Outflows from protoplanetary disks and star-disk interaction

原始惑星系円盤からのアウトフローと円盤と中心星の相互作用

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collaborators:

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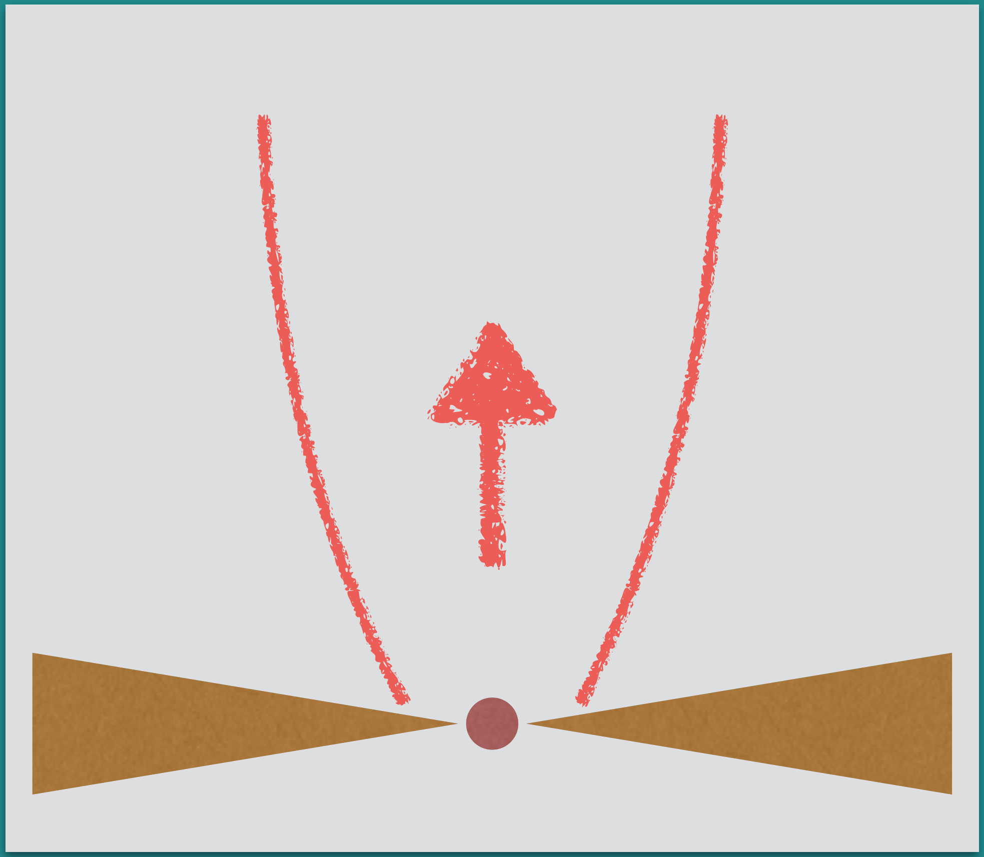
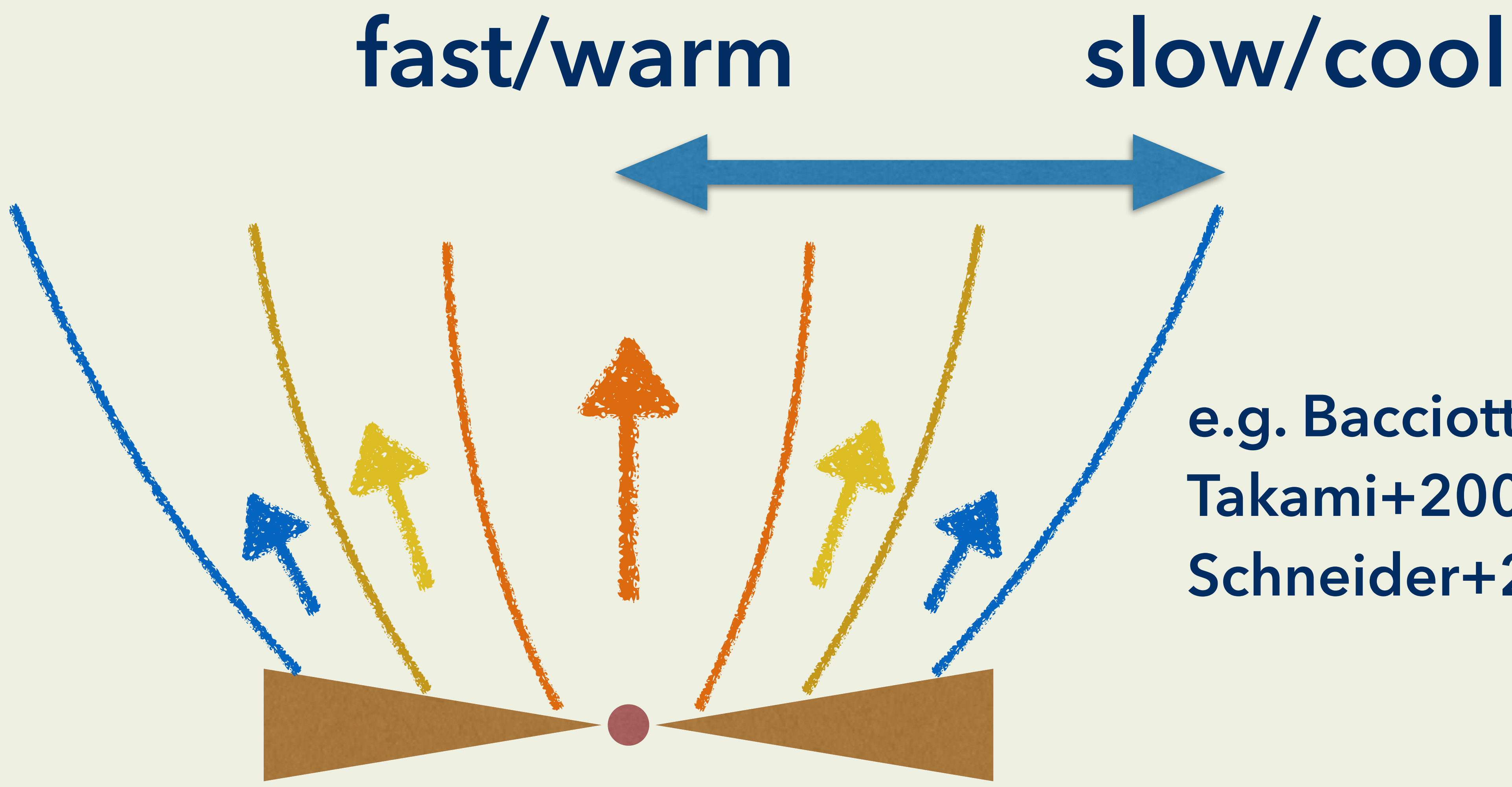


Structure of outflows from CTTSs



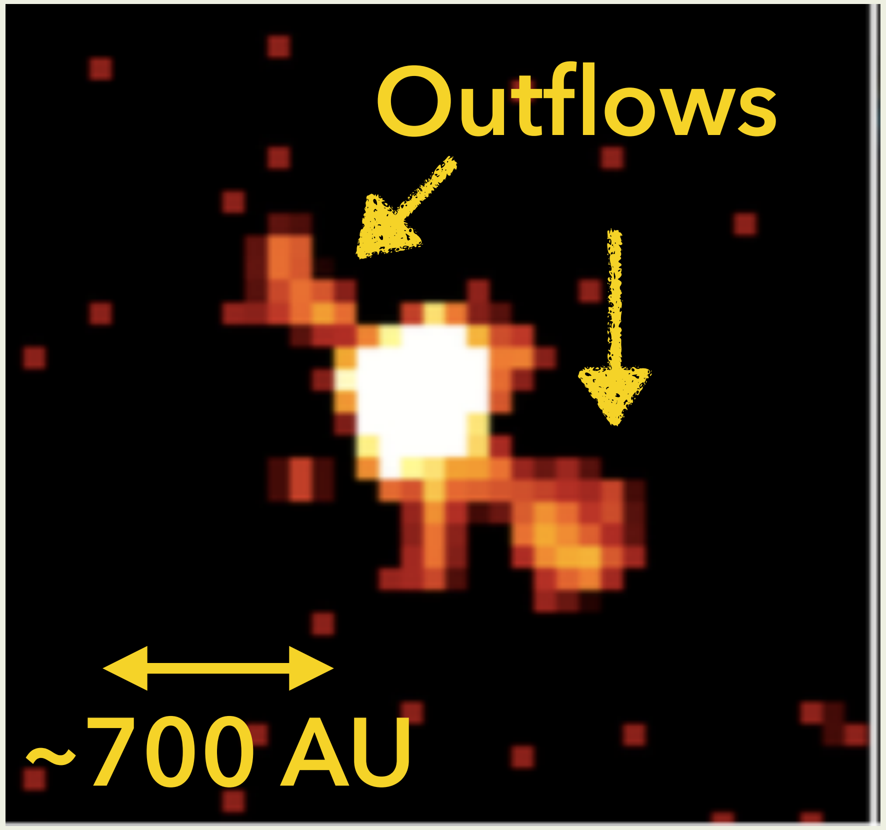
e.g. Bacciotti+2000
Takami+2002
Schneider+2013

observed in a wide range of wavelength :

radio - IR - optical - UV

$$T \leq 10^5\ \mathrm{K}$$

Discovery of X-ray outflows



Chandra discovered X-ray outflows from CTTS DG Tau (Gudel+2008)

