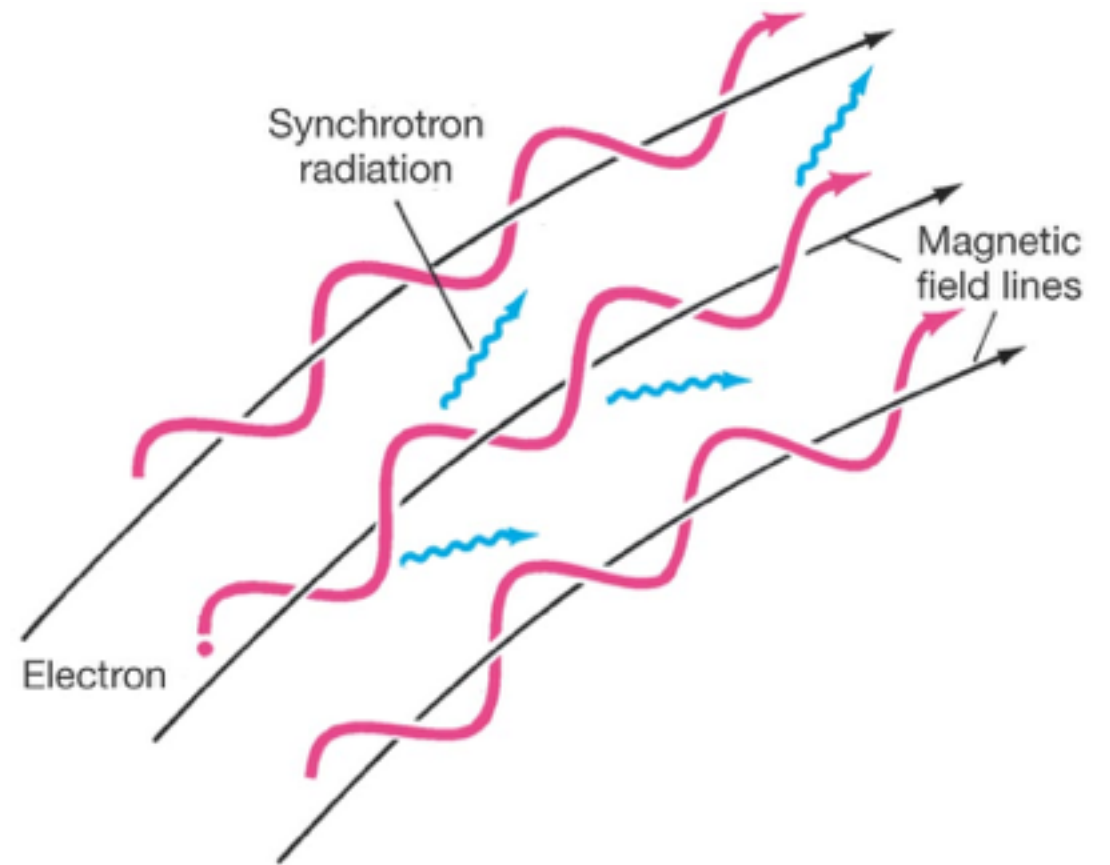
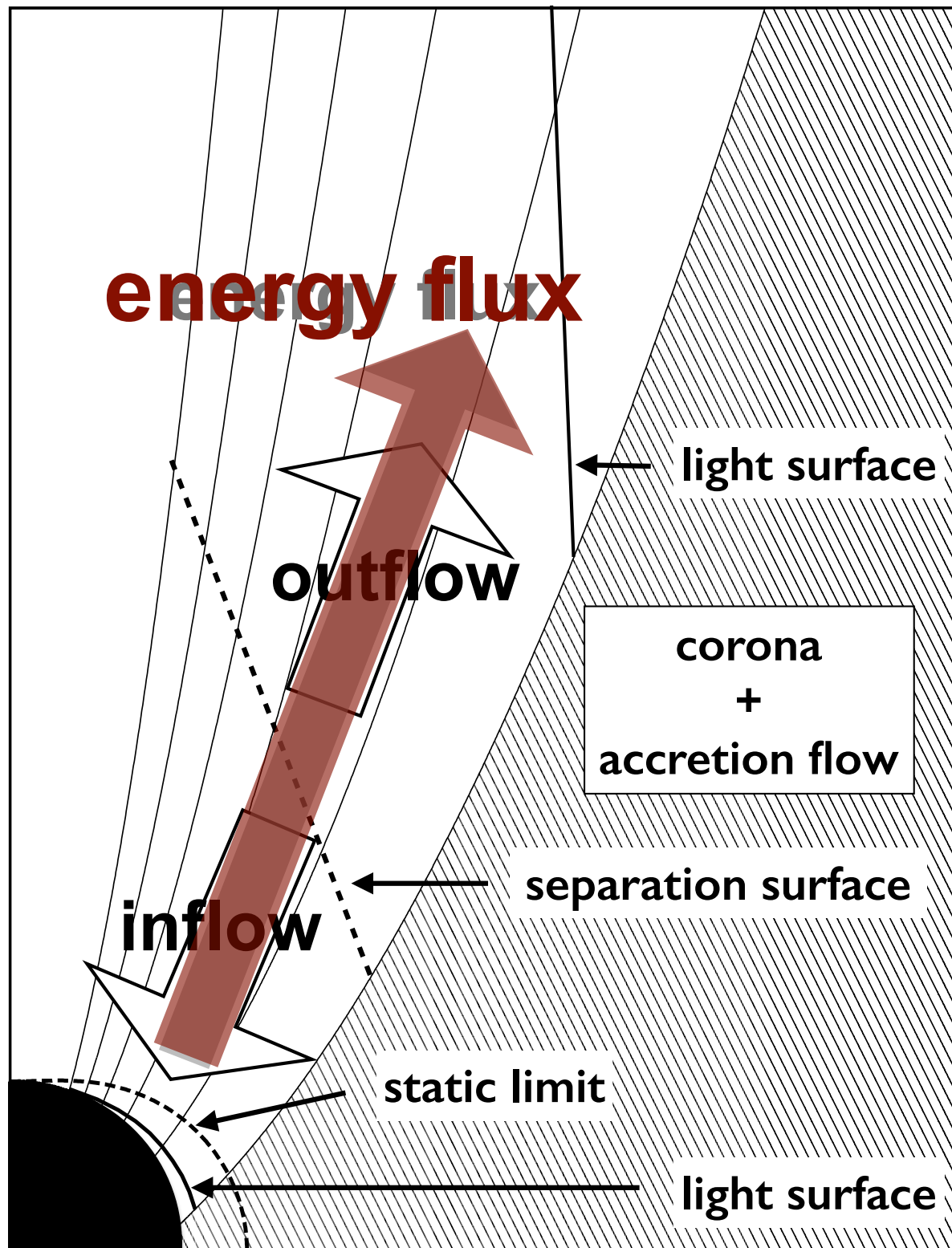
pitch angle

