Gas Accretion onto Magnetized Neutron Stars

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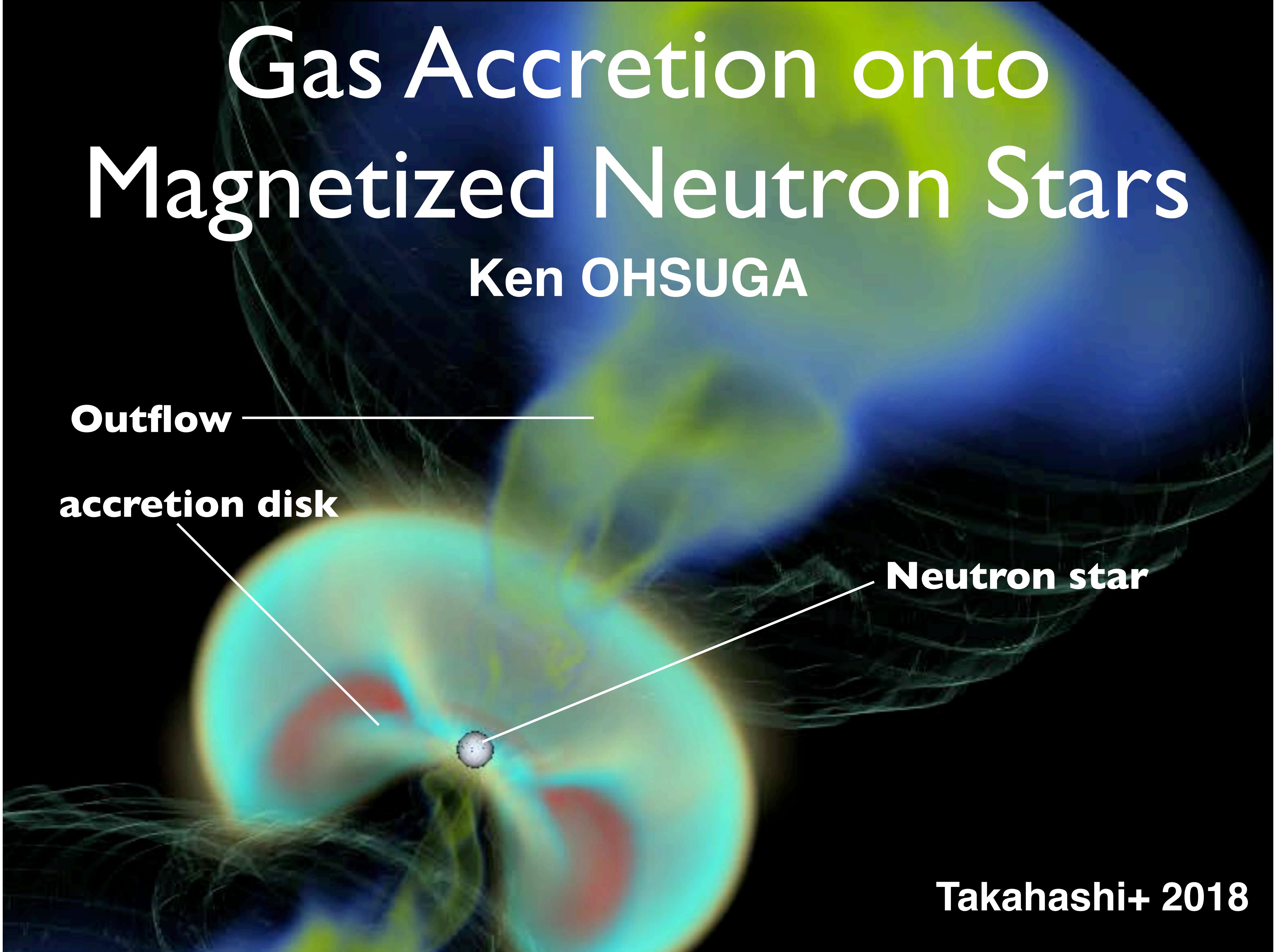


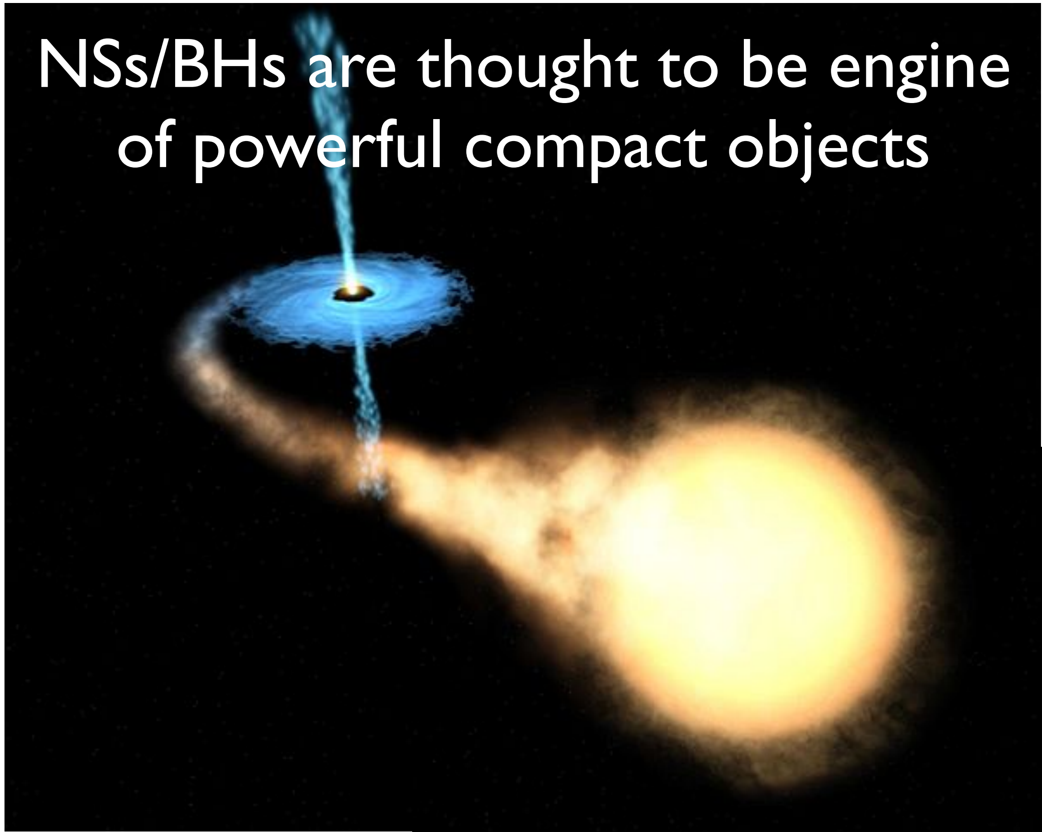
Neutron Stars (Ns) & Black Holes (BHs)