- Along the optical jets
- Length : ~several 100 au
- Temperature: 3.4 MK (!!)
- Mass loss rate: $1.3 \times 10^{-11} M_{\odot} \mathrm{yr}^{-1}$

(Schneider & Schmitt 2008)

Strong soft X-ray emission at the base of the outflows (within a few 10 au from the star): $L_{\mathrm{X}} \approx 10^{29}$ erg s^{-1}

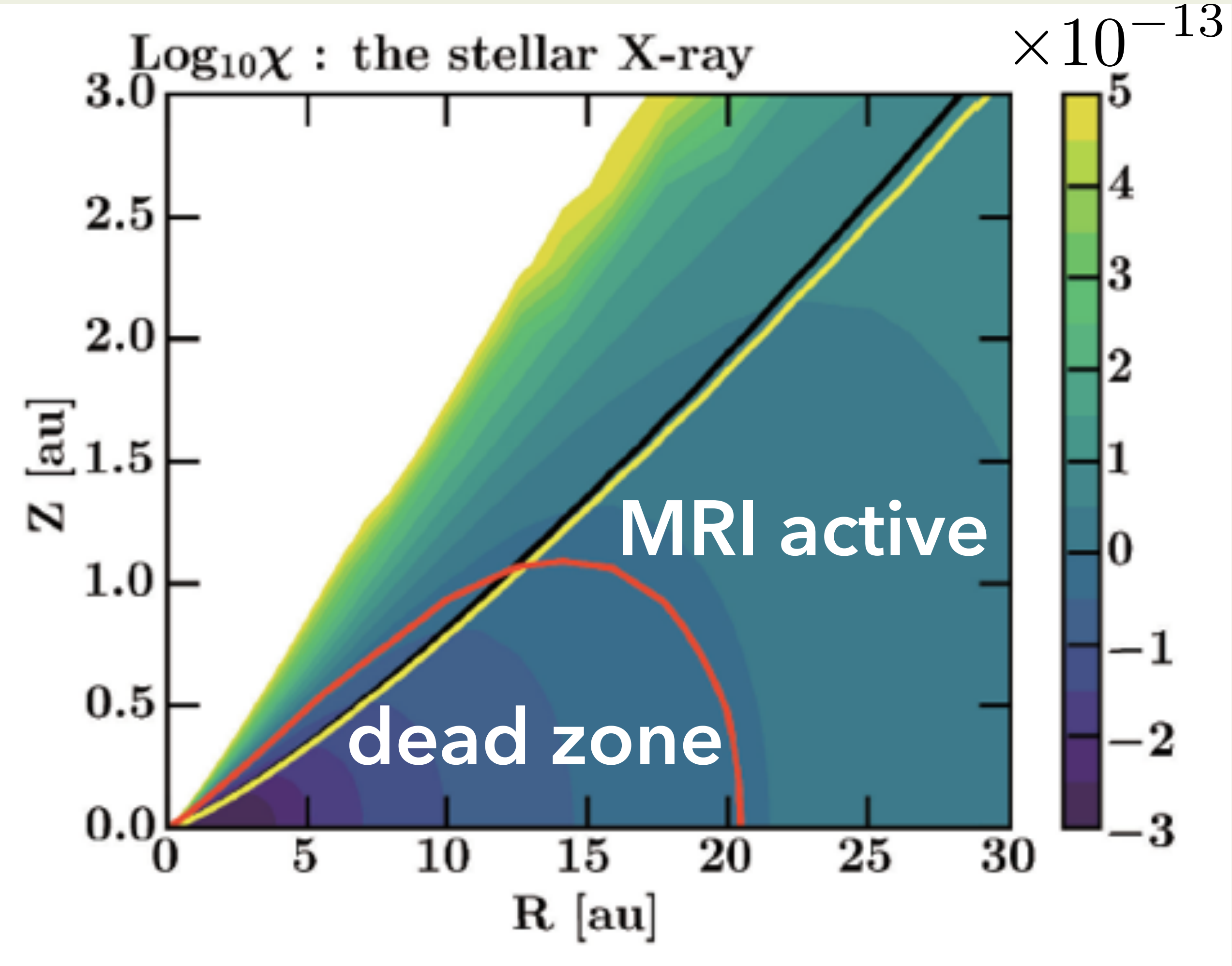
(~10 % of the stellar hard X-ray component, Gudel+2011)

Other CTTS examples (T ~ a few - several MK):
Z CMa (Stelzer + 2009), L1551 IRS 5 (Schneider + 2013)
RW Aur (Skinner & Gudel 2014), RY Tau (Skinner + 2016)

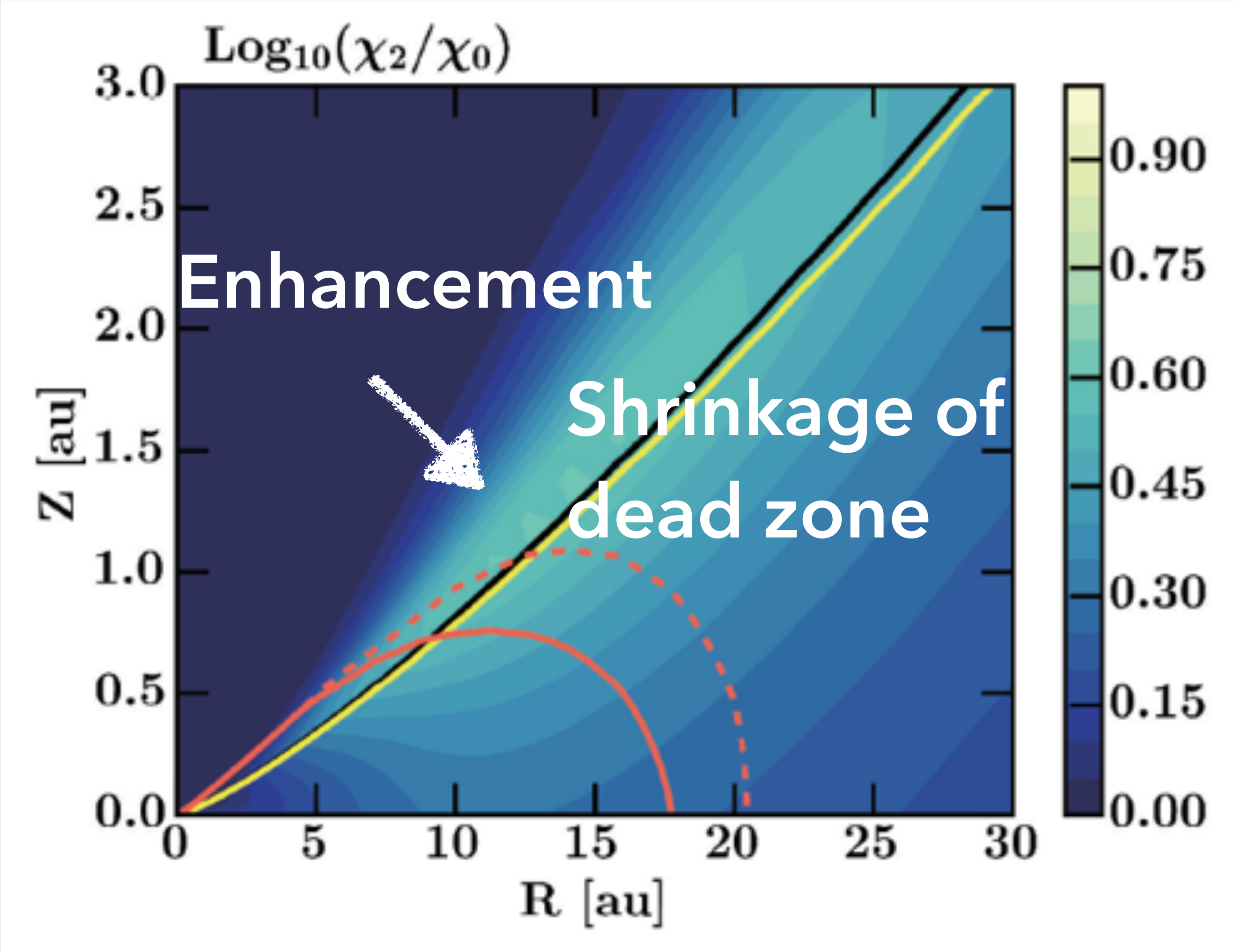
Impact of outflow X-rays on the disk ionization degree

Most of the outflow X-rays (10^29 erg/s)
are coming near the base (<20-30 au, Gudel+2011)

Ionization degree
(radio active nuclei, cosmic rays,
 and stellar X-rays)



Ratio of
the ion. deg. with the outflow XRs @ 10au
to the ion. deg. without the outflow XRs