Pu et al. 2015 (semi-analytical solution)



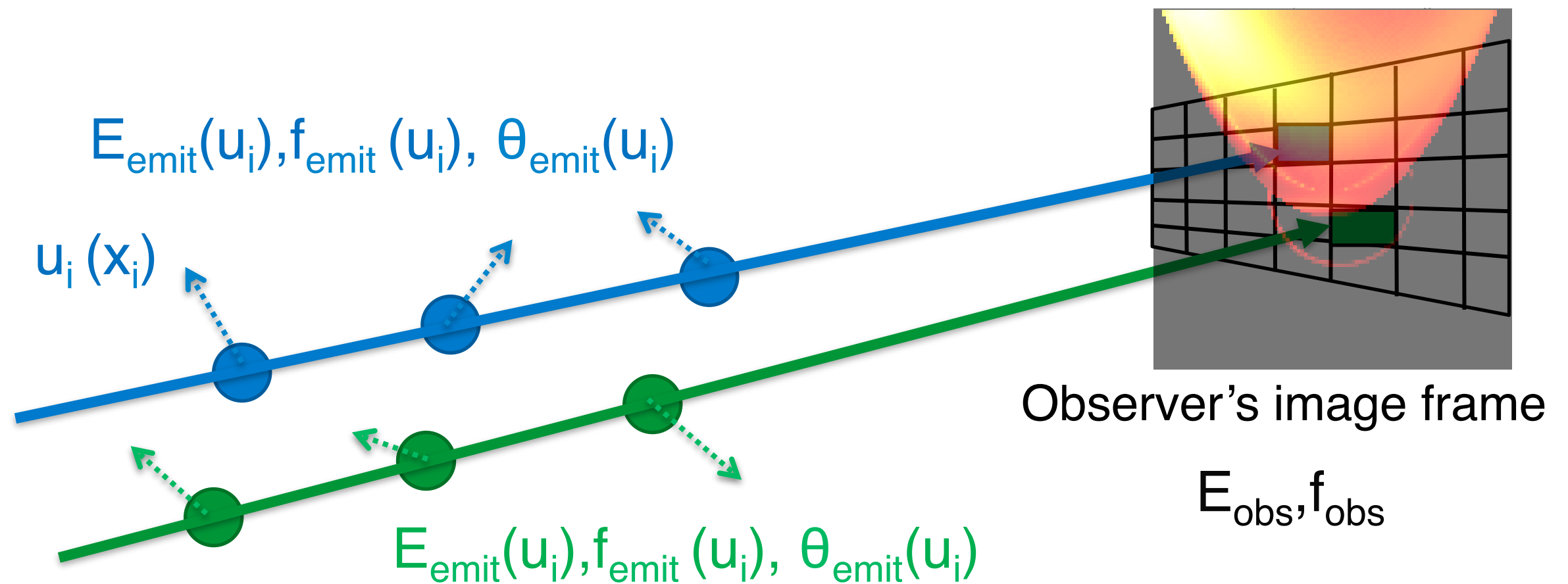
Radiation!