NS
-a few Msun / 10km
-produced by supernovae

Stellar mass BH
-about 10 Msun / 30km
-produced by supernovae

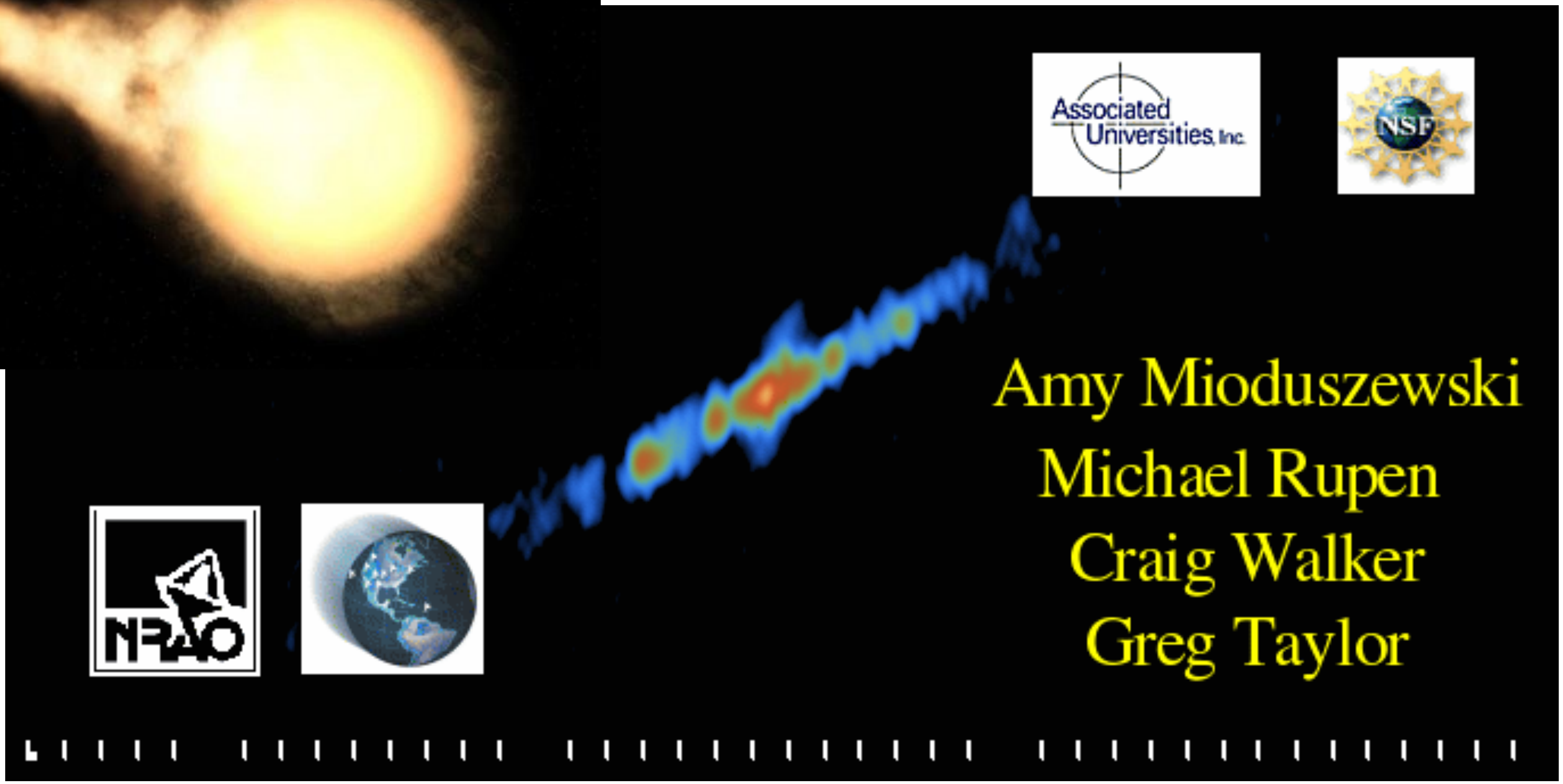
Supermassive BH
-10^{6-9} Msun
-located at the galactic center
-formation mechanism is unknown