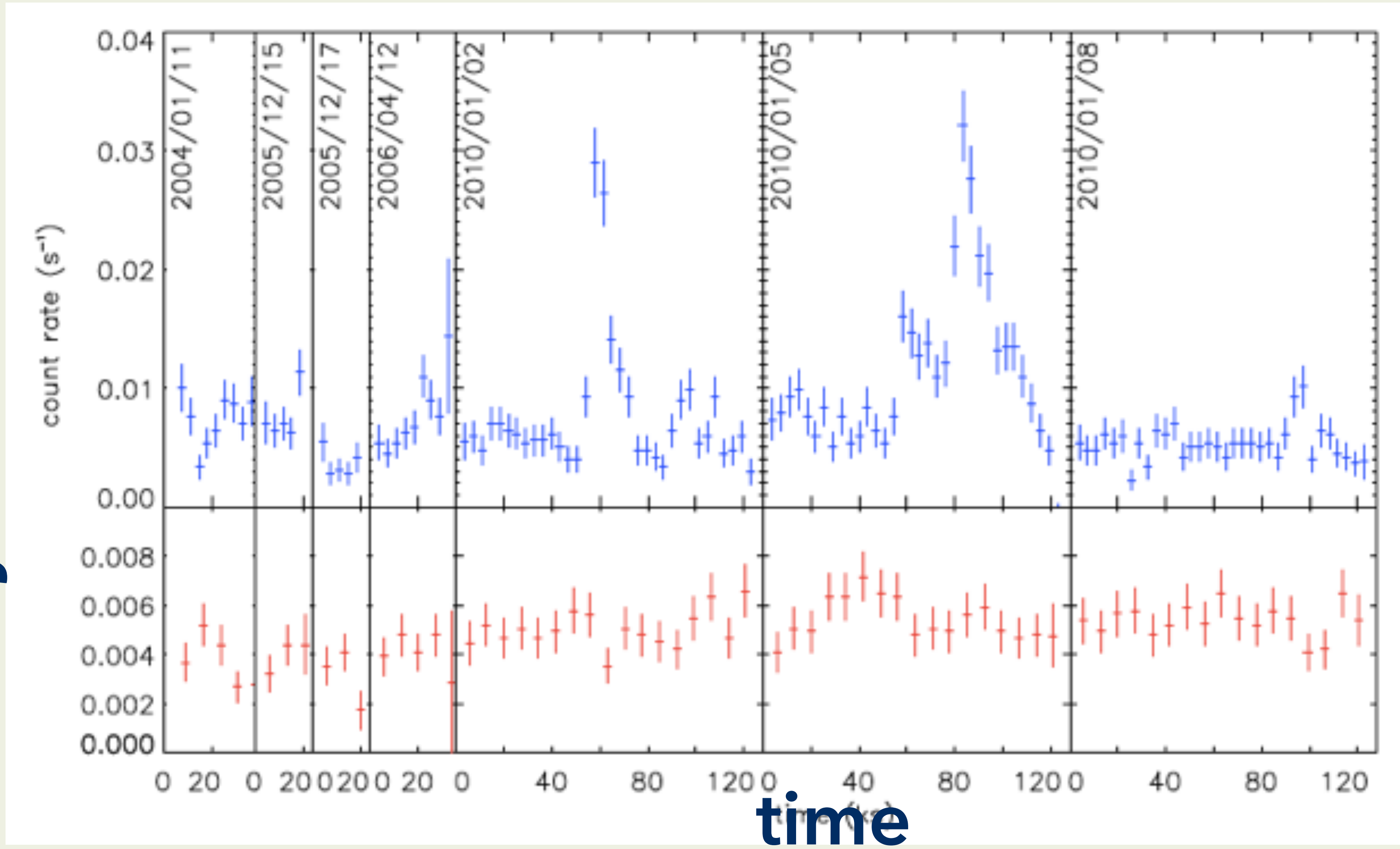
(Essentially the same as Sano+2000 model but stellar X-rays included)

Questions

- What is the heating/driving mechanisms ?
- Where is the most X-ray luminous region in the outflow? (not resolved. should be within ~30 au from the star)
  - Important if it is moderately close to the disk (<~10 au)
  - depends on the heating mechanisms.
- Are X-ray outflows persistent or transient ?
- Are X-ray outflows a common feature for YSOs ?

Puzzles about heating mechanisms

X-ray count rate



time

~6yr obs of DG Tau

X-ray from the star: highly time-variable

X-ray from the outflow base : quasi-steady over ~6yrs (Gudel+2011)

Stellar corona/wind ? Probably No.

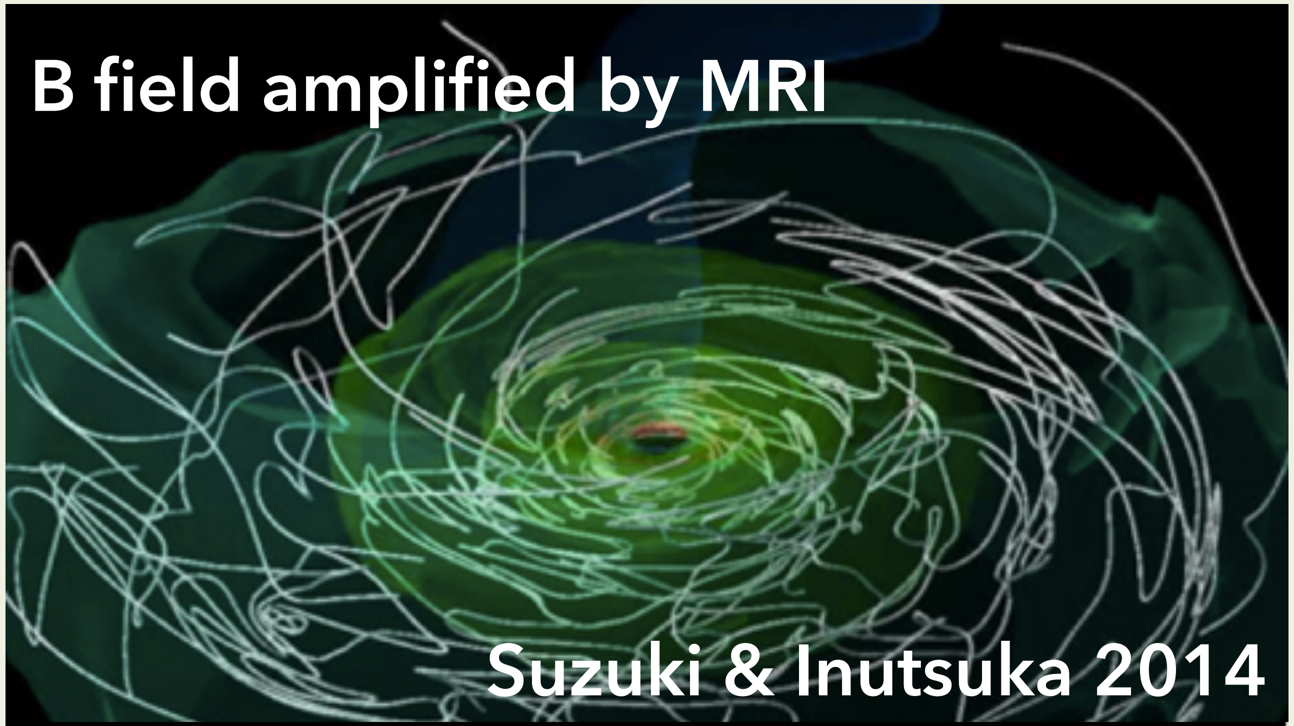
Accretion shock ? Ambiguous, but maybe not for DG Tau.

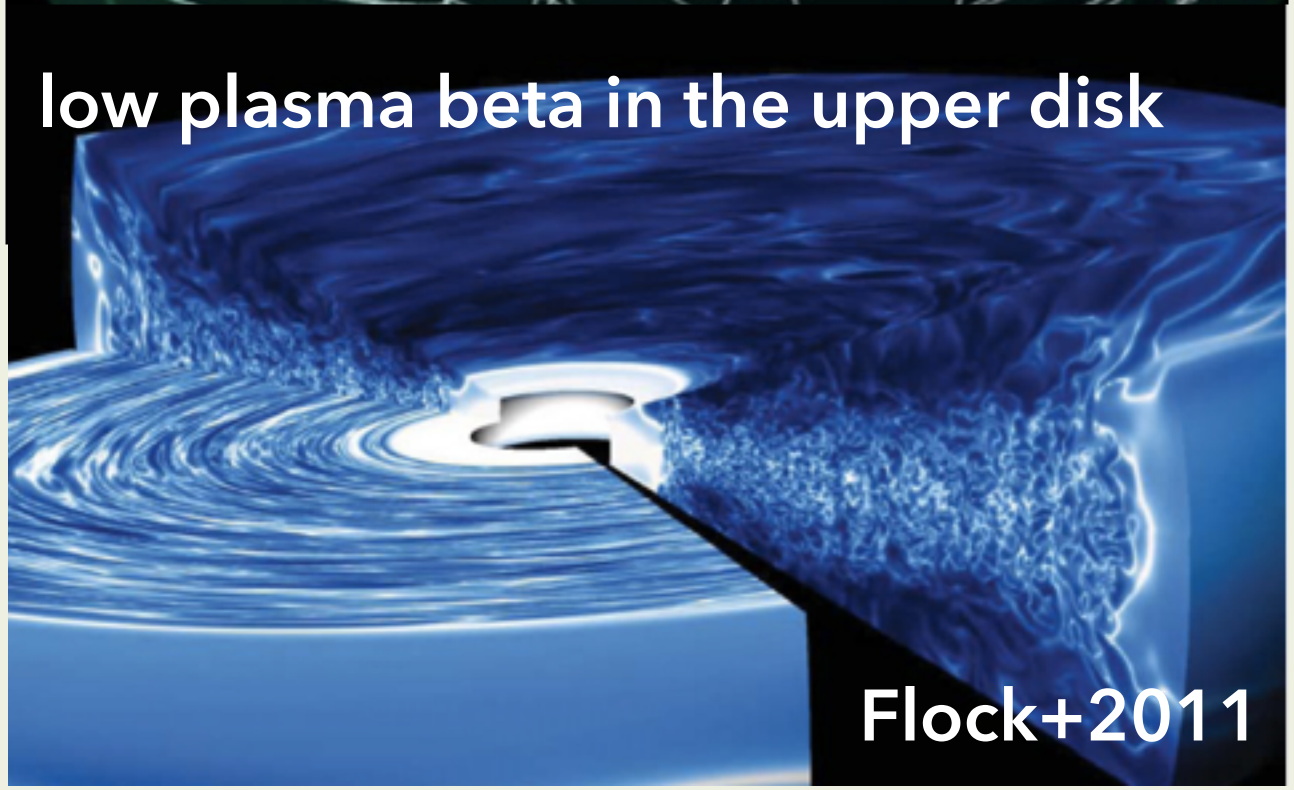
(Gudel + 2011)

