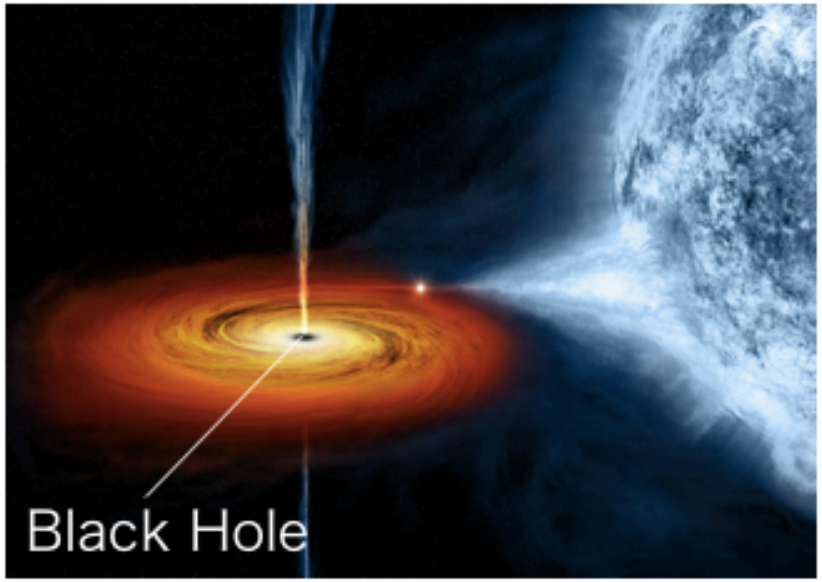
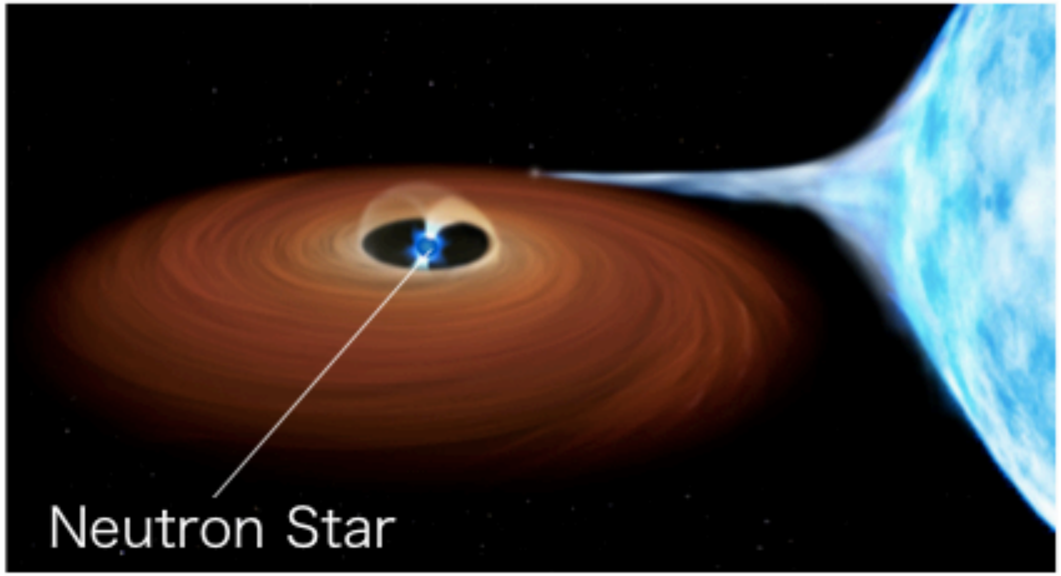
Theory of ULXs;

Numerical Simulation of super-Eddington accretion onto black holes and neutron stars





Ken OHSUGA (NAOJ)

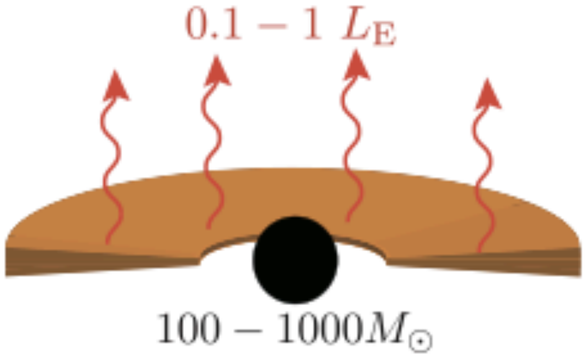
H.R.Takahashi, T.Kawashima (NAOJ), S.Mineshige, T.Ogawa (Kyoto Univ.)

Engine of ULX ?

IMBH + sub-Eddington disk

If the IMBHs exist, sub-Eddington disk can explain the huge luminosity of ULXs;

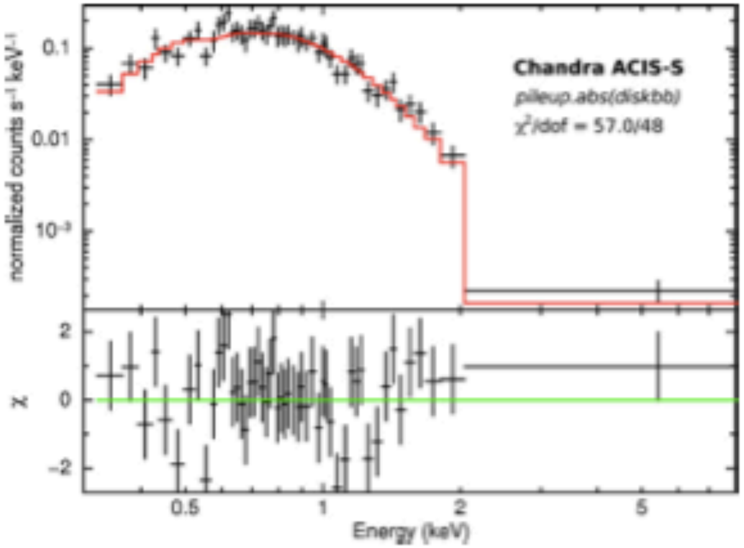
$0.1L_{Edd}(10^{3}$Msun$)$~10^{40}erg/s.



Makishima et al. 00, Miller et al. 04, Farrell et al. 09, Servillat et al. 11, etc.
also Kabayashi's Talk

ESO 243-49 HLX-1 (Farrell et al. 09)

- >500Msun?, >9000Msun?
- Lx ~ 10^{42}erg/s
- Cool disk; 0.2keV

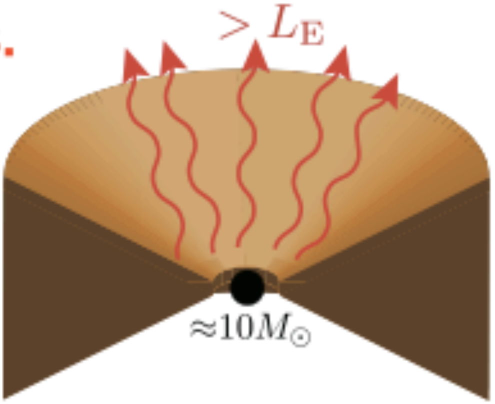


Servillat et al. 11

Engine of ULX ?

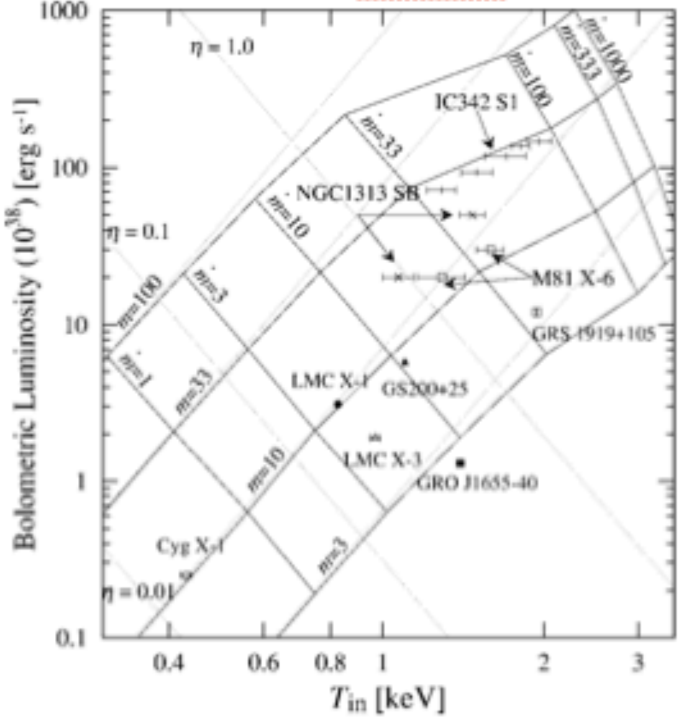
Super-Eddington Disk

Even if the BH mass is around 10Msun, super-Eddington disks can reproduce the huge luminosity; **10L$_{\mathrm{Edd}}$(10Msun) ~10^{40}erg/s.**



King 04, 08; Ohsuga et al. 05, 09, 11, Gladstone et al. 09; Middleton et al. 11, Sadowski 13, 15, Takahashi et al. 16