High-energy phenomena

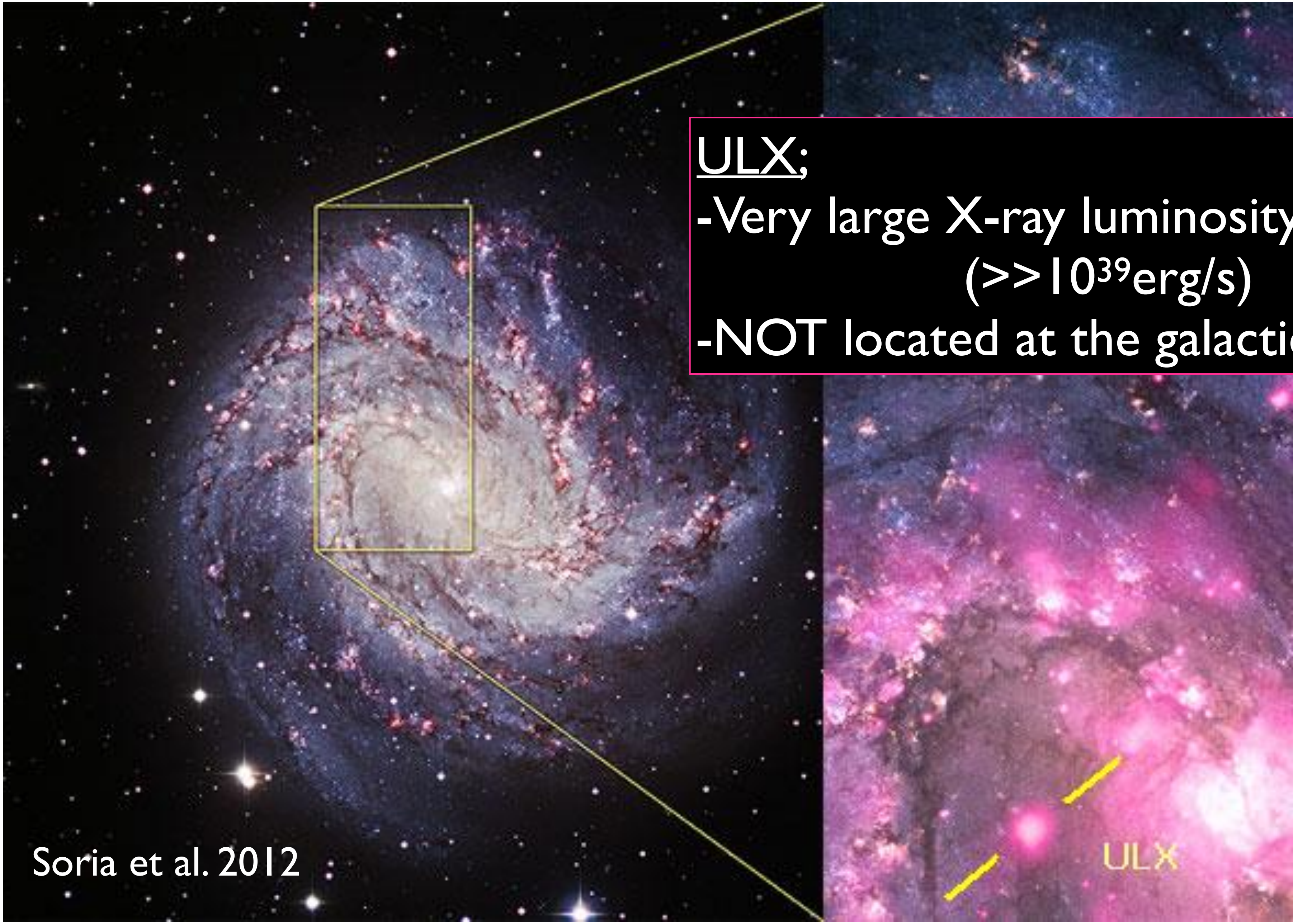


Cyg X-1

SS433



Ultra-luminous X-ray sources (ULXs)



ULX;

-Very large X-ray luminosity ($>>10^{39}$erg/s)

-NOT located at the galactic center

Central object of ULX ?

NS
- a few Msun / 10km
- produced by supernovae

Stellar mass BH
- about 10 Msun / 30km
- produced by supernovae

← Big difficulty

Supermassive BH
- $10^{6\text{-}9}$ Msun
- located at the galactic center
- formation mechanism is unknown

← **NO**

ULXs are off-center X-ray sources.

Accretion Power

Potential energy is converted to radiation energy (and jet energy)

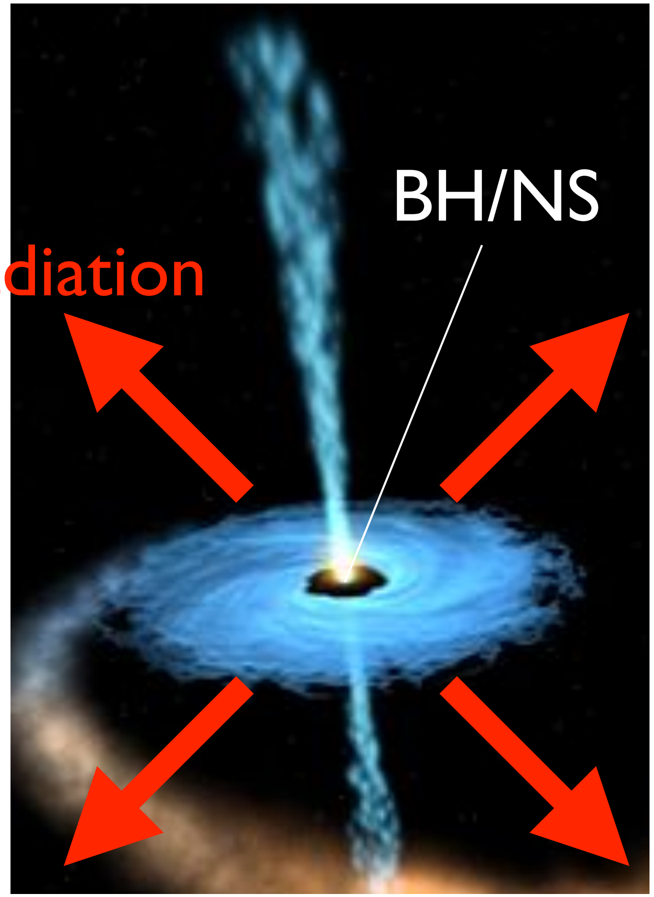
$$\frac{GM}{r}\dot{M}$$

Potential energy per unit time

↓

$$L$$

Radiation energy per unit time (Luminosity)

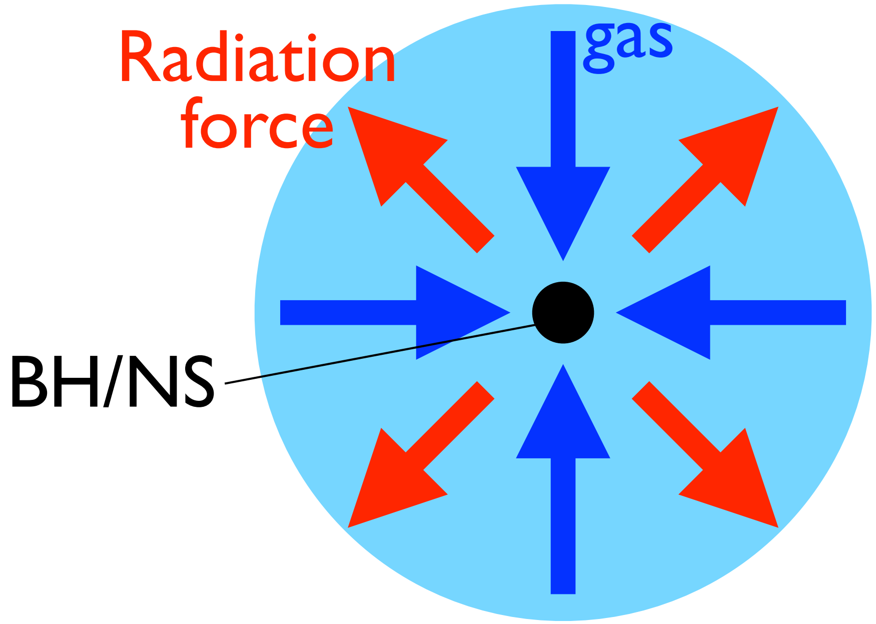


Eddington Luminosity

Gravity = Radiation force

Eddington luminosity

$$L_{\rm Edd} \sim 10^{38} \left(\frac{M}{M_{\rm sun}} \right) {\rm erg/s}$$



-Gas accretion stops if luminosity is larger than Eddington luminosity because of GRAVITY < RADIATION FORCE.