Shock heating ? Very difficult. $T \approx 3.8 \text{ MK} \left(\frac{v_{\text{jump}}}{500 \text{ km s}^{-1}} \right)^2$

Need very large v and shock at the base (not observed) (Raga + 2002)

Our approach :
Magnetic heating in the disk atmosphere





Good example of the magnetically heated atmosphere:
Solar corona (~1MK)

credit: TRACE/NASA

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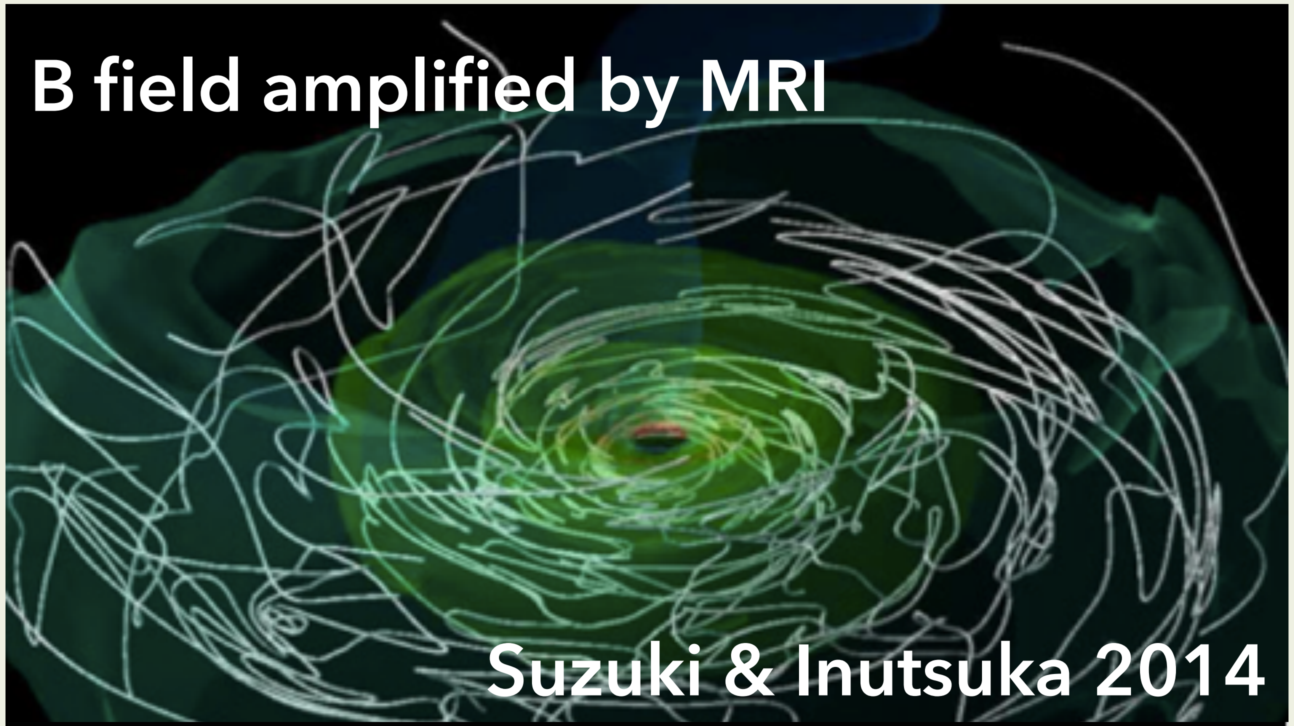
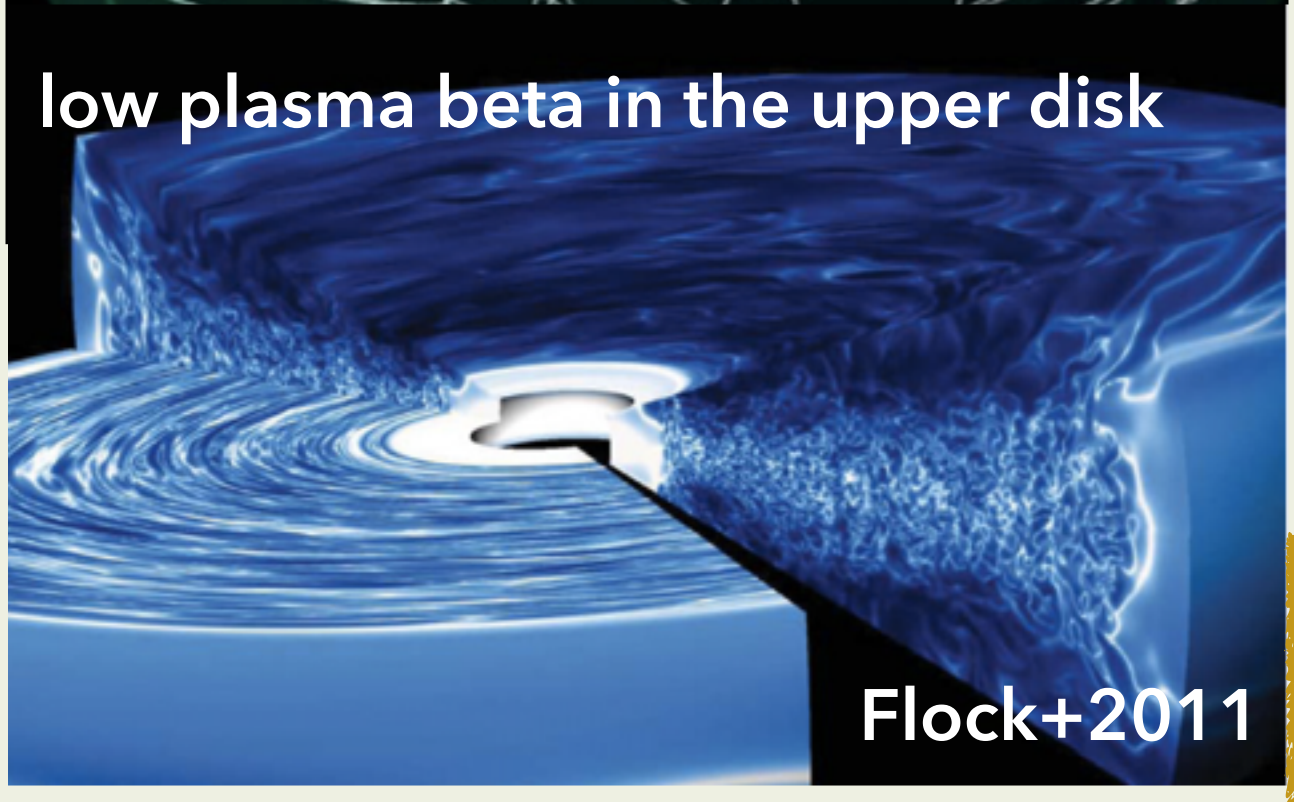
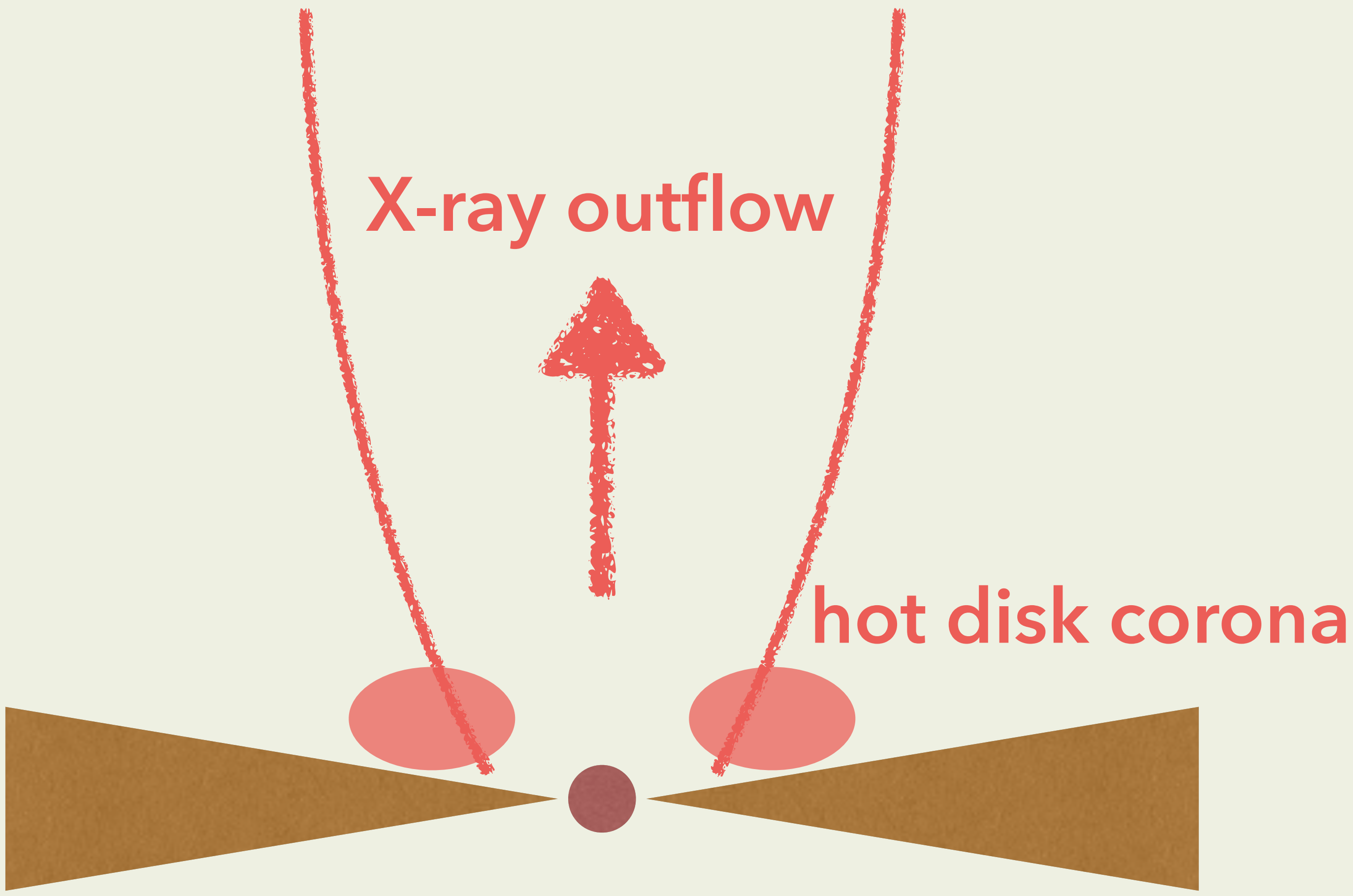
Magnetic heating in the disk atmosphere