Watarai et al. 01

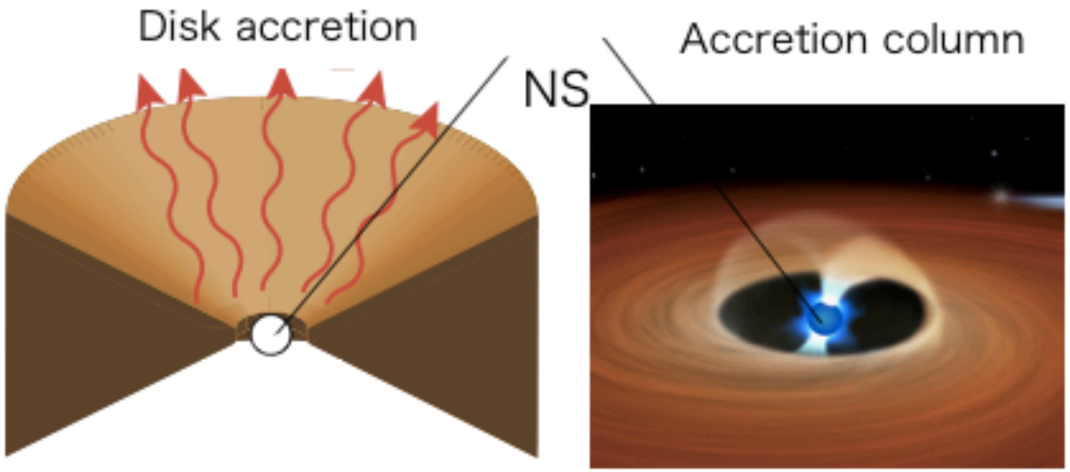


In L-Tin diagram, IC342 S1 evolve according to the slim disks model.

Engine of ULX ?

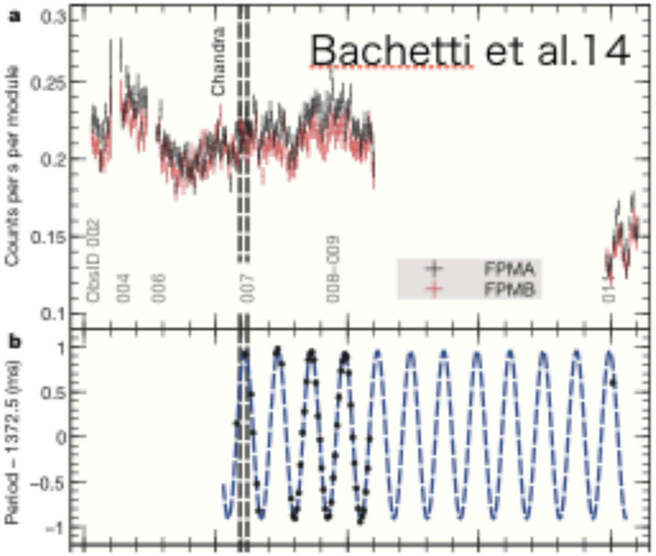
NS + Super-Eddington flow

If the central objects of ULXs are NSs, super-Eddington is necessary because the mass of NSs is a few Msun.



Basko & Sunyaev 76; Ohsuga 07; King & Lasota 16; Kawashima et al. 16; Takahashi & Ohsuga submitted

also Israel's Talk, Pottschmidt's Talk, Suleimanov's Talk

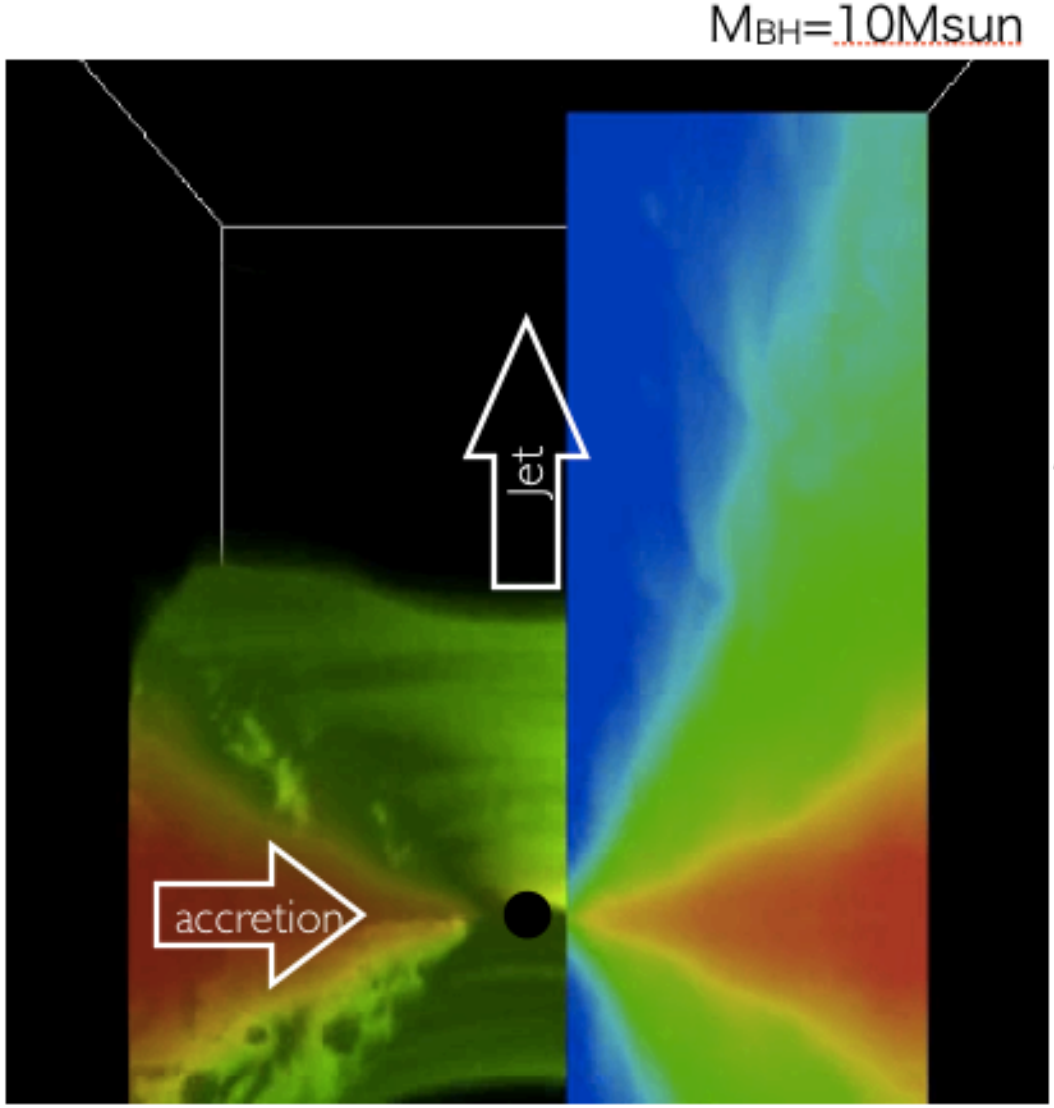

Bachetti et al.14

M82 X-2 (ULX pulsar); Engine is super-Eddington accretion onto NS.

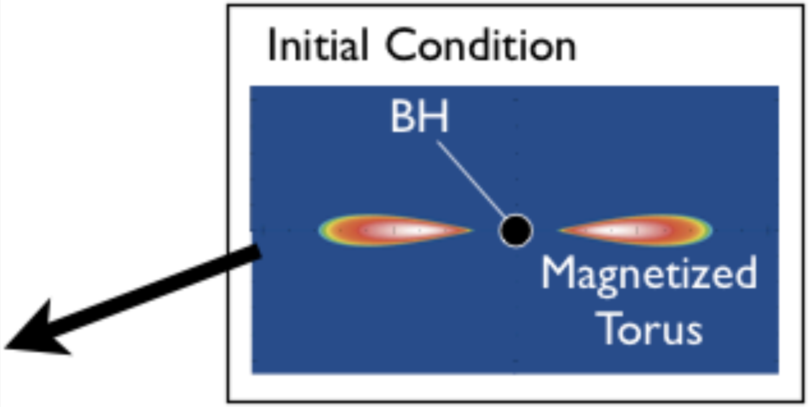
Today’s plan

- We introduce Radiation-MHD simulations of super-Eddington accretion flows around BHs.
- We compare with our results and observations of ULXs.
- We show our simulations of super-Eddington flows around NSs (accretion column/disk accretion).