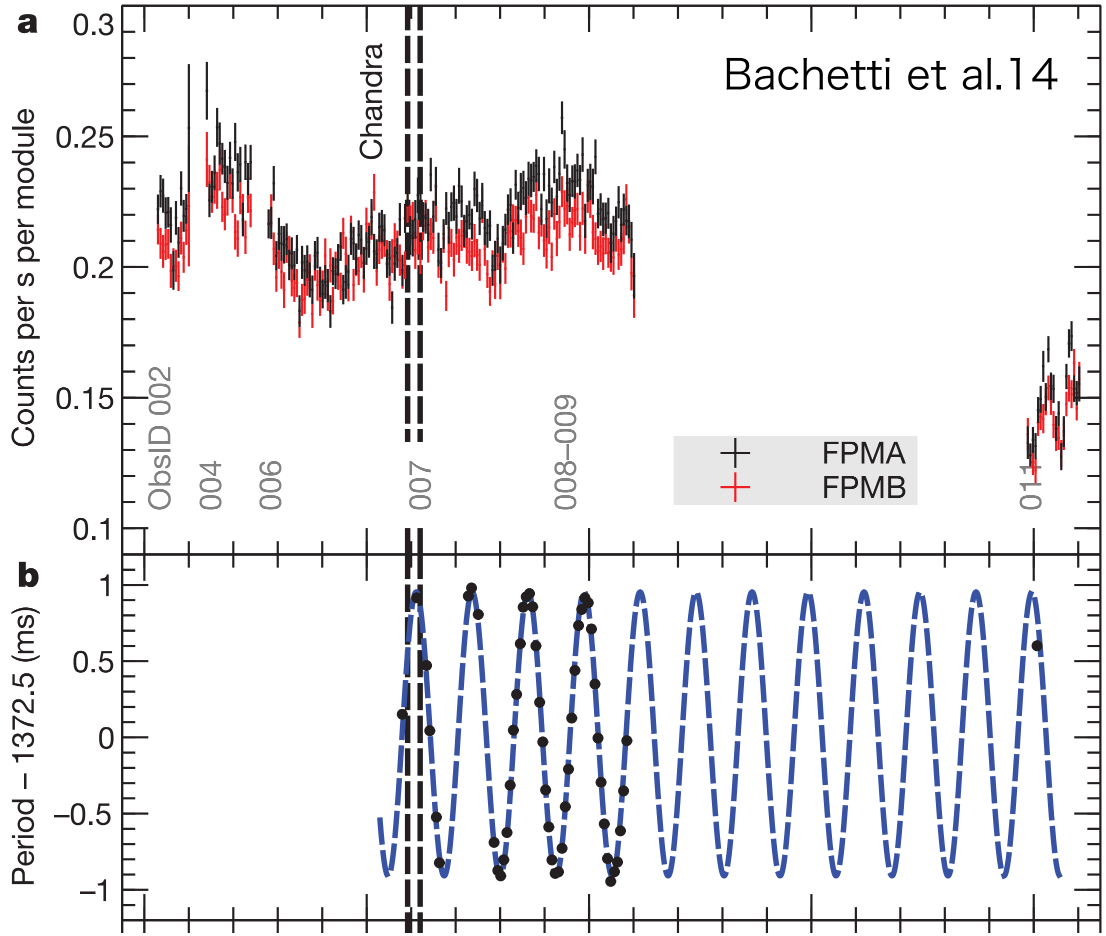
-Thus, the Eddington luminosity is the upper limit of the luminosity.

Neither stellar mass BH (~10Msun) nor NS (~Msun) cannot explain large luminosity of ULXs (>>10^{39}erg/s)

Pulsed ULXs

However, X-ray pulse is detected in some ULXs.

Central objects of Pulsed ULXs are probably NSs !



Inconsistency

-Pulsed emission can be explained by NS.
-But NS is rejected if the Eddington luminosity is upper limit of the luminosity.

Summary

-By performing numerical simulations, we reveal that the NS luminosity can exceed the Eddington limit.
-Accretion onto magnetized NS can explain basic features of ULXs.

Basic equations

We solve a full set of general relativistic radiation-magnetohydrodynamic equations

MHD

mass cons. $$\partial_t\left(\sqrt{-g}\rho u^t\right)+\partial_i\left(\sqrt{-g}\rho u^i\right)=0$$

Gauss's law $$\partial_i\left(\sqrt{-g}B^i\right)=0$$

Induction eq. $$\partial_t\left(\sqrt{-g}B^i\right)=-\partial_j\left[\sqrt{-g}\left(b^j u^i-b^i u^j\right)\right]$$

energy momentum cons. for MHD $$\partial_t\left(\sqrt{-g}T^t_\nu\right)+\partial_i\left(\sqrt{-g}T^i_\nu\right)=\sqrt{-g}T^\kappa_\lambda\Gamma^\lambda_{\nu\kappa}+\sqrt{-g}G_\nu$$