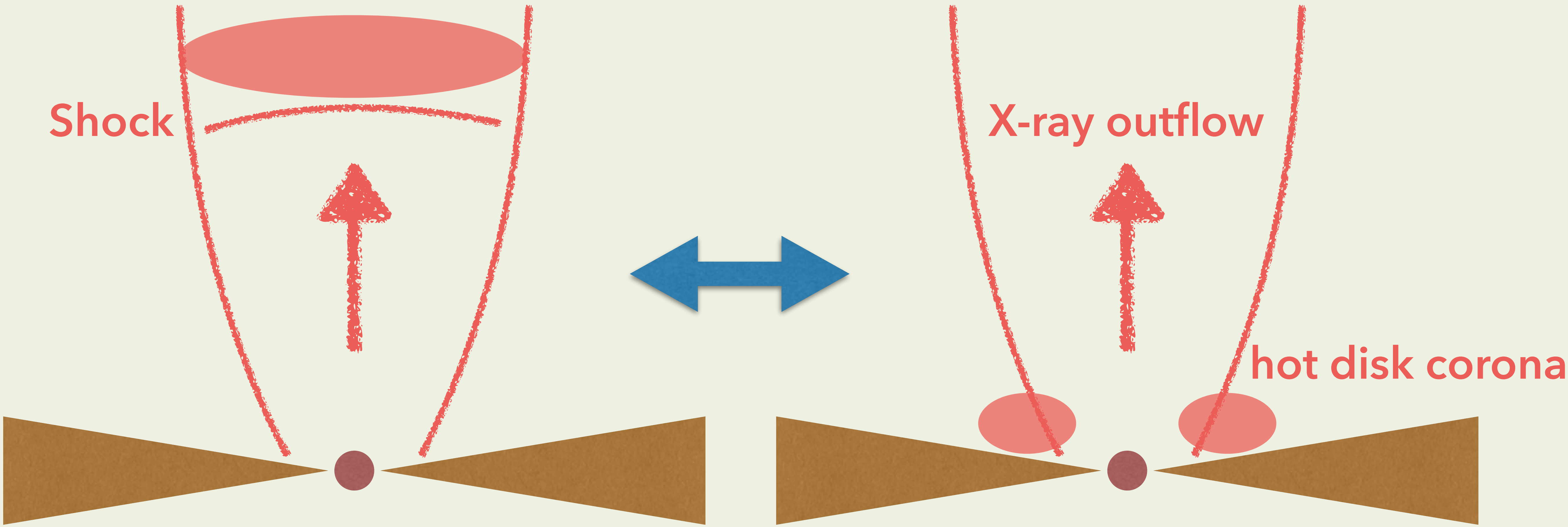


Magnetic heating may account for the quasi-steady heating at the base

We developed a theoretical model of X-ray outflows from a hot disk corona

ST, Suzuki, and Shibata, submitted to ApJ

Our approach : Magnetic heating in the disk atmosphere



Shock heating picture

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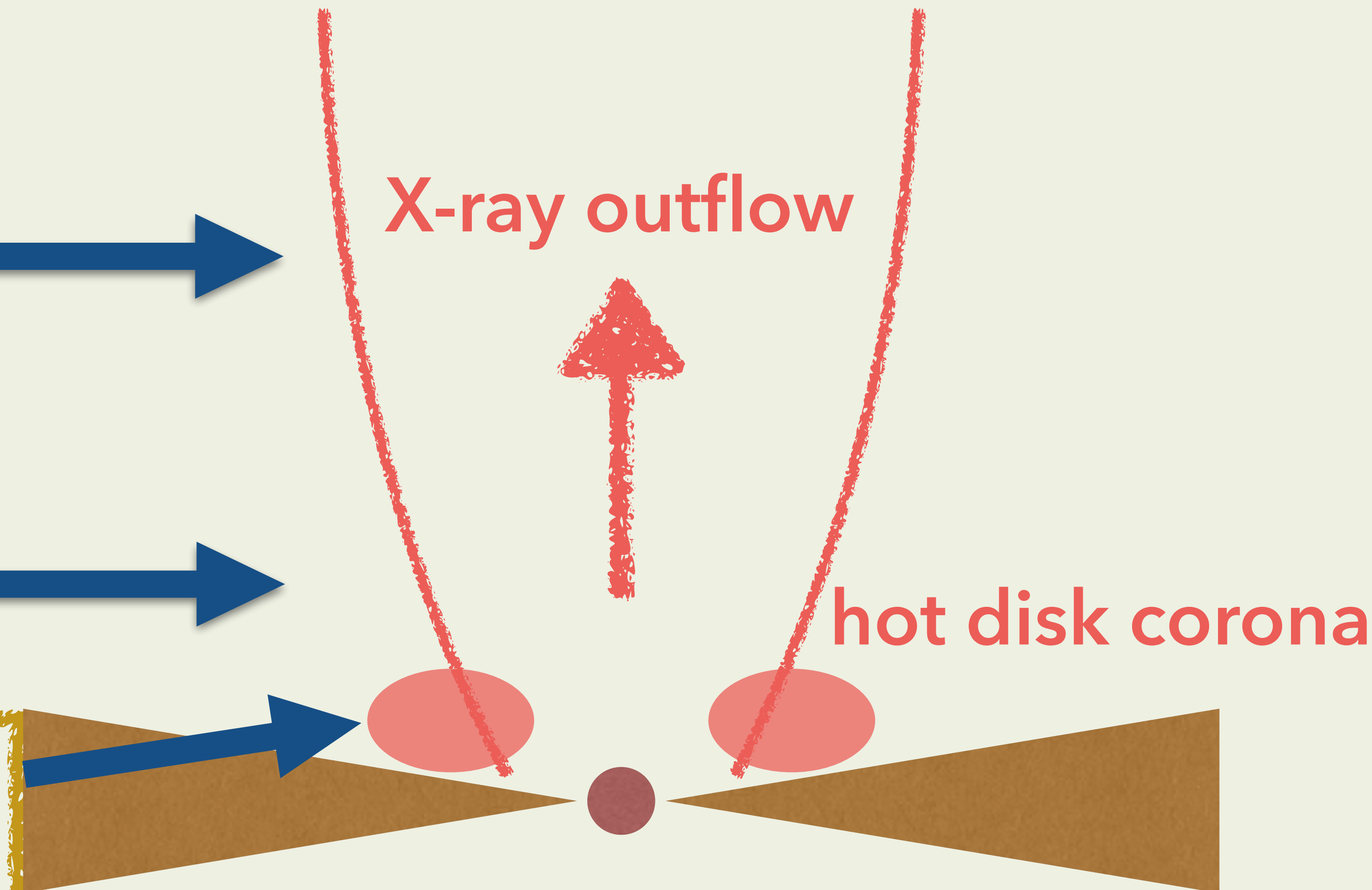
Our approach :
Magnetic heating in the disk atmosphere