Super-Eddington flow around BH



$L_{bol} \gtrsim L_{edd}$, $Mdot \sim 60\ L_{edd}/c^2$

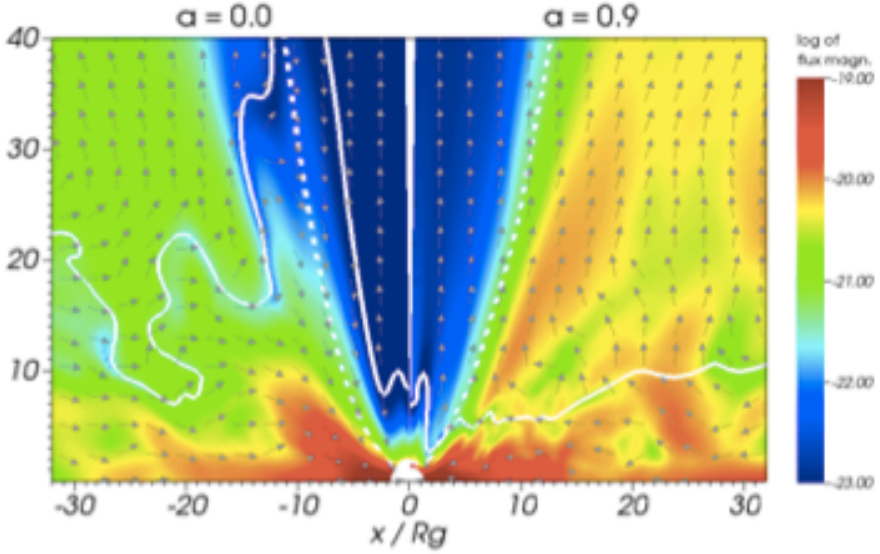


Ohsuga et al. 2009
Ohsuga & Mineshige 2011
see also Ohsuga et al. 2005

Radiation-pressure supported disk + radiatively-driven jet (~0.3c)

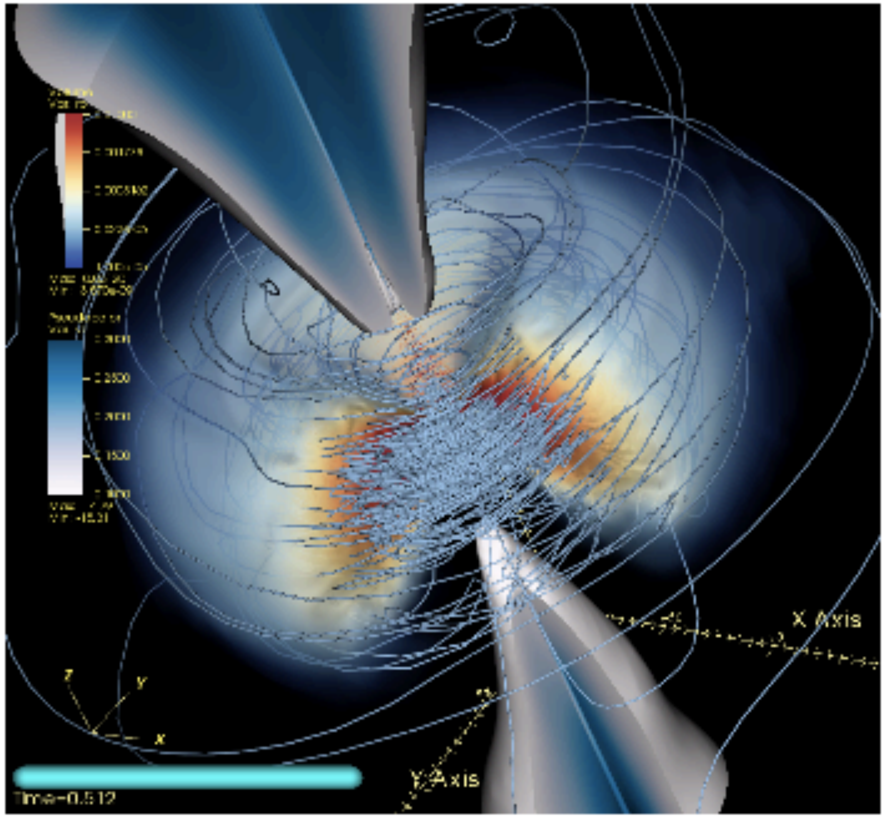
Other Simulations of Super-Eddington Disks

Sadowski et al. 2013

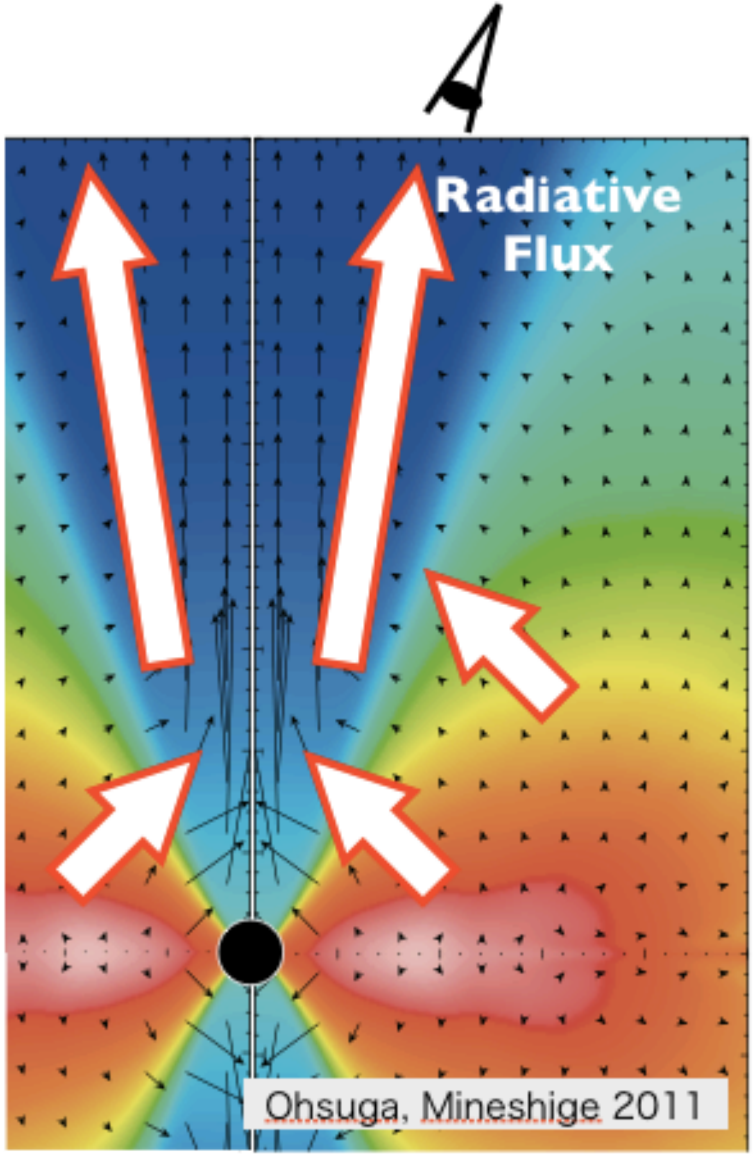


Super-Eddington disks around BHs are reconfirmed (see also Sadowski+ 14, 15; Mckinny+ 13; Jiang+ 14, etc.)

Takahashi & Ohsuga 2016



Large Luminosity



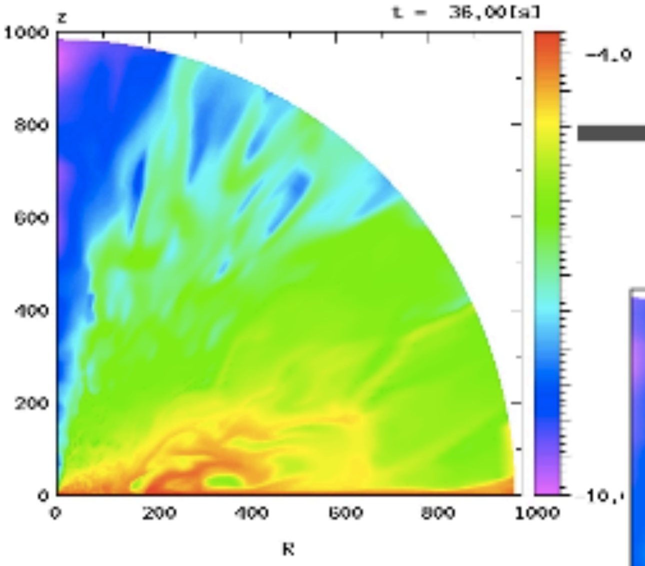
Ohsuga, Mineshige 2011

The radiative flux is mildly collimated since the disk is optically and geometrically thick.

Thus, observed luminosity is much larger than the Eddington luminosity except for the edge-on view (e.g., **$22L_{Edd}$** for ≲20° in the case of Mdot~$100L_{Edd}/c^2$, L_{disk}~$3L_{Edd}$).

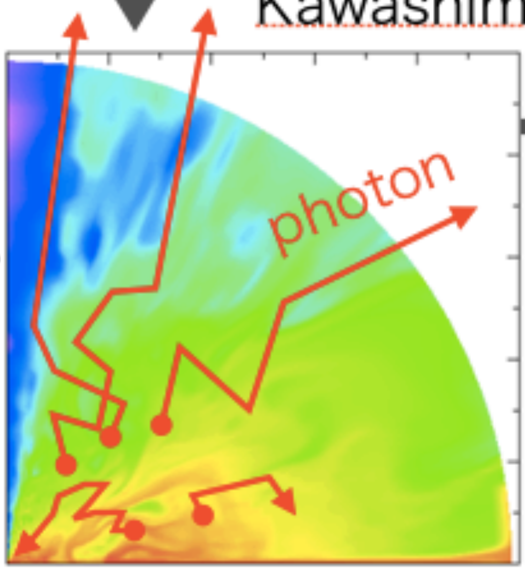
Super-Eddington flows can explain the large X-ray luminosity of ULXs.