jet emission at **sub-mm** is mainly
contributed by
Synchrotron radiation



(a)

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley



- **ray tracing** (photon trajectory in curved spacetime)
- **dynamics/distribution of surrounding materials** (correction of energy/ frequency/ angle)
- **radiative transfer** (physical process take place locally)

Synchrotron emission

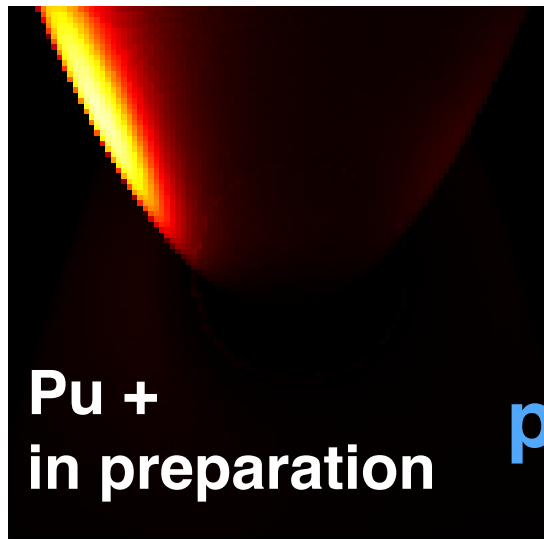
- **thermal** (relativistic Maxwellian) energy distribution of electrons
- function of
 1. **electron temperature**
 2. magnetic field
 3. electron number density
- **power-law** energy distribution of electrons
- function of:
 1. **energy cut off**
 2. **power-law index**
 3. magnetic field
 4. electron number

significant uncertainties!

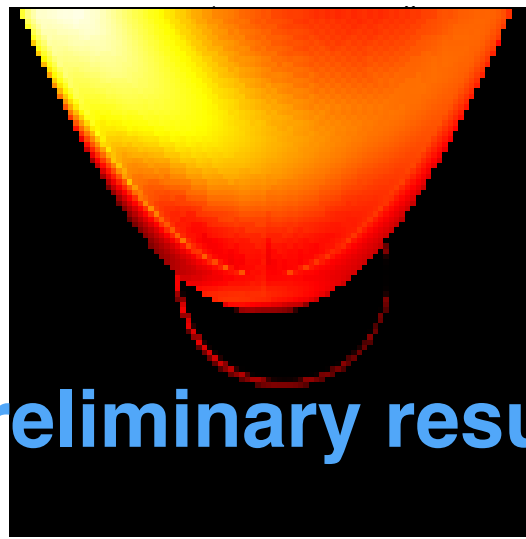
Zoology of Jet Images

- semi-analytical GRMHD jet model

- **thermal** synchrotron (disk+jet)
- isothermal jet
- post processing of GRMHD simulation results