3. Outflow property
(T, mass loss rate, velocity)

2. Driving mechanism

1. Thermal property at the base
(T, density, …)



Magnetic heating may account for
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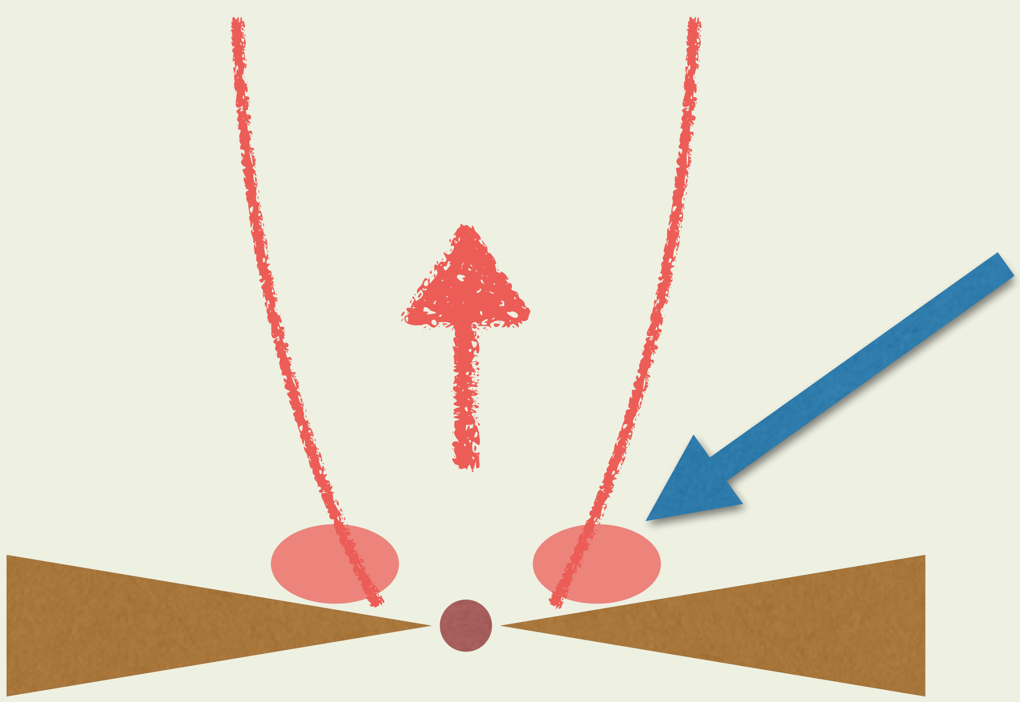
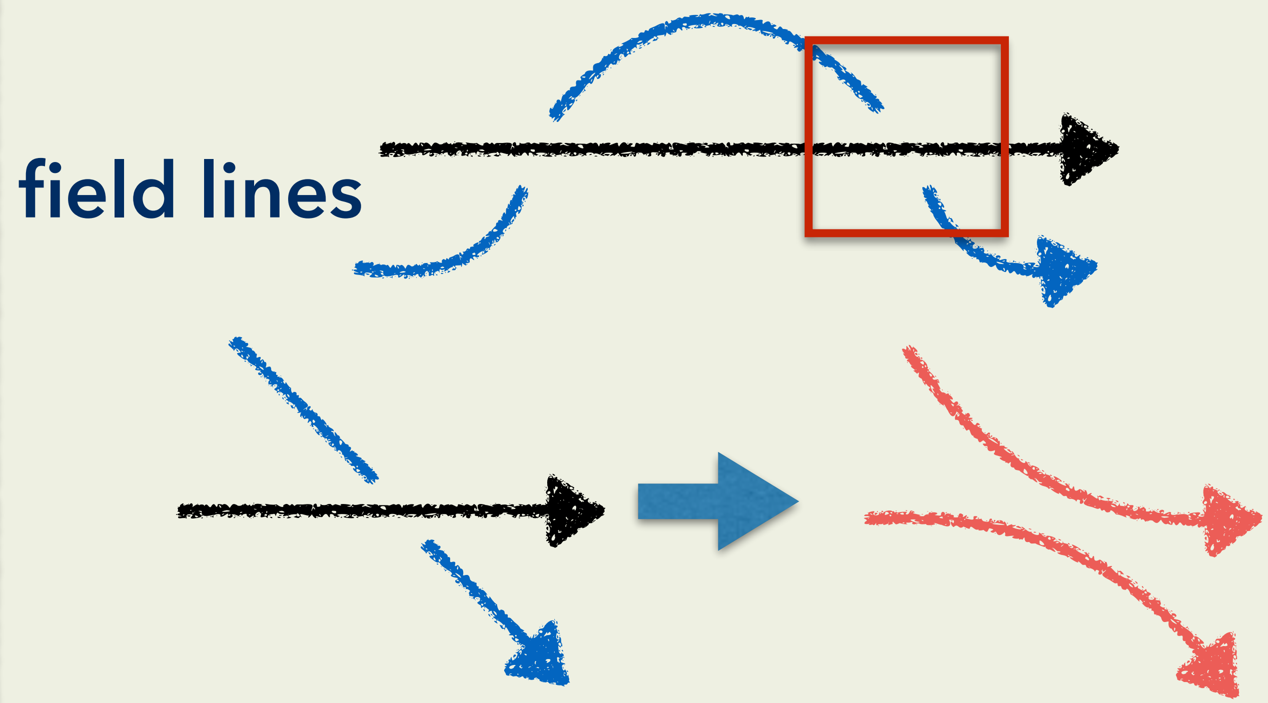
Supply and dissipation of magnetic energy



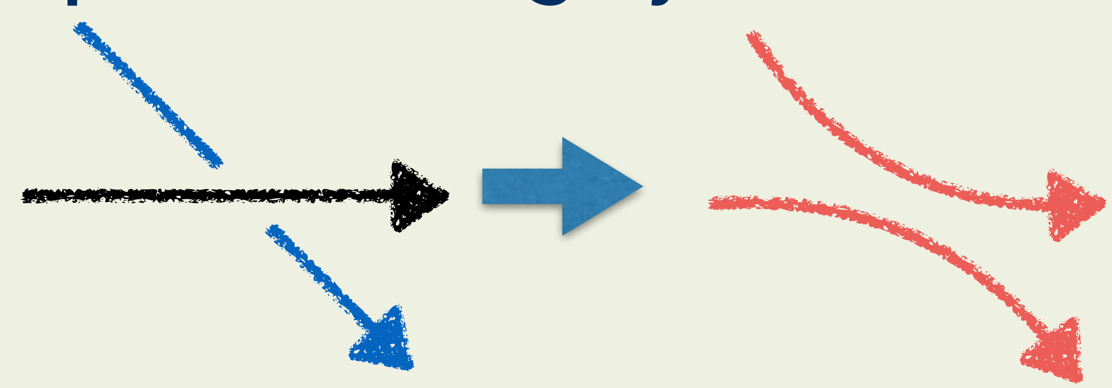
Rise of a magnetic loop

(e.g. Hirose & Turner 2011, Io & Suzuki 2014)



magnetic reconnection heating

Example of heating by 3D reconnection



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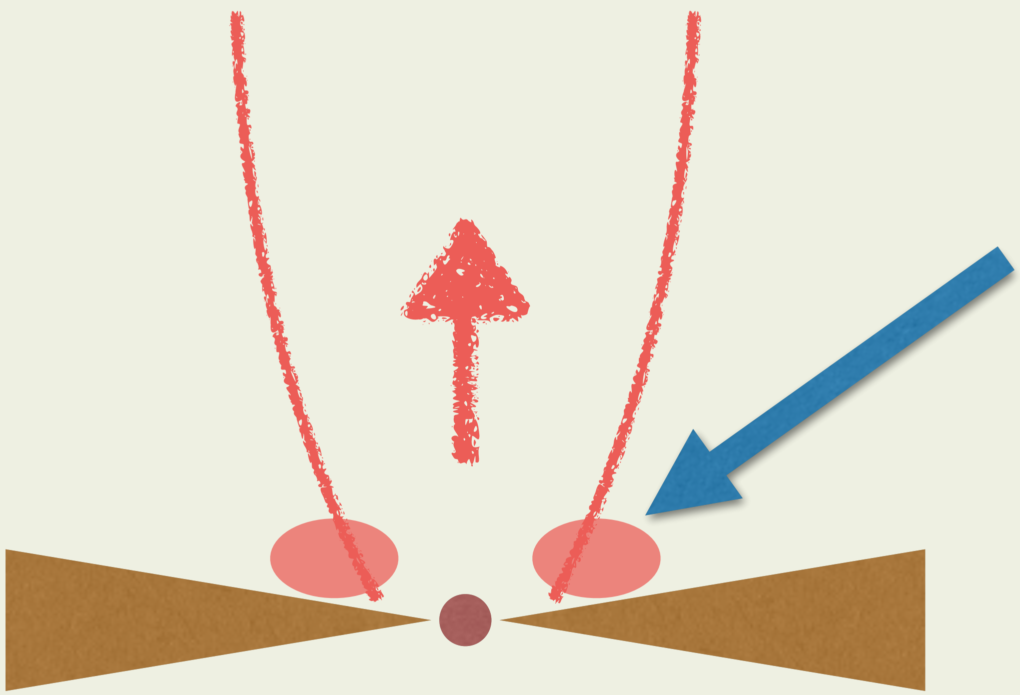