ULX spectra

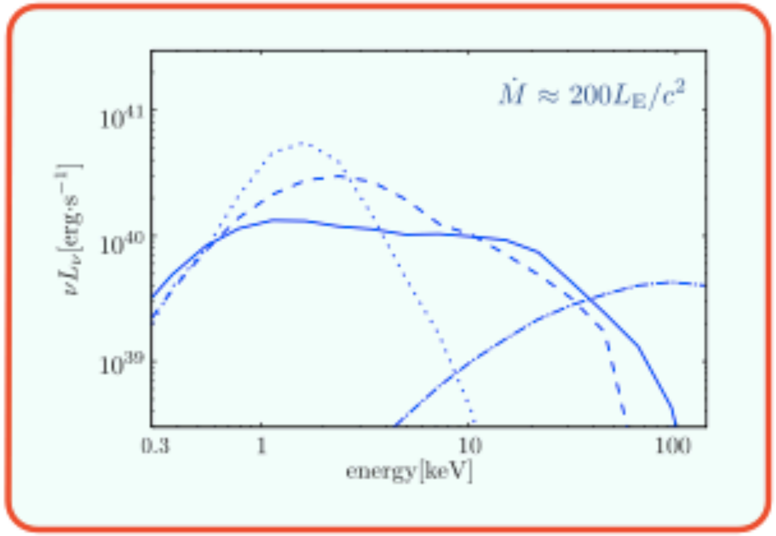


Step1;
RHD simulation
Ohsuga et al. 2005,
ApJ, 628, 368

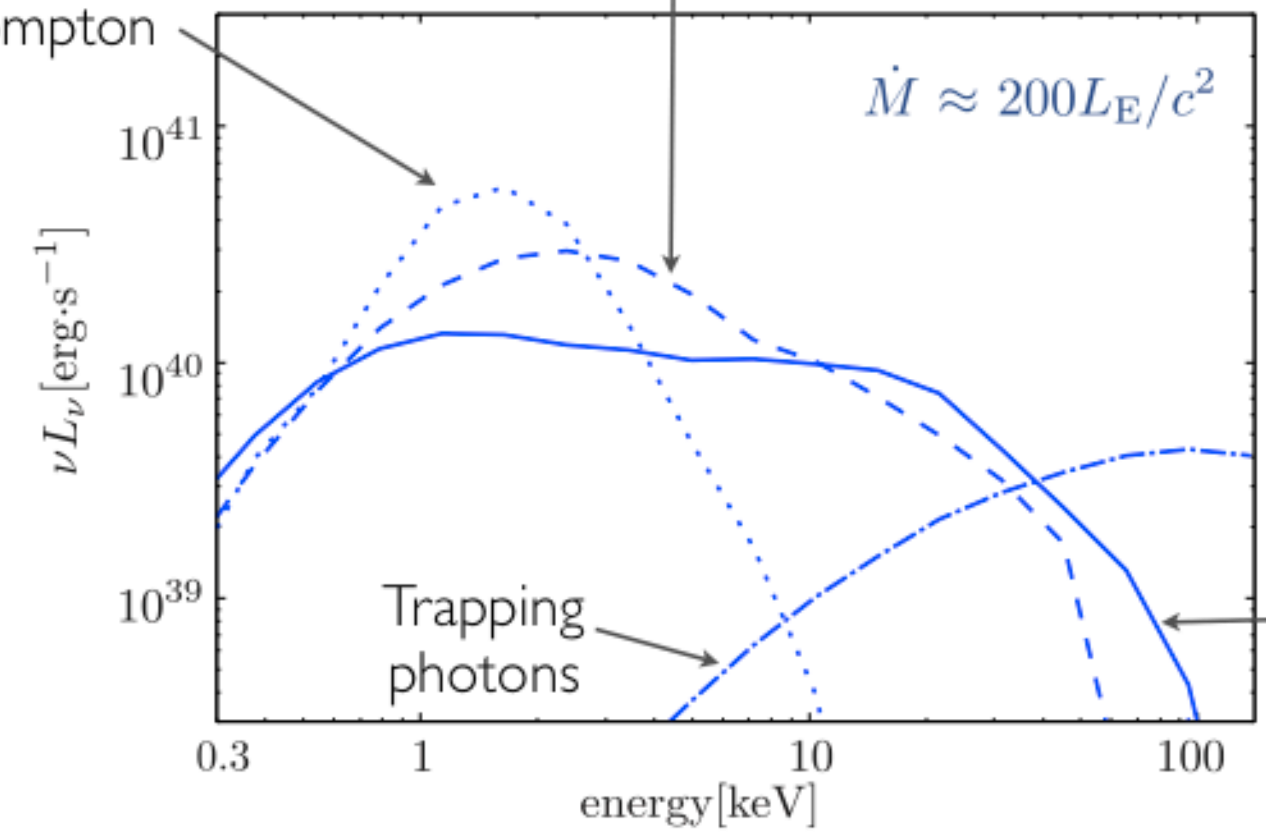
Step2; Monte Carlo Radiation transfer
(fee-free, thermal & bulk compton)
Kawashima, Ohsuga et al. 2012