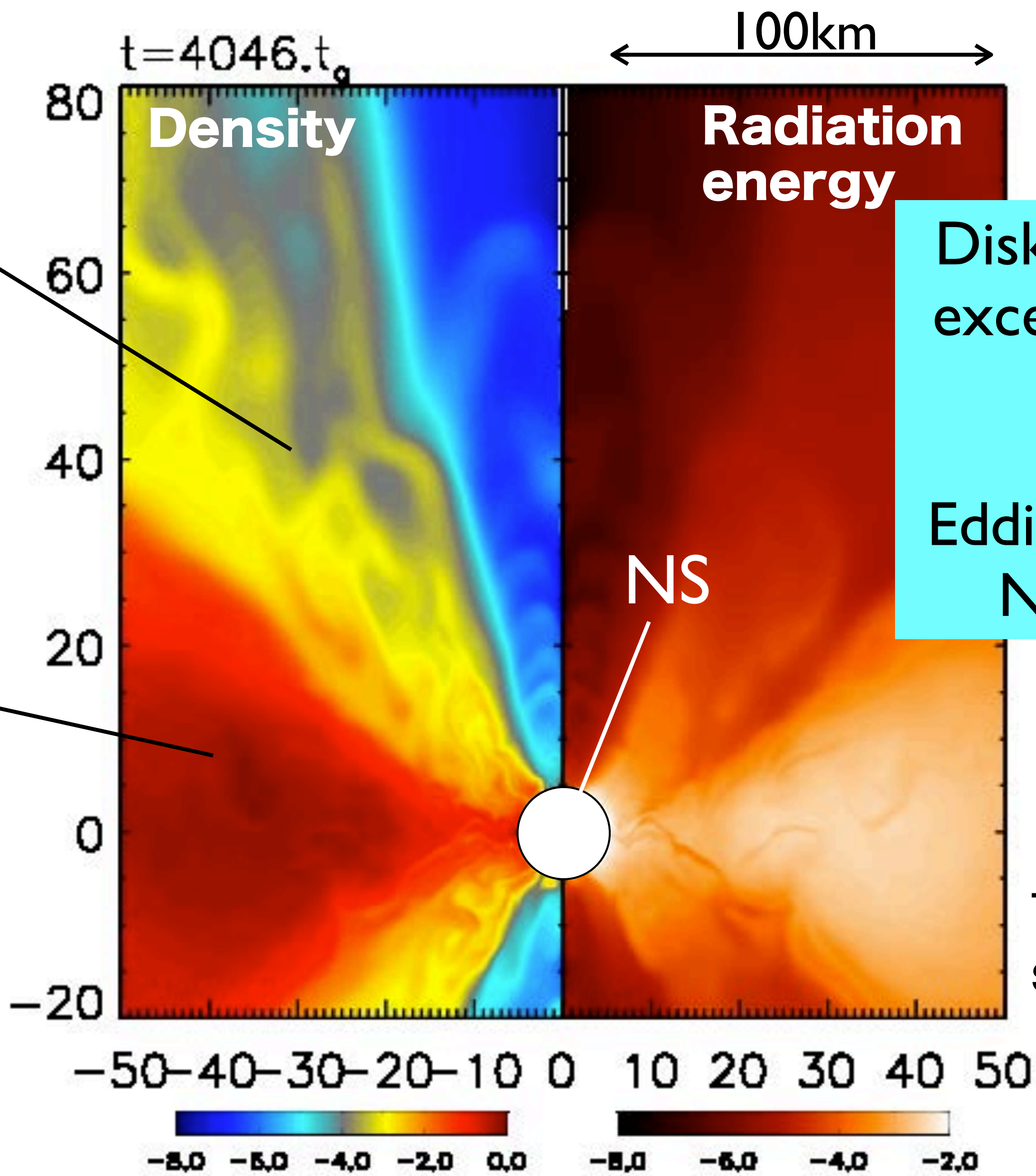
energy momentum cons. for radiation $$\partial_t\left(\sqrt{-g}R^t_\nu\right)+\partial_i\left(\sqrt{-g}R^i_\nu\right)=\sqrt{-g}R^\kappa_\lambda\Gamma^\lambda_{\nu\kappa}-\sqrt{-g}G_\nu$$

Radiation

Non-magnetized NS

Powerful outflow

Accretion disk



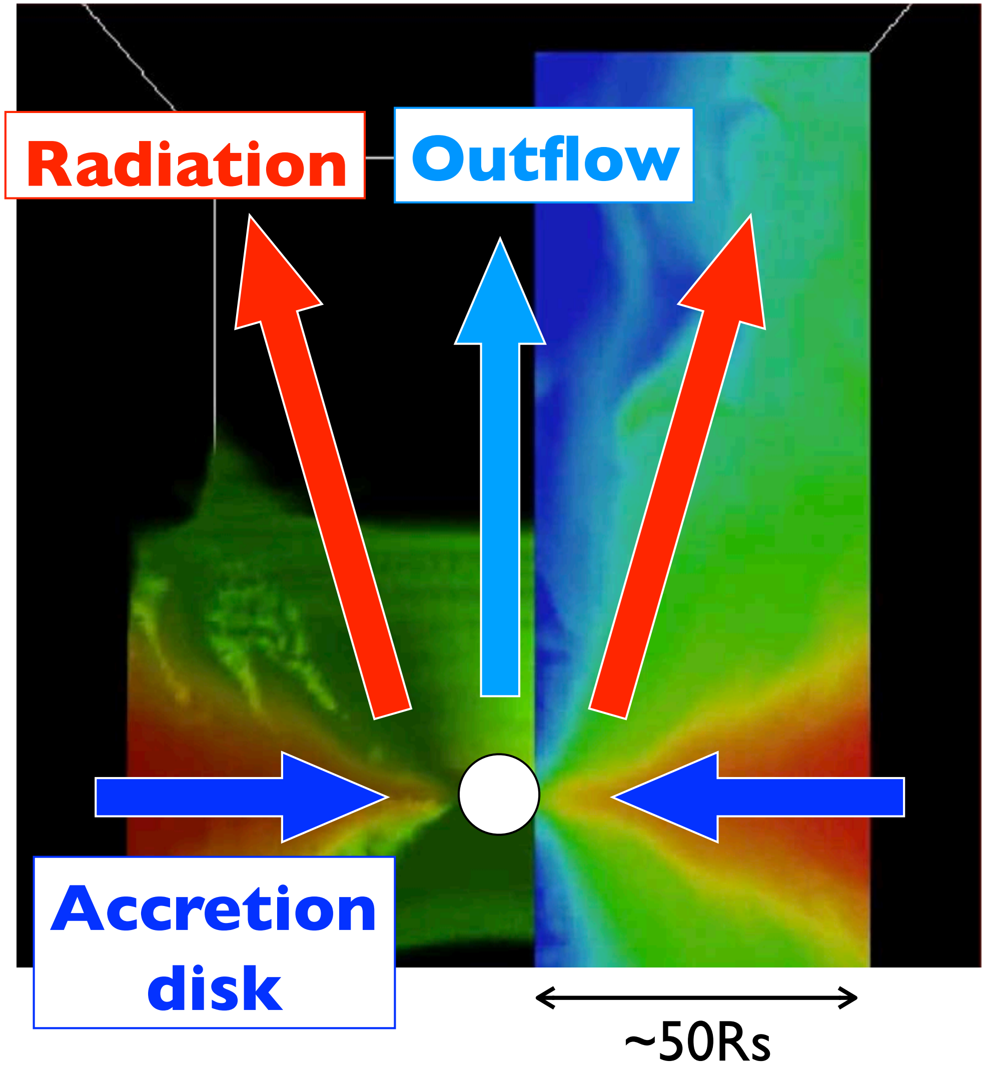
Disk luminosity largely exceeds the Eddington luminosity.

Eddington luminosity is NOT upper limit!

Takahashi et al. 2018
see also Ohsuga 2007

Why is super-Eddington feasible?