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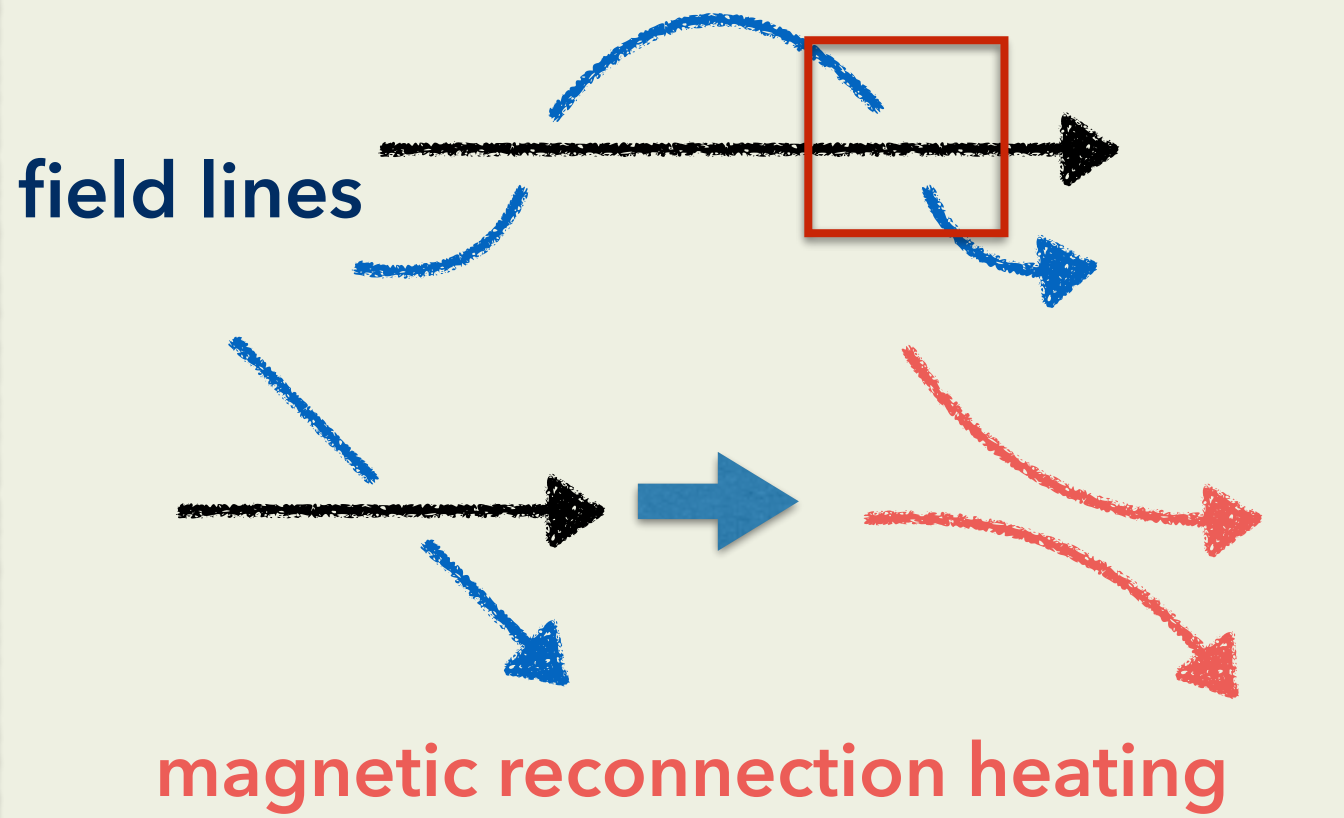


Energy released by reconnection : $e_{\mathrm{mag}} = f \dfrac{B^2}{8\pi}$

Energy injection timescale : ~ growth timescale of Parker instability τ_{P}

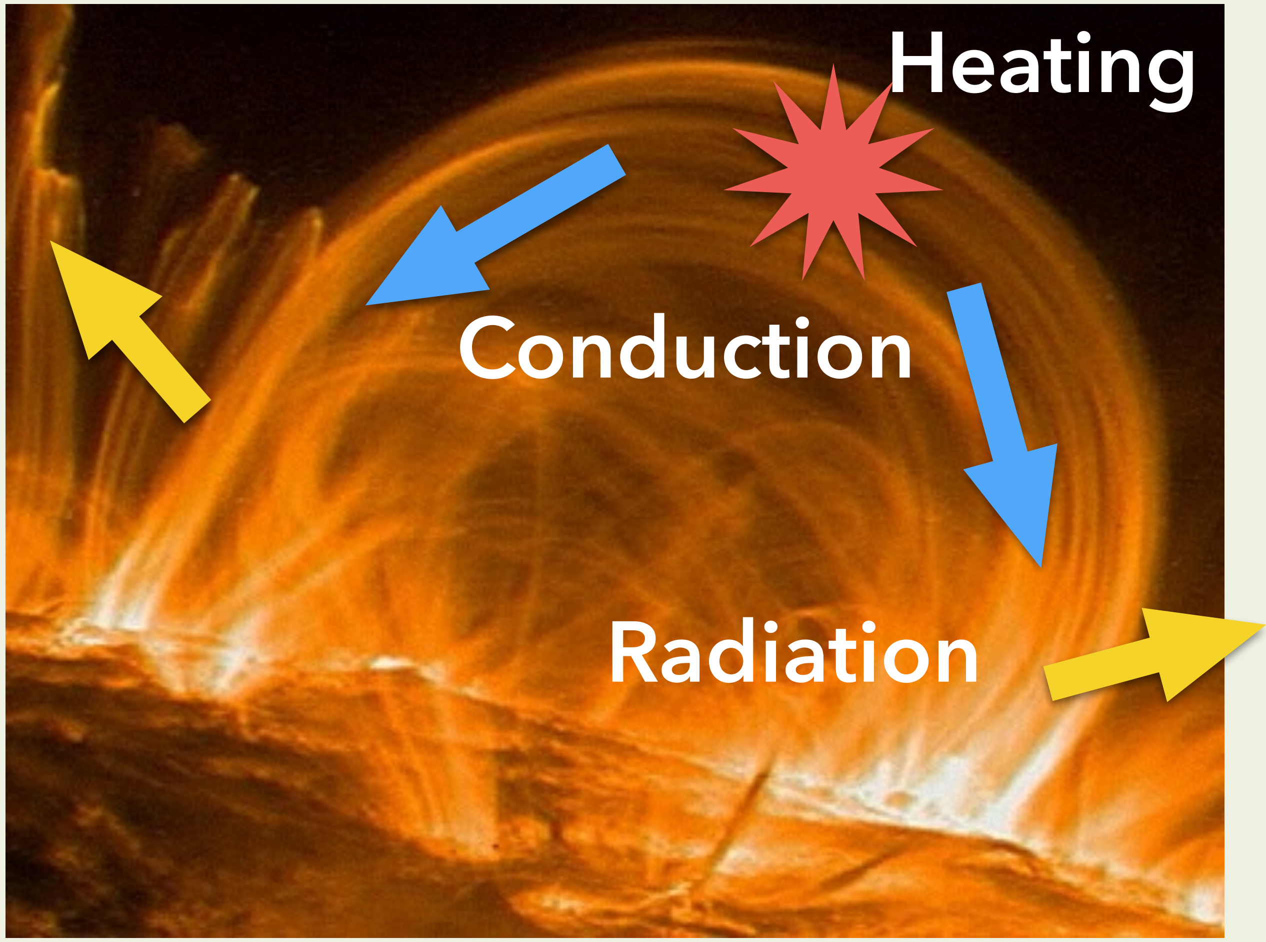
Heating rate [erg/s/cm^3]: $E_{\mathrm{H}} = \dfrac{e_{\mathrm{mag}}}{\tau_{\mathrm{P}}}$

Disk coronal temperature & density: energy balance between the heating and cooling

In a quasi-steady state,

heating ~ conduction cooling ~ radiative cooling

(1) (2)



credit: TRACE/NASA

(1) determines the temperature

(2) determines the density
(called RTV scaling law)

The thermal property at the base can be determined.

Scaling relations : coronal temperature

Disk model (Kusaka + 1970)

$$T_{\rm disk} = 10^3 \left(\frac{r}{0.1\ \rm au}\right)^{-3/4}\ \rm K$$

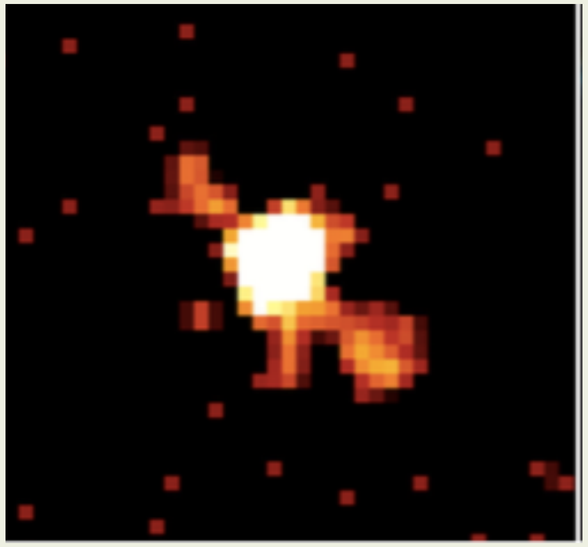
$$\rho_{\rm disk} = 10^{-8} \left(\frac{r}{0.1\ \rm au}\right)^{-15/8}\ \rm g\ cm^{-3}$$

Disk plasma beta

$$\boxed{T_{\rm c} \approx 3.4 \times 10^6\ \rm K \left(\frac{M_*}{M_\odot}\right)^{-1/7} \left(\frac{\beta_{\rm disk}}{100}\right)^{-3/7} \left(\frac{r}{0.1\ \rm au}\right)^{-15/28}}$$

We confirm that the outflow temperature should be similar to the coronal temperature Tc, because we can neglect cooling effects during its propagation.

Consistent !



- Temperature: 3.4 MK (Gudel+2008)
- Mass loss rate: $1.3 \times 10^{-11} M_\odot {\rm yr}^{-1}$ (Schneider & Schmitt 2008)

Scaling relations : Mass loss rate

Mass loss rate: $\dot{M} = (\rho A v)_{\rm base}$

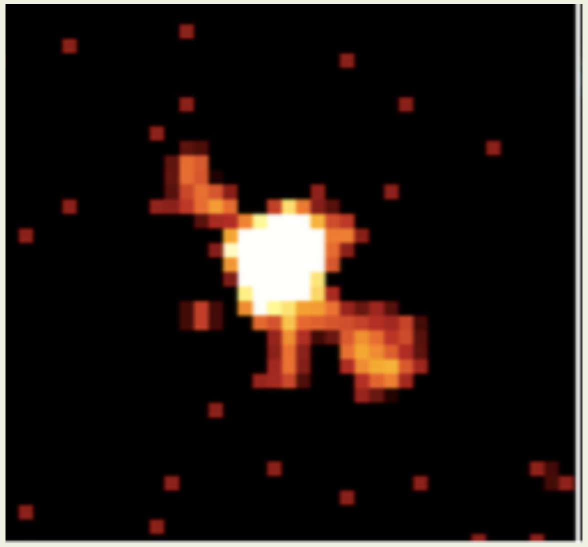
Coronal density

$$\rho_{\rm c} \approx 3.1 \times 10^{-17}\ {\rm g\ cm^{-3}} \left(\frac{M_*}{M_\odot}\right)^{3/14} \left(\frac{\beta_{\rm disk}}{100}\right)^{-6/7} \left(\frac{r}{0.1\ {\rm au}}\right)^{-123/56}$$

The velocity depends on the driving mechanism (magnetic pressure, magnetocentrifugal, etc. Kudoh & Shibata 1997) : Magnetocentrifugal

$$\boxed{\dot{M} \approx 2.5 \times 10^{-11}\ {\rm M_\odot\ yr^{-1}} \left(\frac{M_*}{M_\odot}\right)^{1/14} \left(\frac{\beta_{\rm disk}}{100}\right)^{-9/7} \left(\frac{r}{0.1\ {\rm au}}\right)^{43/28}}$$

Consistent !