SED



Thermal & Bulk Compton

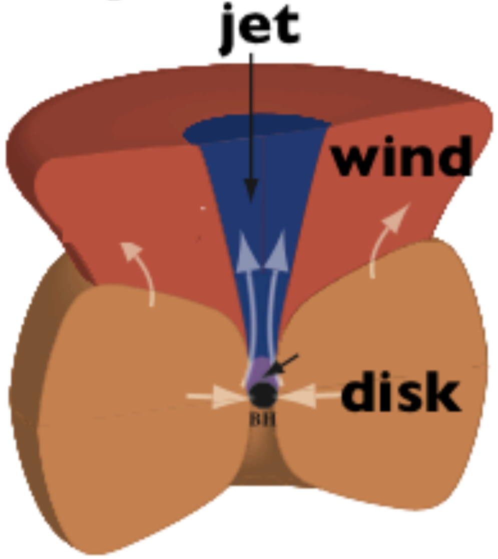


Without Compton

With only thermal Compton

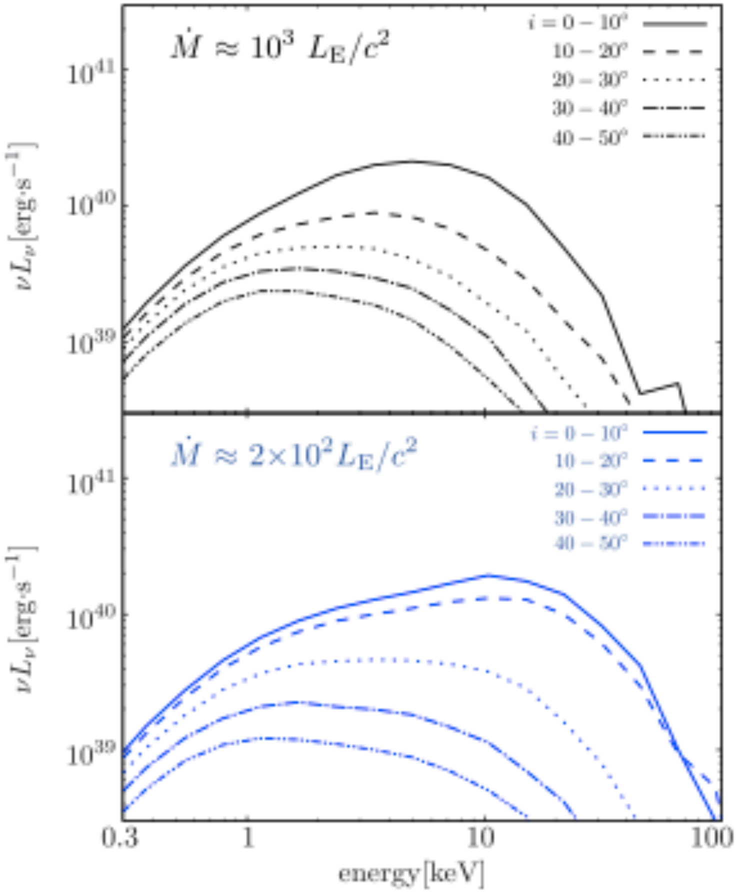
Trapping photons

Thermal & Bulk Compton



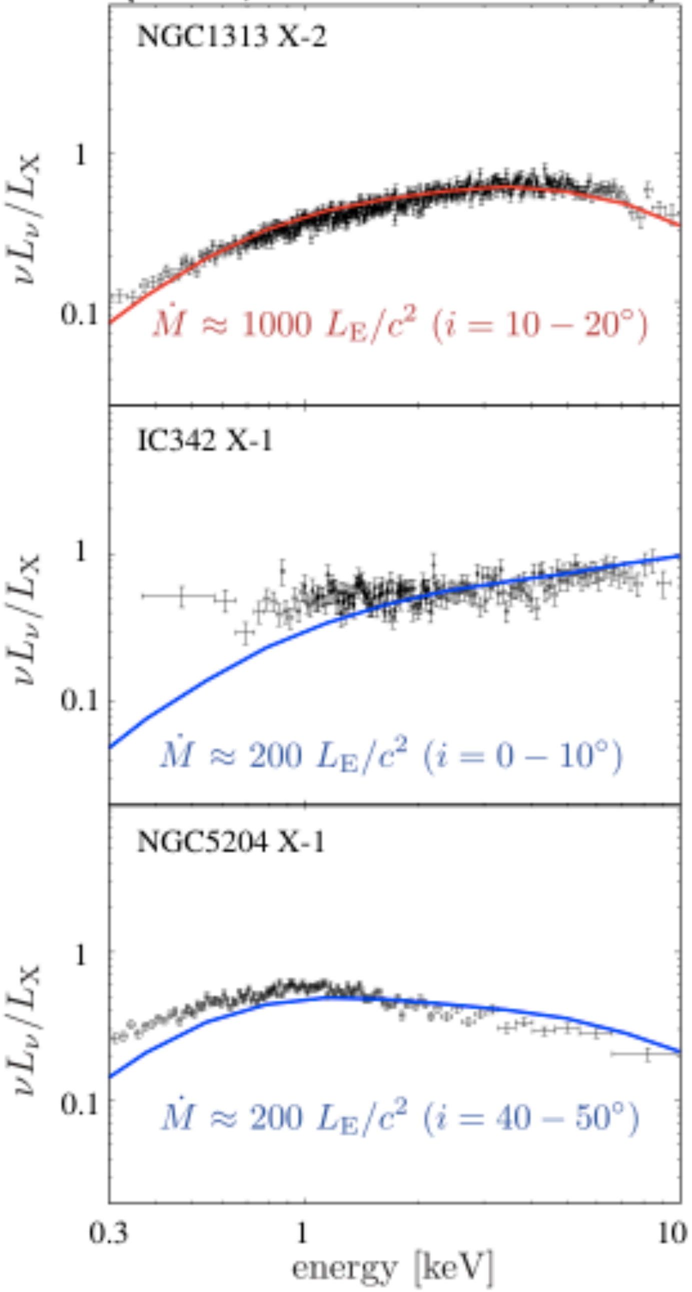
Spectra become harder by not only thermal comptonization but also bulk comptonization.

Emergent spectra are sensitive to the Mdot and inclination angle.



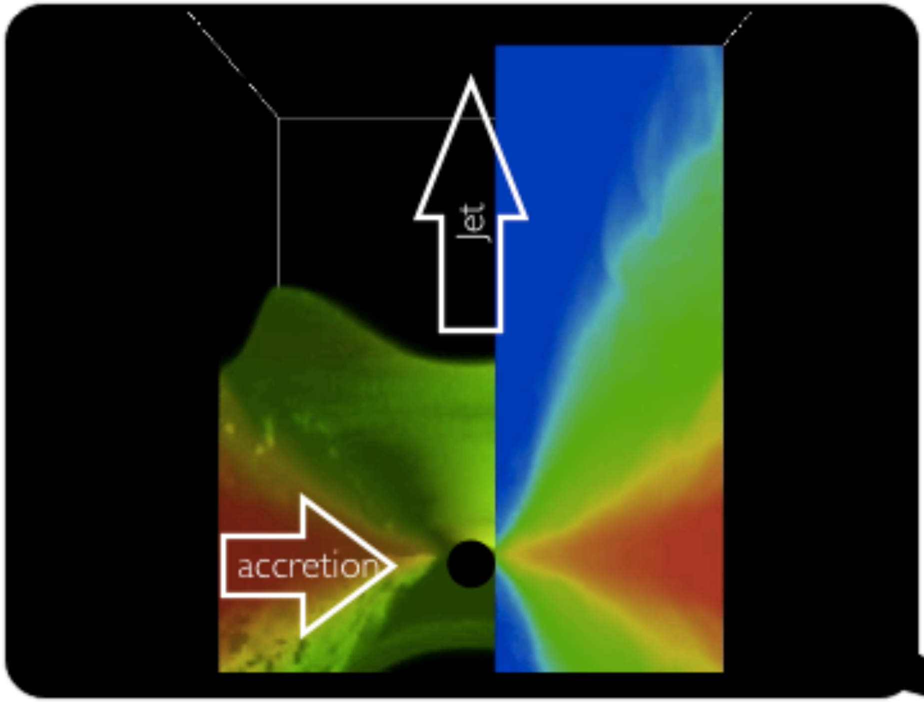
Simulated spectra nicely fit the observations.

Kawashima et al. 2012
(data; Gladstone 2009)