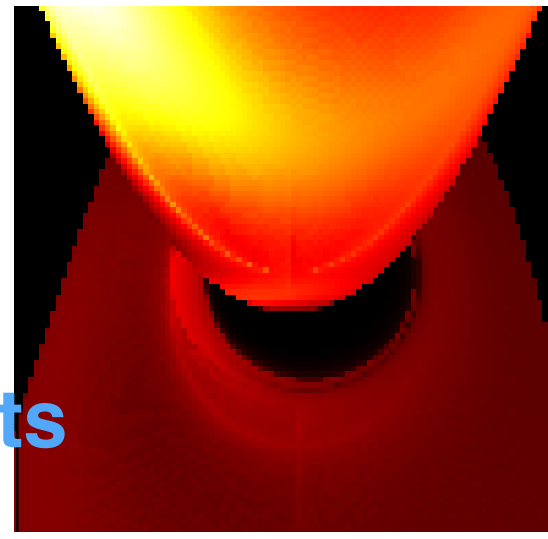


- **non-thermal** synchrotron

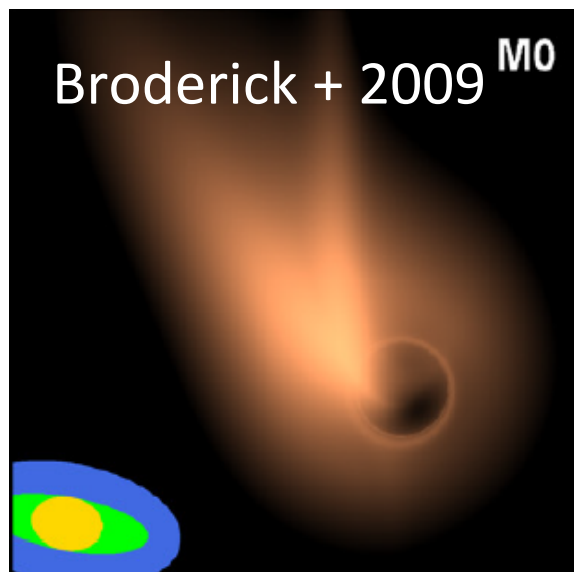
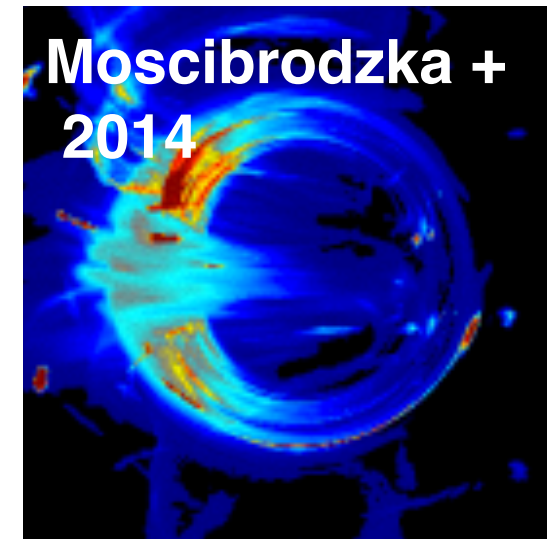


preliminary results

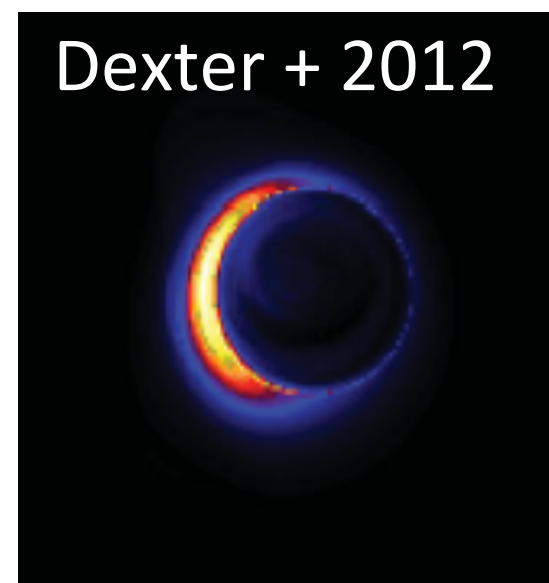
- **thermal** synchrotron
- isothermal jet



- **thermal** synchrotron
- isothermal jet + “counter jet”



- **thermal** + **non-thermal** synchrotron (disk)
- **non-thermal** synchrotron (jet)
- semi-analytical force-free jet model



- **thermal** synchrotron (disk)
- **non-thermal** synchrotron (jet)
- post processing of GRMHD simulation results

even more challenge...

- time-dependent feature
(need to consider light-crossing time)
- evolution of electron energy distribution
- non equal-partition between the field and non-thermal electrons
- pair-production?

example of time-dependent ray tracing
(by Yun and Pu)



Summary

- GRMHD jet model
 - due to frame-dragging effect, jet can be powered by the rotating black hole
 - semi-analytical approach provide a complementary understanding of the relativistic jets, compared to GRMHD numerical simulations (e.x. free from numerical dissipation)
- Synchrotron Radiation Image
 - important for upcoming sub-mm VLBI observation will reach micro-arcsec resolution
 - very challenge! (uncertain electron properties)