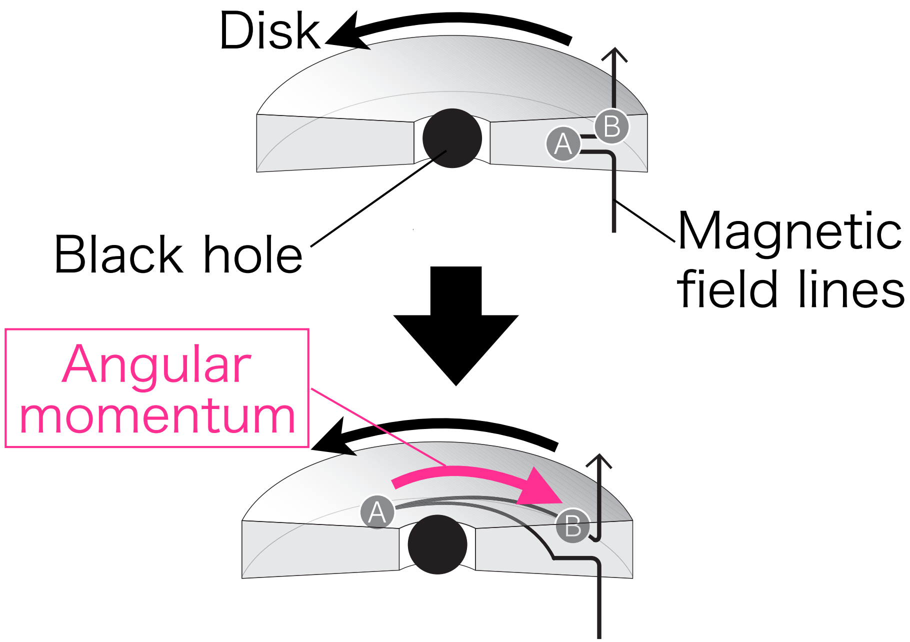
Mass density



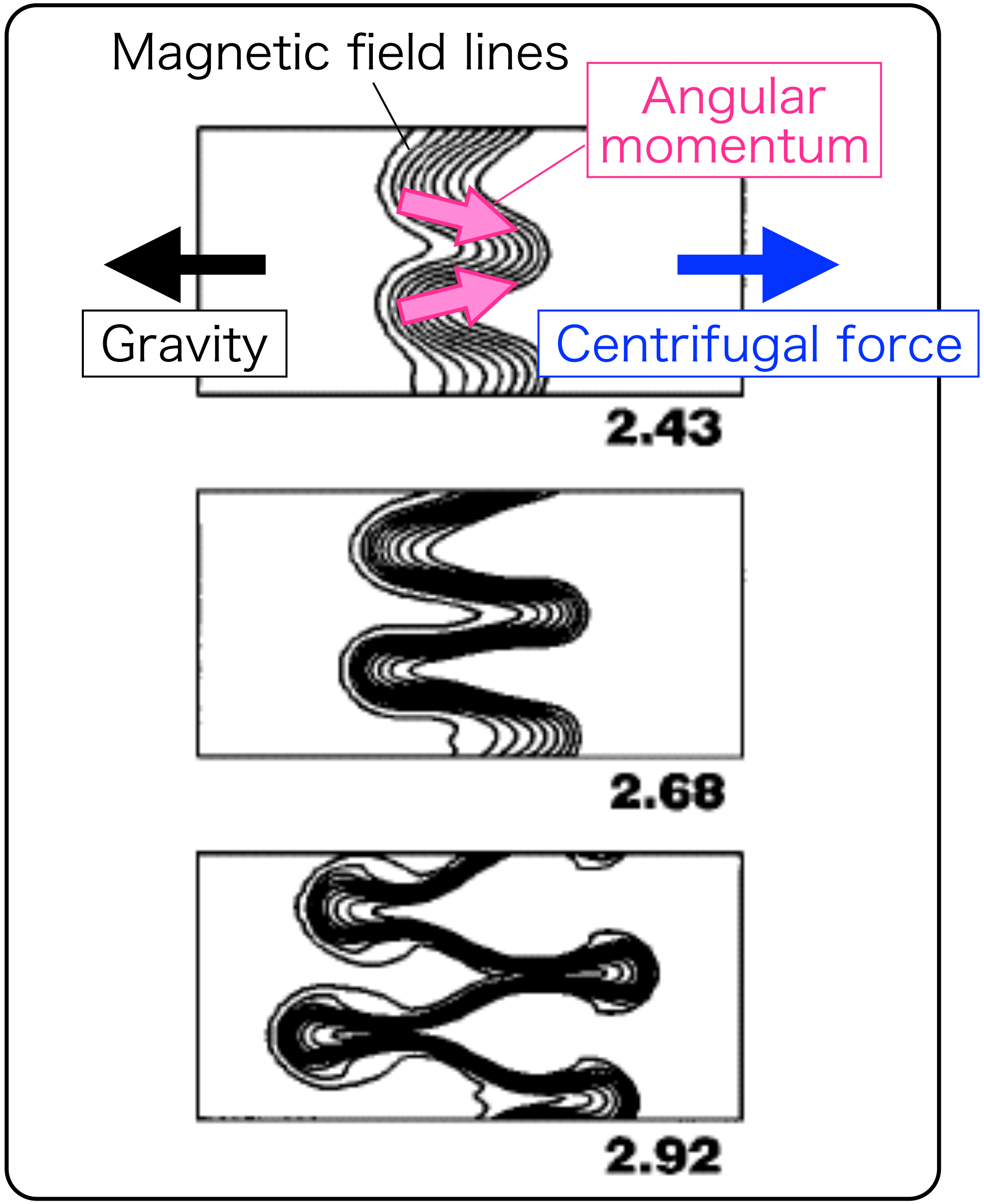
Radiation energy mainly goes in the vertical direction.
→Radiation force deos not prevent disk accretion.