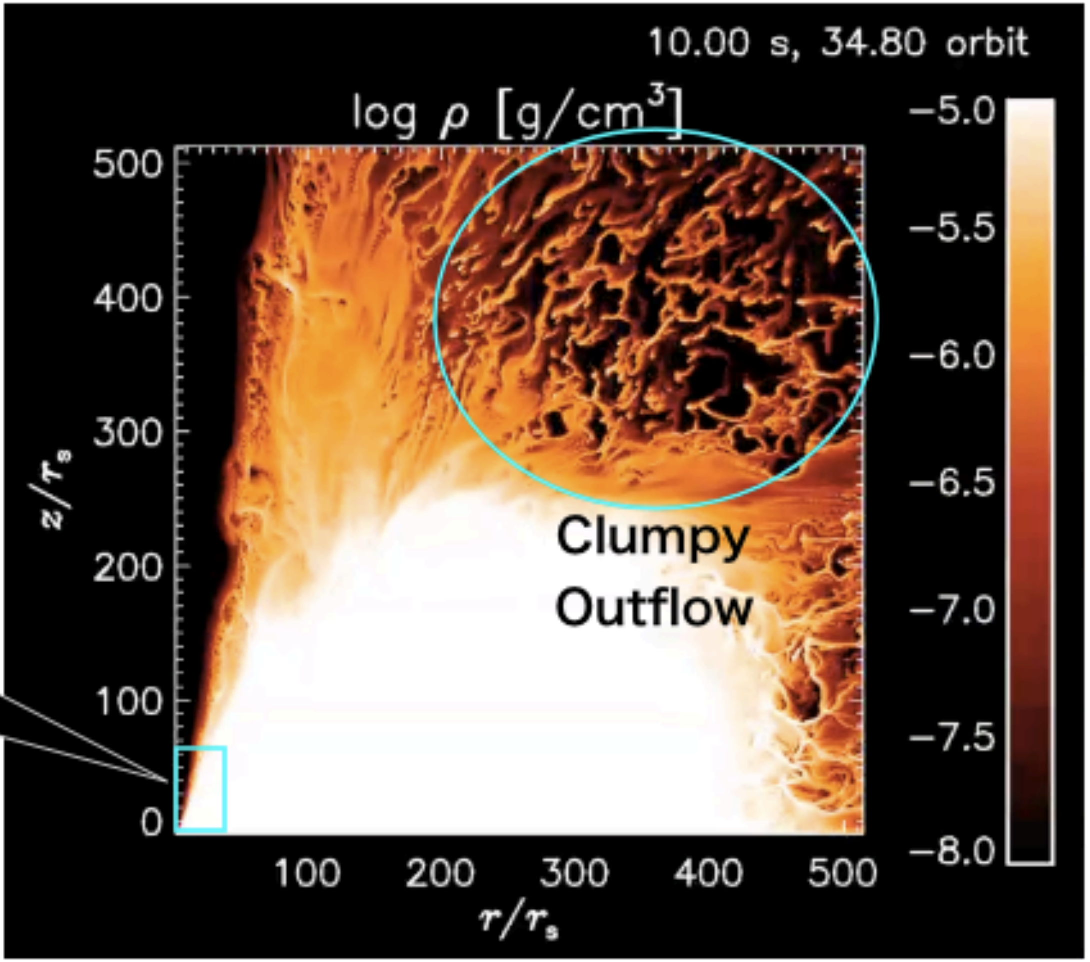


Clumpy Outflow

Super-Eddington disk+ Jet



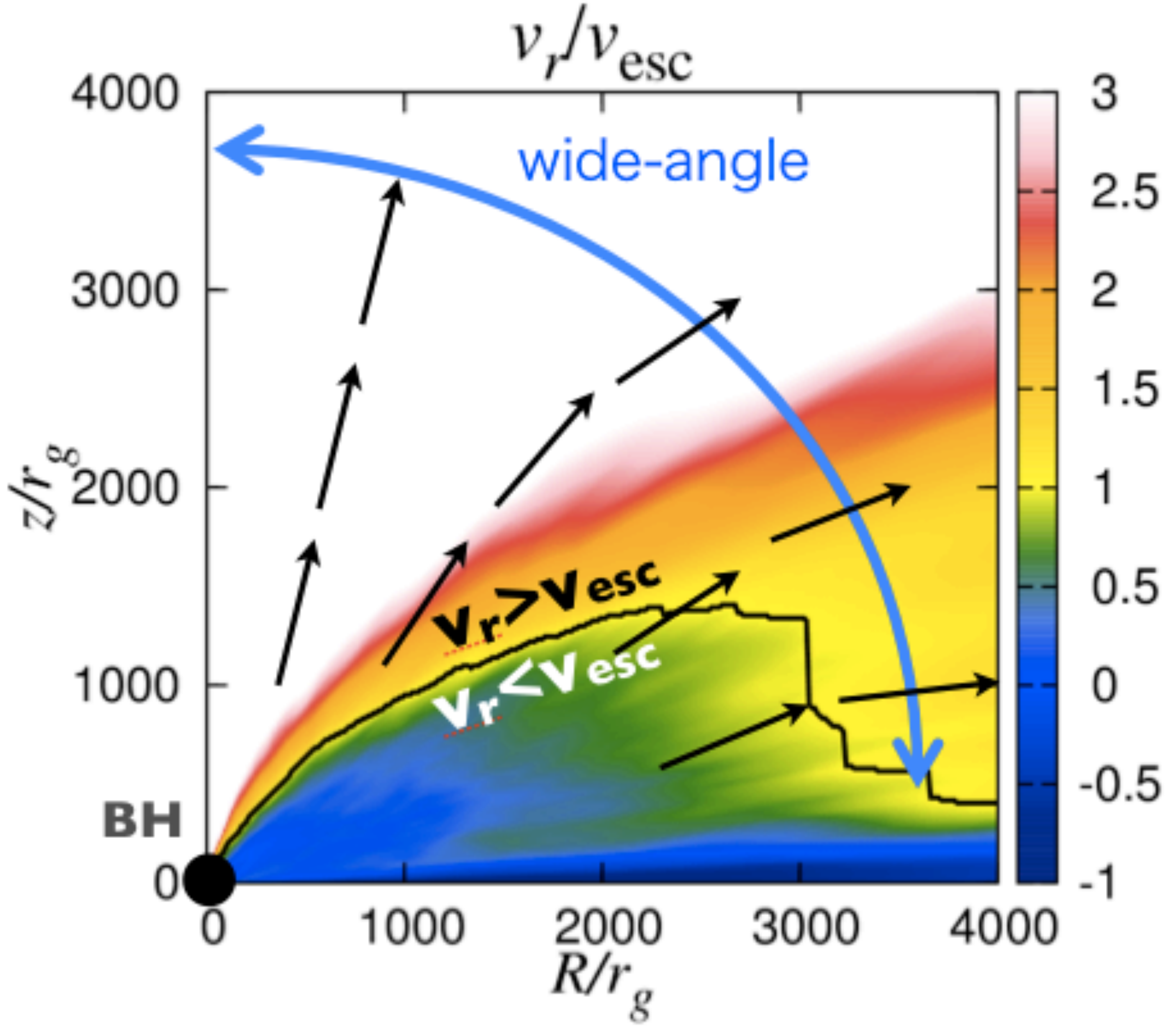
Takeuchi, Ohsuga, Mineshige 2013, 2014



Our simulations succeeded in reporoducing the clumpy outflow.

Time-dependent, Clumpy outflow

Wide-angle outflow



At $\theta < 45°$, we find $v_r > v_{esc}$ (**~0.3c**) near the black hole.

In θ ~45°-80°, outflow velocity gradually increases and exceeds v_{esc} at r ~1000-4000Rs.

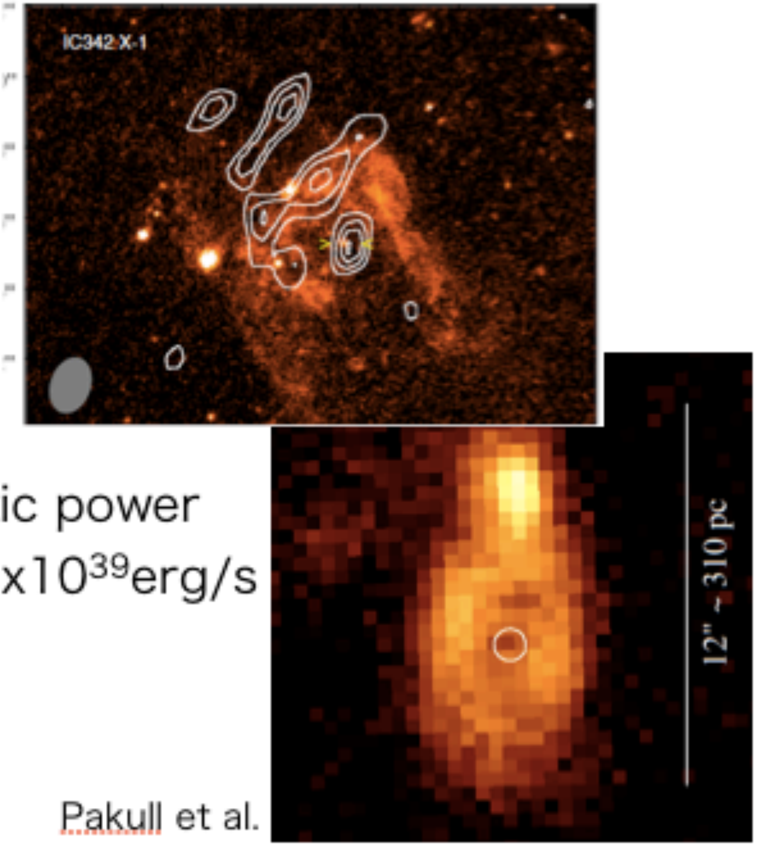
Kinetic power of the outflow is **3×10^{39}erg/s, ~Lx**

Hashizume et al. 2015

Outflow of ULXs

Shock excited bubbles:

Cseh et al. 2012

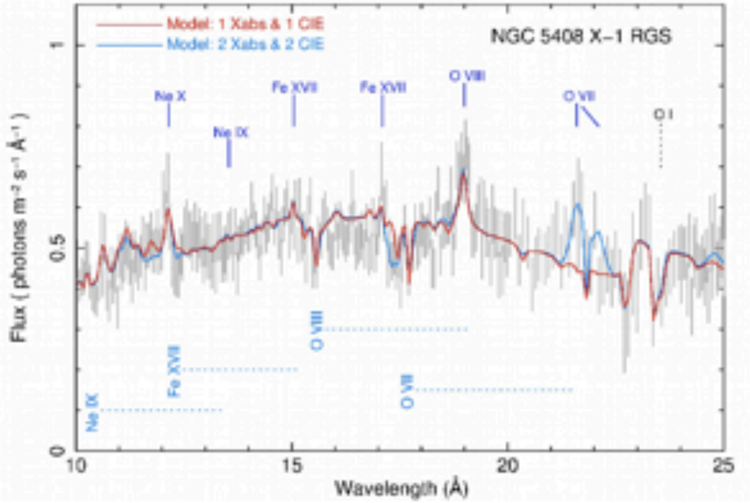


Kinetic power
~ 3-5x10^{39}erg/s

Pakull et al.

Blueshifted lines;

Matthew, Middleton, Fabian, 2016



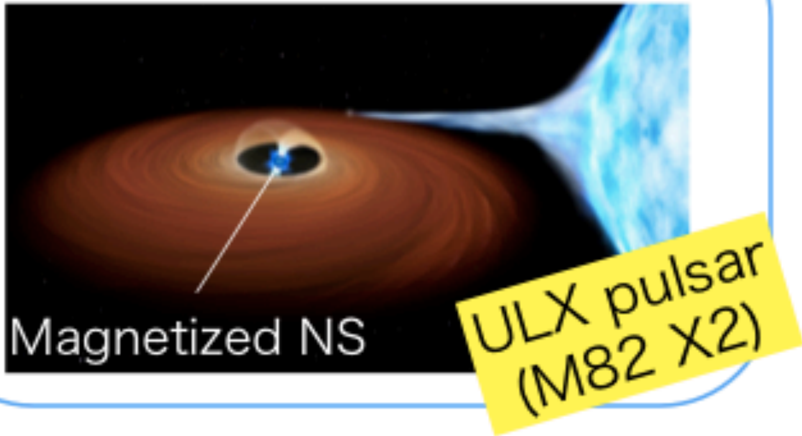
Velocity ~ 0.2-0.3c

Kinetic power and velocity of our simulations are consistent with observations.