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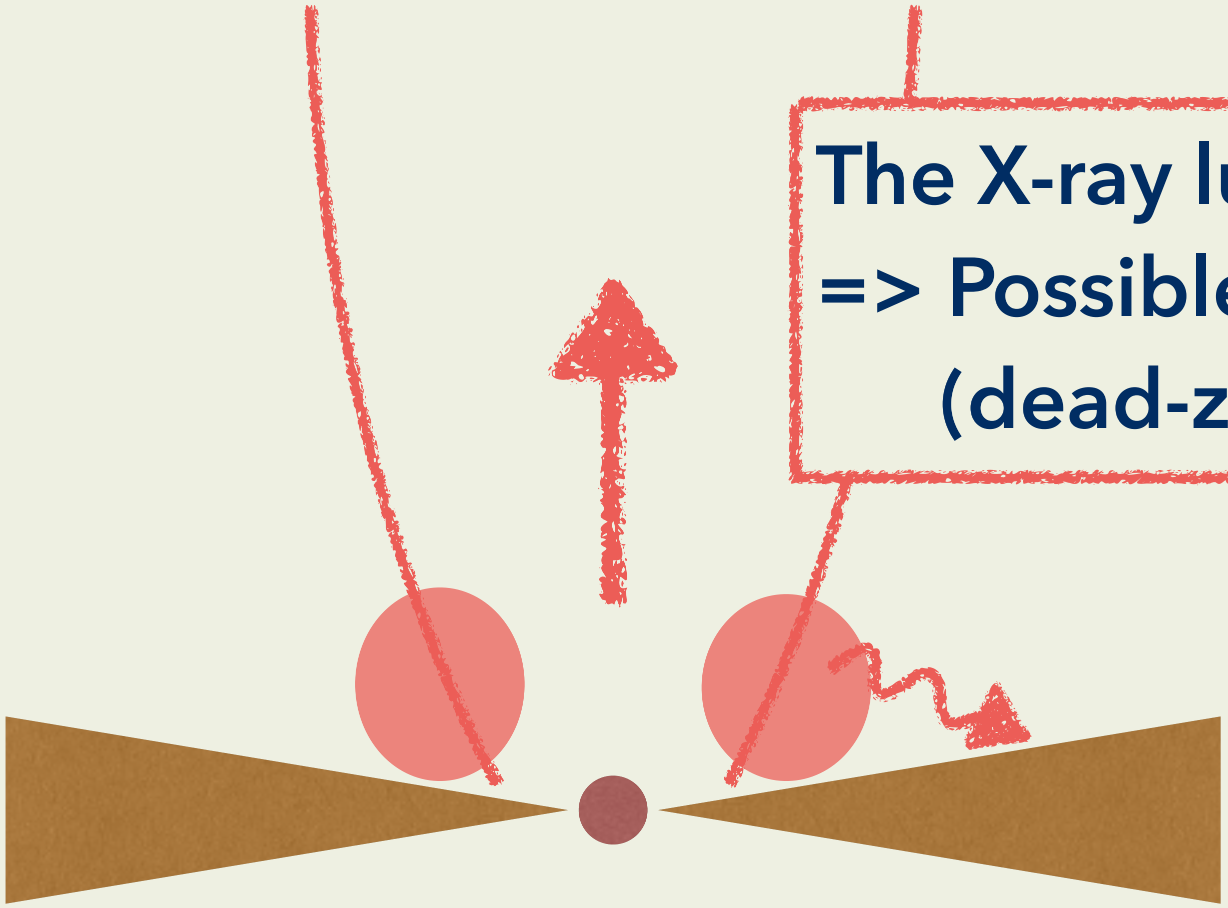
What can we learn?



The X-ray luminous region will be near the disk
=> Possible significant impact on the disk
(dead-zone size, non-ideal MHD effects)

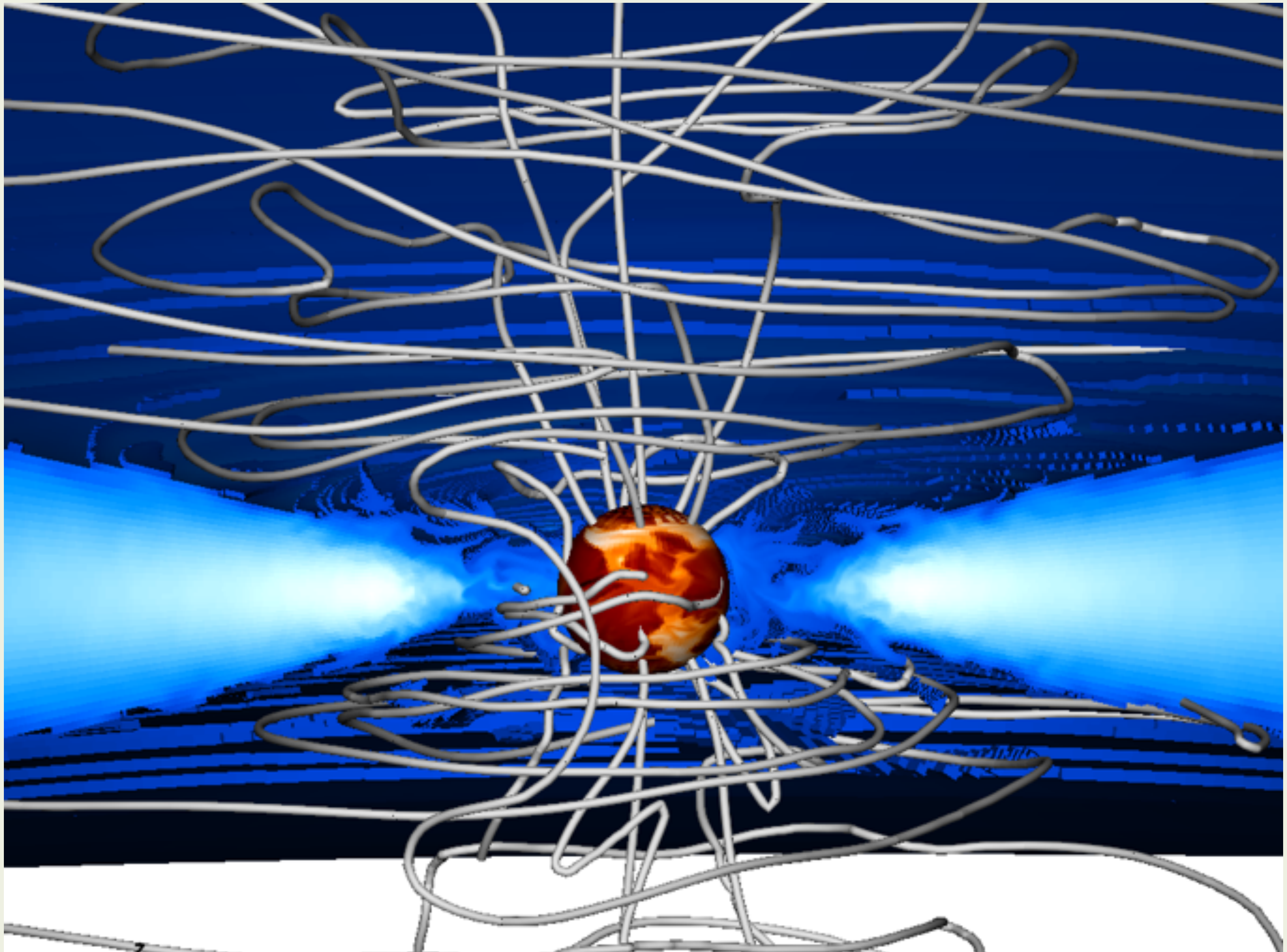
The disk B can be inferred from the outflow temperature T:

$$B_{\phi,\mathrm{disk}} \approx 20\ G \left(\frac{T_{\mathrm{c}}}{4.0 \times 10^{6}\ \mathrm{K}}\right)^{7/6} \left(\frac{r}{0.1\ \mathrm{au}}\right)^{-11/16}$$

3D MHD modeling

Inner disk structure: star-disk interaction important

We started 3D MHD modeling using the Athena ++ code developed by the Princeton team and K. Tomida.



Summary

- We developed a theoretical model of X-ray outflows from young stellar objects. In this model magnetic reconnection in the disk atmosphere plays an important role in heating the outflows.
- The estimated temperature and mass loss rate are consistent with observations in the case of the field strength of ~20 G and the heating region is < 0.1 au. Our scaling relation for the temperature will be useful for estimating the field strength.
- We started MHD simulations of the star-disk interaction.