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

Magnetorotational instability

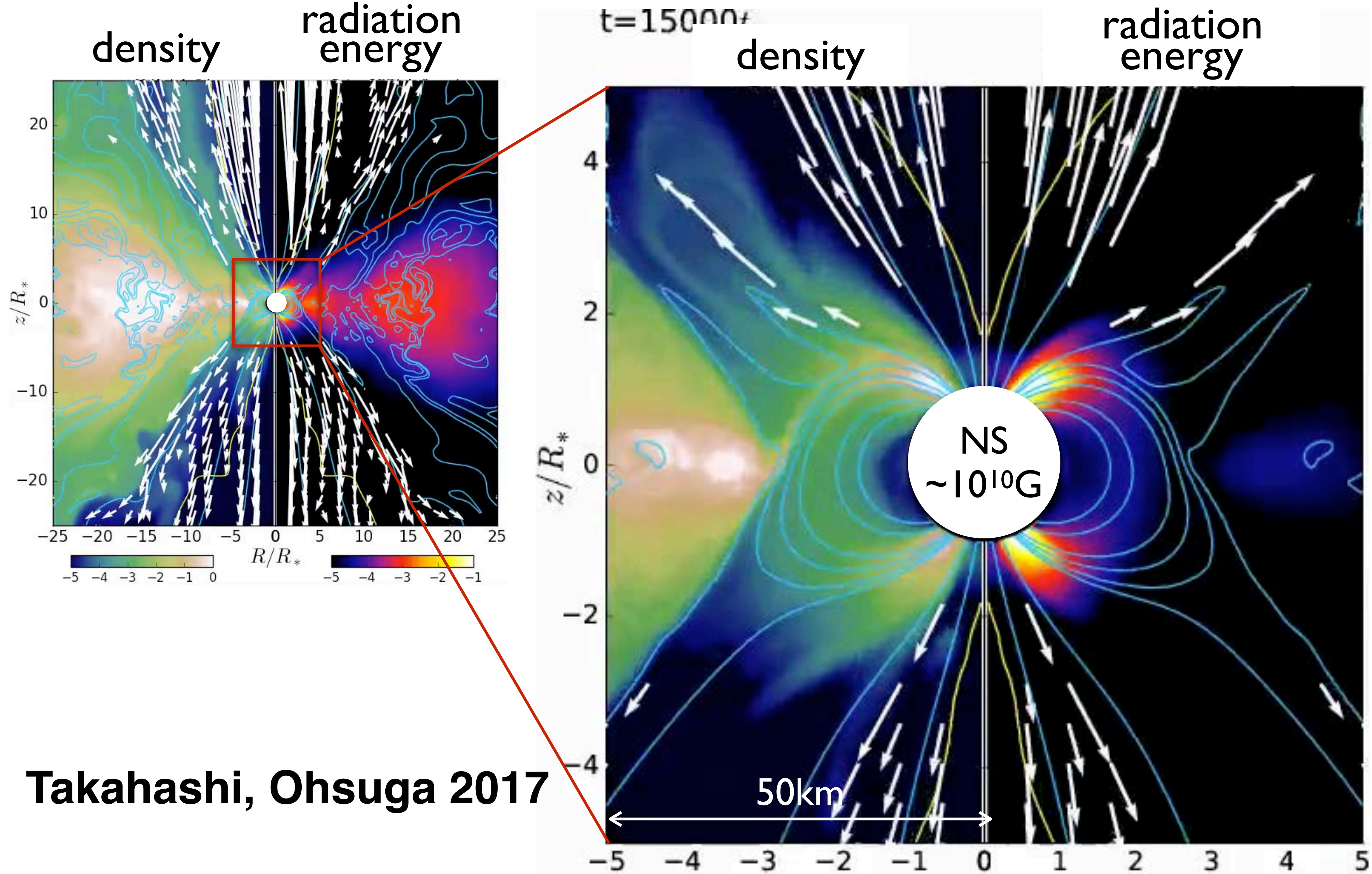


Angular momentum transport induced by magnetorotational instability (MRI) leads to mass accretion



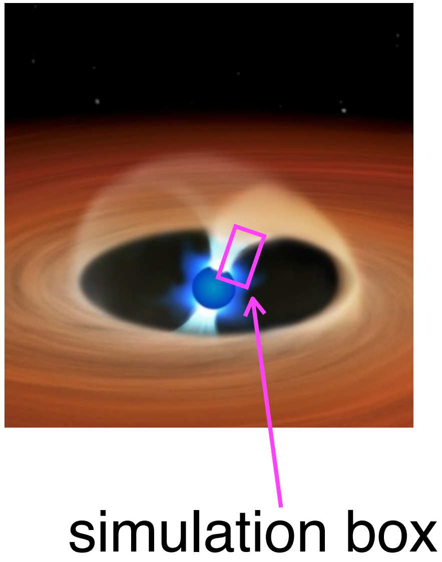
Hawley & Balbus 1991
See also Velikhov 1959