also Pinto's Talk

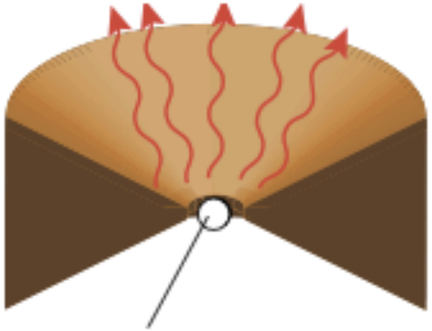
Super-Eddington Accretion onto NSs

Super-Eddington accretion column



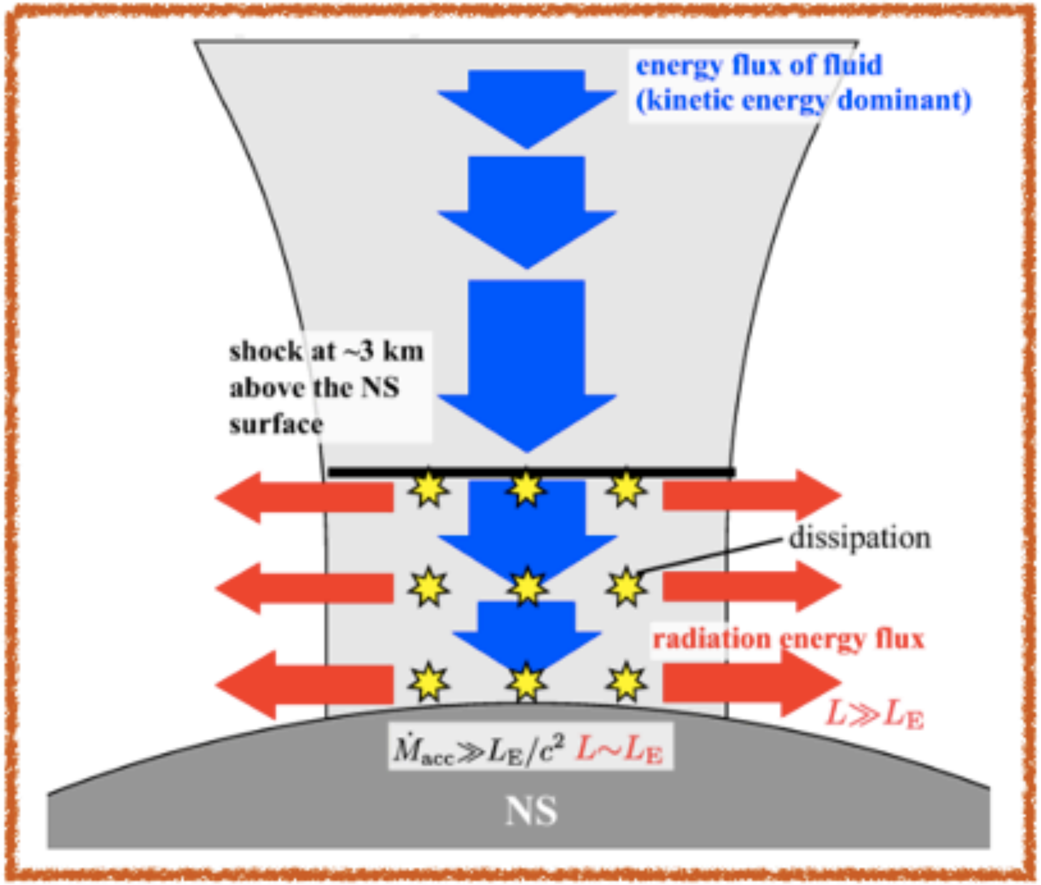
If the magnetic fields of NS prevent the disk accretion, the accretion column would appear.

Super-Eddington disk accretion

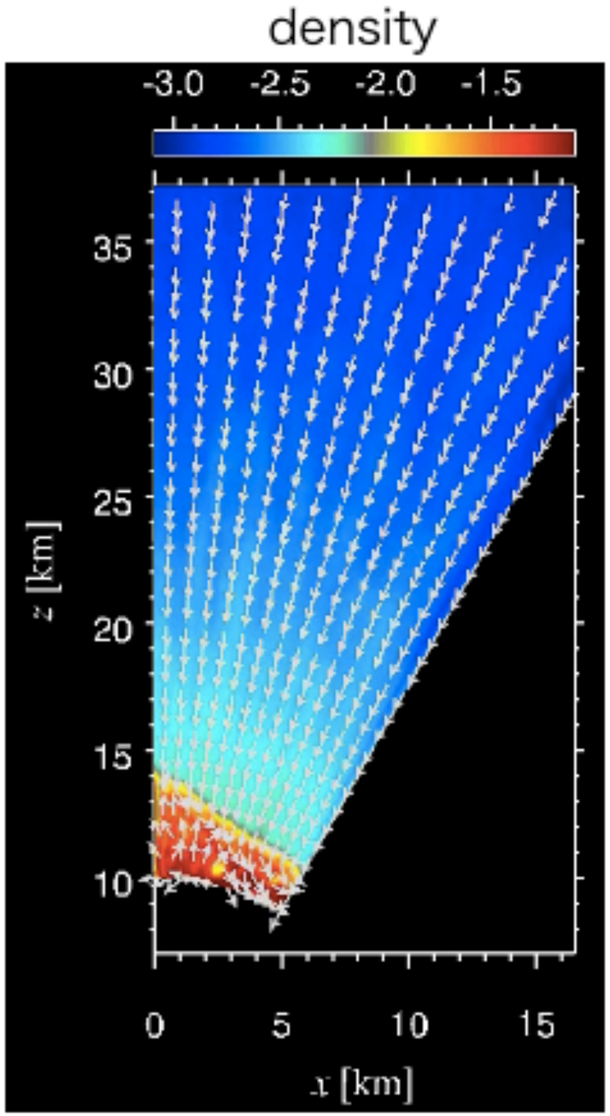


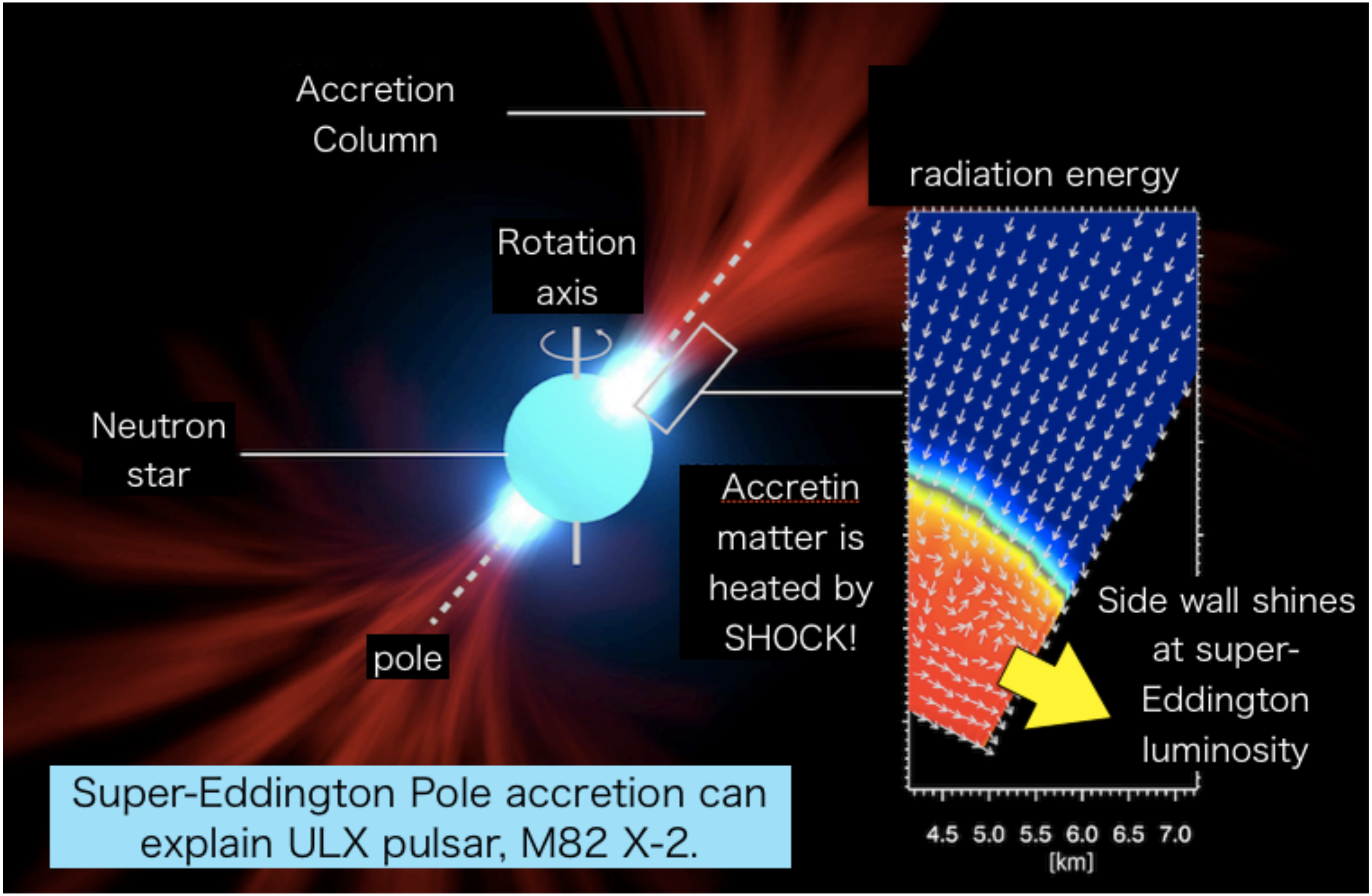
If NS is unmagnetized or very weakly magnetized, the matter would accretes through the accretion disks.

super-Eddington accretion column



Kawashima et al. 2016





Accretin matter is heated by SHOCK!