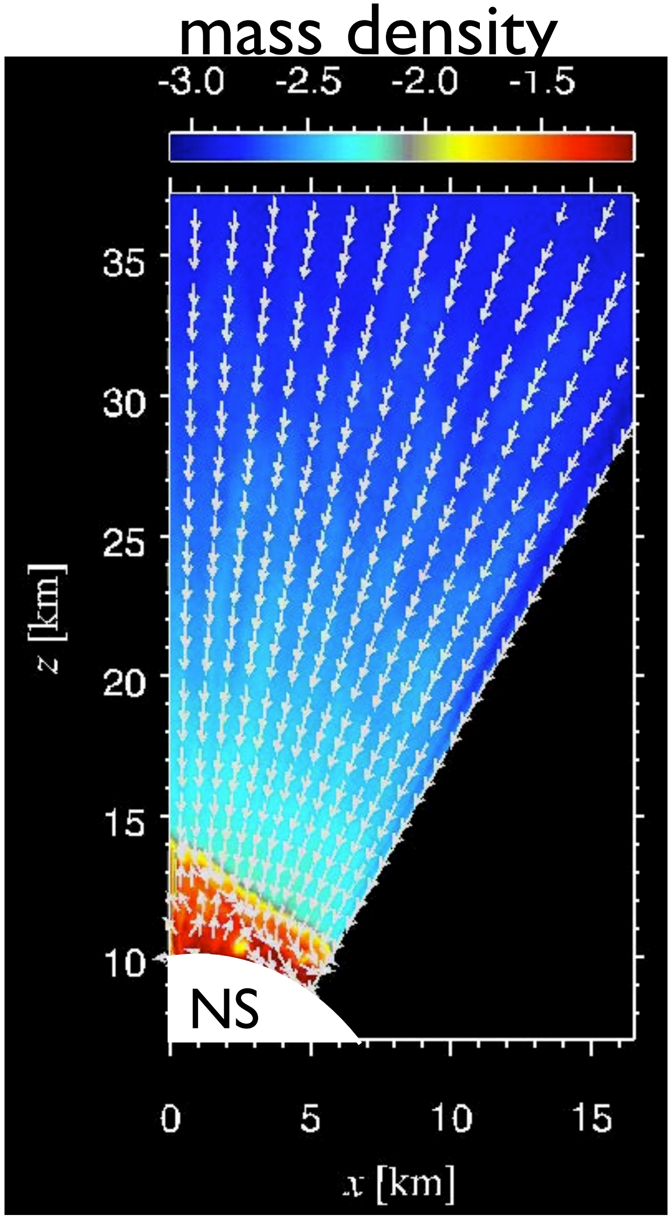
Magnetized NS

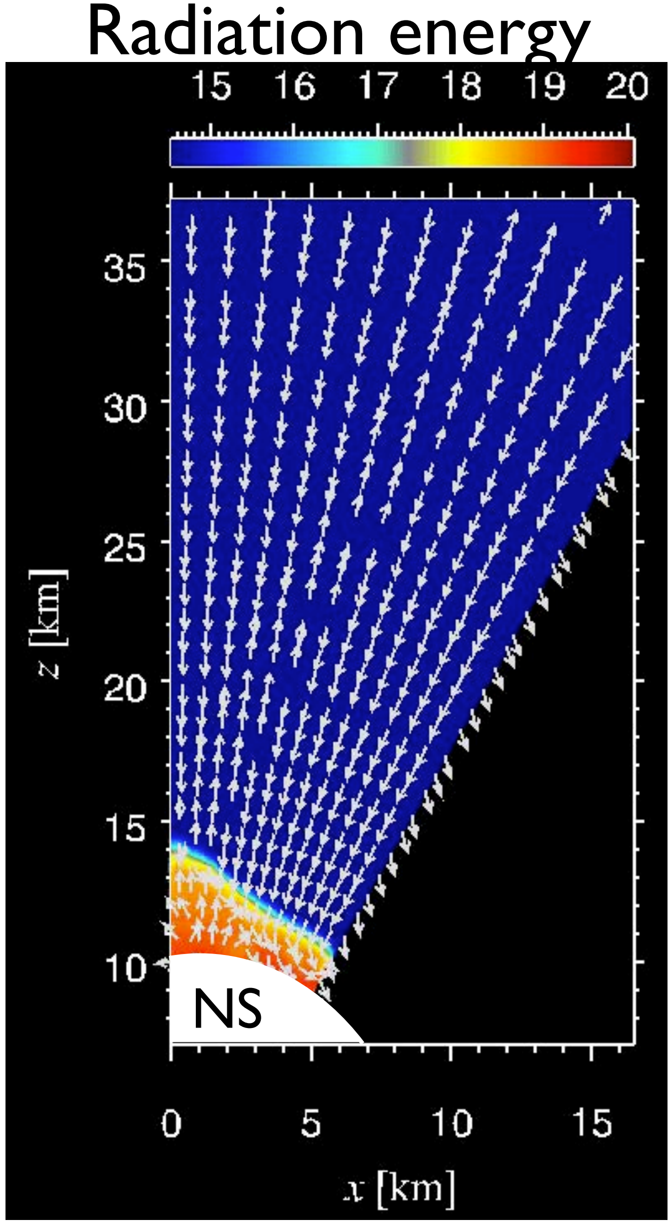


Takahashi, Ohsuga 2017

Sim. of Accretion column

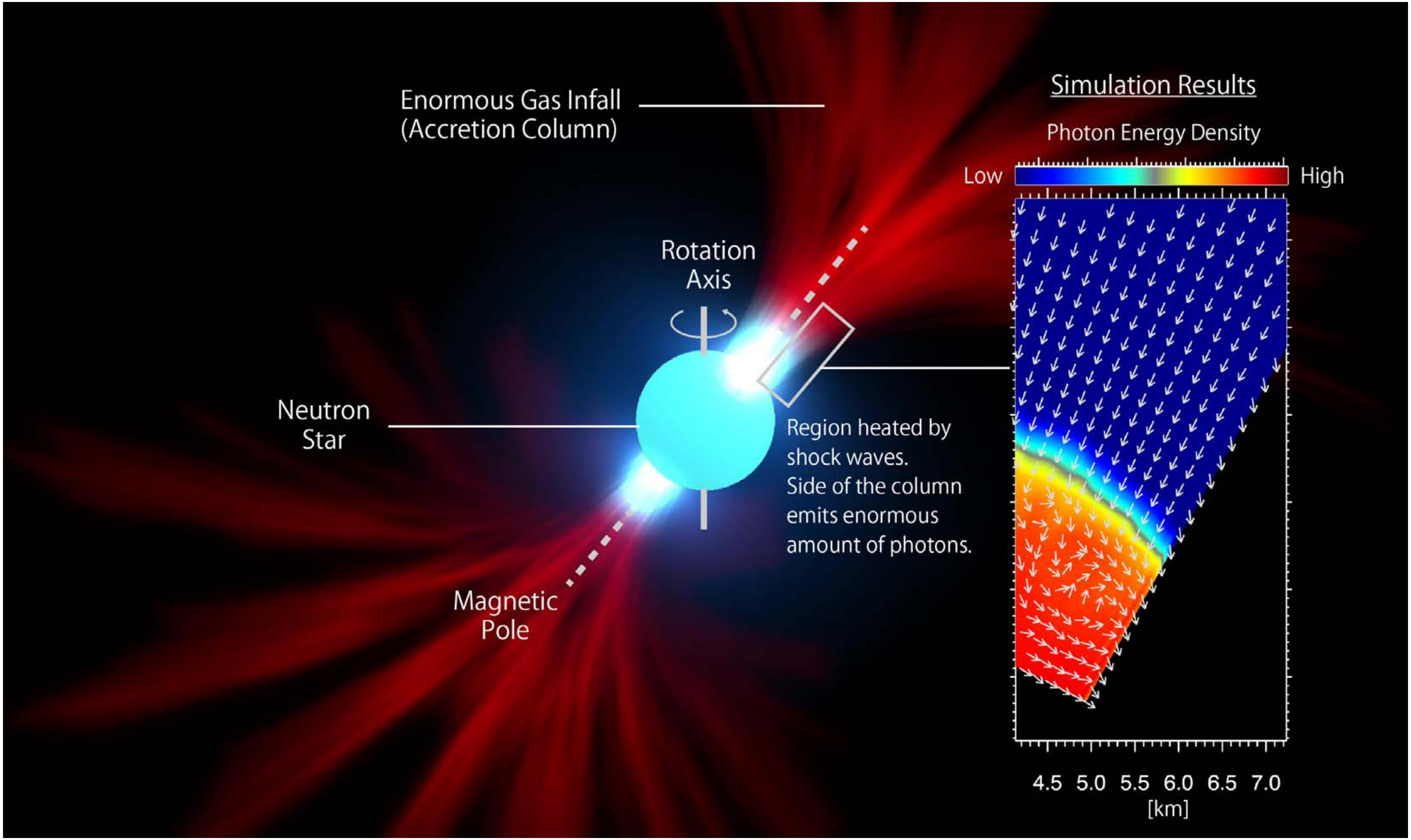






Kawashima et al. 2016

Model for ULX Pulsar



SUMMARY

- We performed **general relativistic radiation magnetohydrodynamics simulations** of gas accretion and outflow around NSs.
- Our simulation revealed that the luminosity can exceed the Eddington luminosity (**super-Eddington flow is feasible**).
- The central objects of pulsed ULXs would be super-Eddington flows onto **the magnetized NSs**.