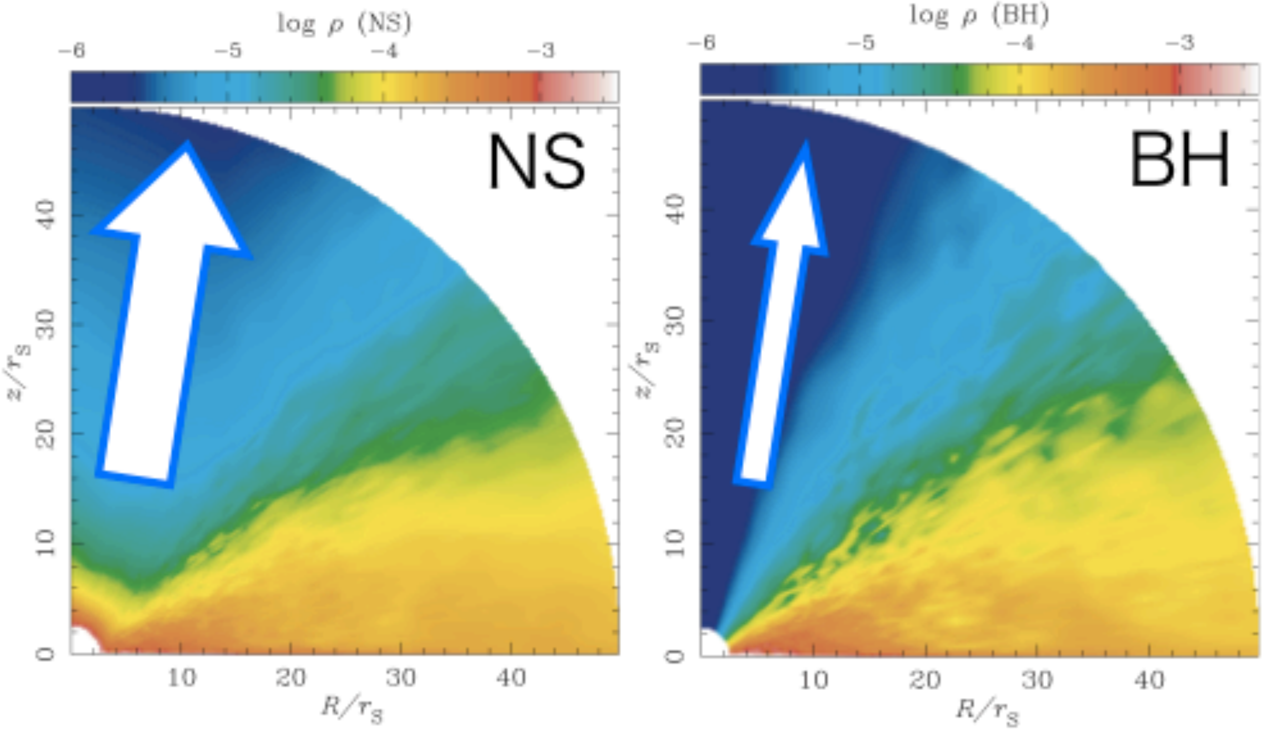
Side wall shines at super-Eddington luminosity

Super-Eddington Pole accretion can explain ULX pulsar, M82 X-2.

disk accretion; NS vs BH

In Ohsuga 2007, super-Eddington accretion onto NSs was for the first time investigated by Radiation-HD simulations.

Ohsuga 2007

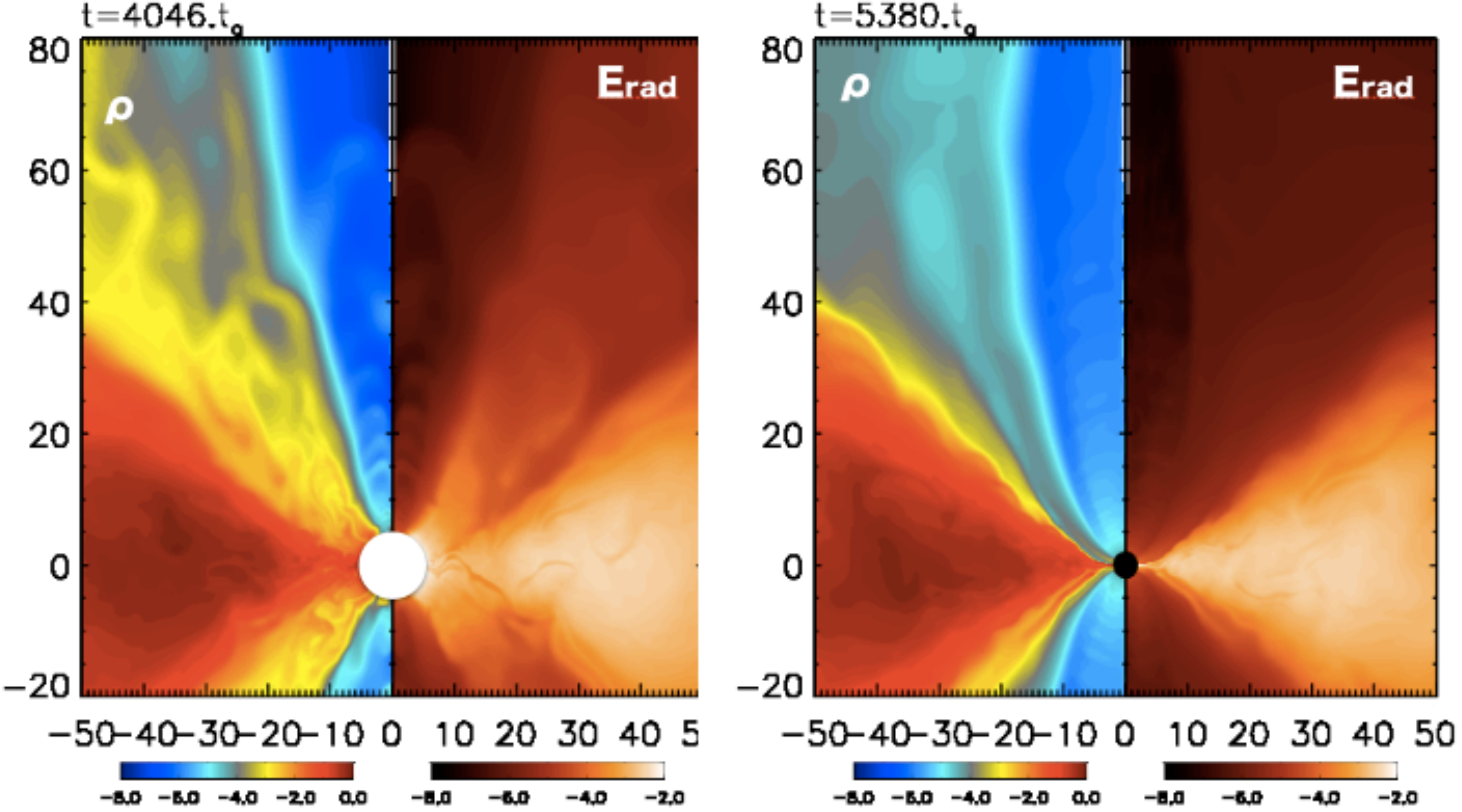


Shell-shaped structure appears around NS.

Energy conversion efficiency is larger for NS than BH.

More powerful outflows are generated from the super-Eddington disks around NS.

disk accretion; NS vs BH



non-rotating NS
(M~1.4Msun, R~4.8Rg)

non-rotating BH
(M~10Msun, R~2Rg)

Takahashi, Ohsuga submitted.

Accretion Rate (L_{Edd}/c^2)	NS	BH
R=20Rg	300	300
Inner Boundary	0	200

Outflow Rate (L_{Edd}/c^2)	NS	BH
R=200Rg	690	390

Luminosity (L_{Edd})	NS	BH
Radiation	3.2	3.0
Kinetic	4.9	0.2
Thermal	<<0.01	<<0.01
Magnetic	0.5	0.3

- Super-Eddington disks around NSs show the powerful outflows, and mainly release the energy via the outflow (Kinetic power > Radiation Luminosity). In the case of BH, we find Kinetic power < Radiation Luminosity.
- Energy conversion efficiency is larger for NSs than for non-rotation BHs (Note that rotating BH is the most powerful).

Summary

Super-Eddington Accretion onto Black Holes

- Our simulations support that the engine of ULXs is stellar mass BHs + super-Eddington disks. Because our model roughly explain the observations (luminosity, SED, clumpy outflows, bubbles).

Super-Eddington Accretion onto Neutron Stars

- Super-Eddington accretion column and disk accretion onto NSs are feasible and very powerful.

- ULXs might be explained even if the central object is NS. At least, M82 X-2 would be powered by the super-Eddington accretion column.