Cosmic Plasma Revisited:
New Landscape of High-Energy Astrophysical Bursts
YITP, Kyoto U. (2023.10.27)

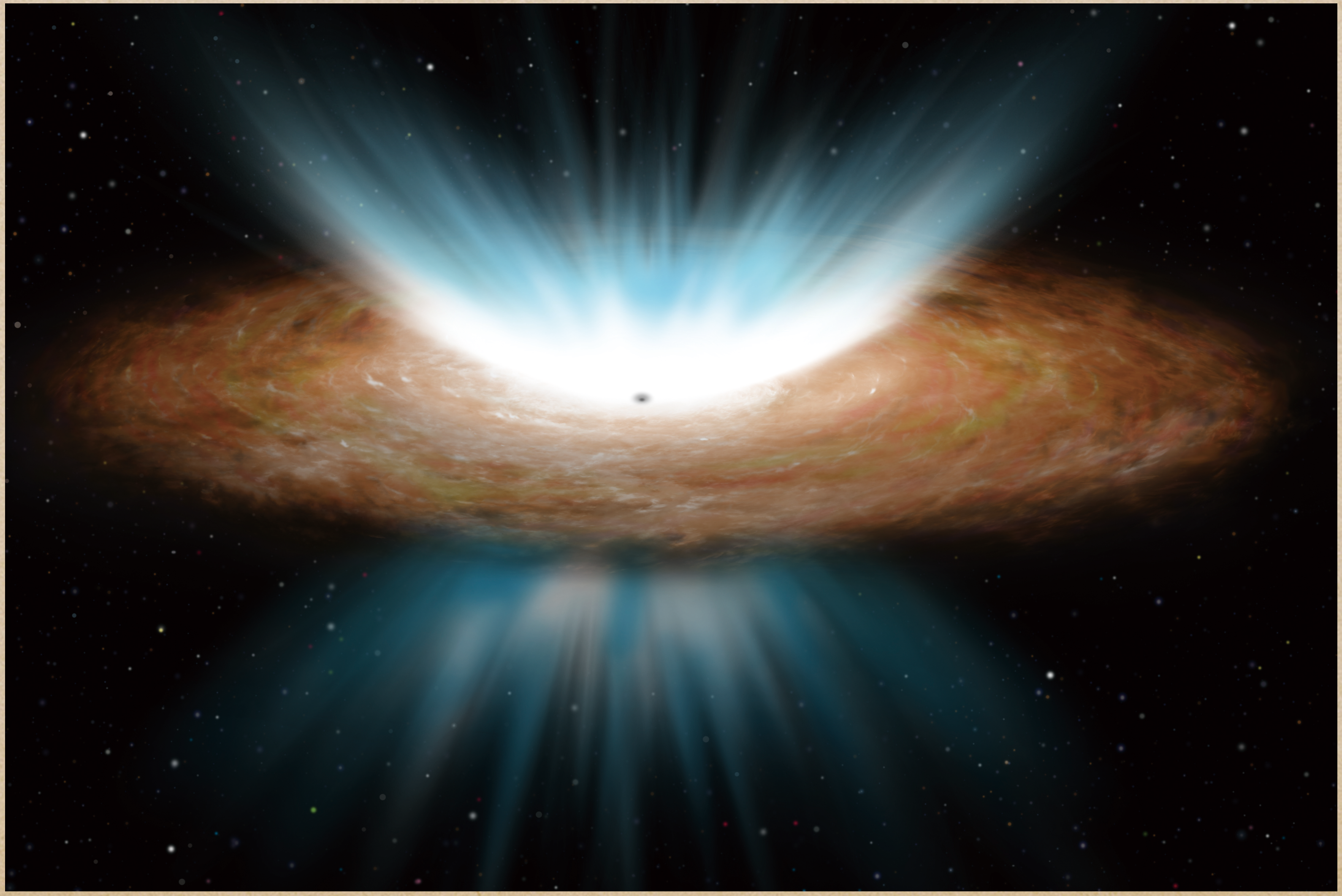
Ultra Fast Outflows (UFO) from Active Galactic Nuclei (AGN)

Misaki Mizumoto

(U. of Teacher Edu. Fukuoka)

Scope of this talk

- Hot and fast winds (UltraFast Outflow; UFO) exist in some AGN. They are accretion disk winds, launching from the close vicinity of the central supermassive black hole.

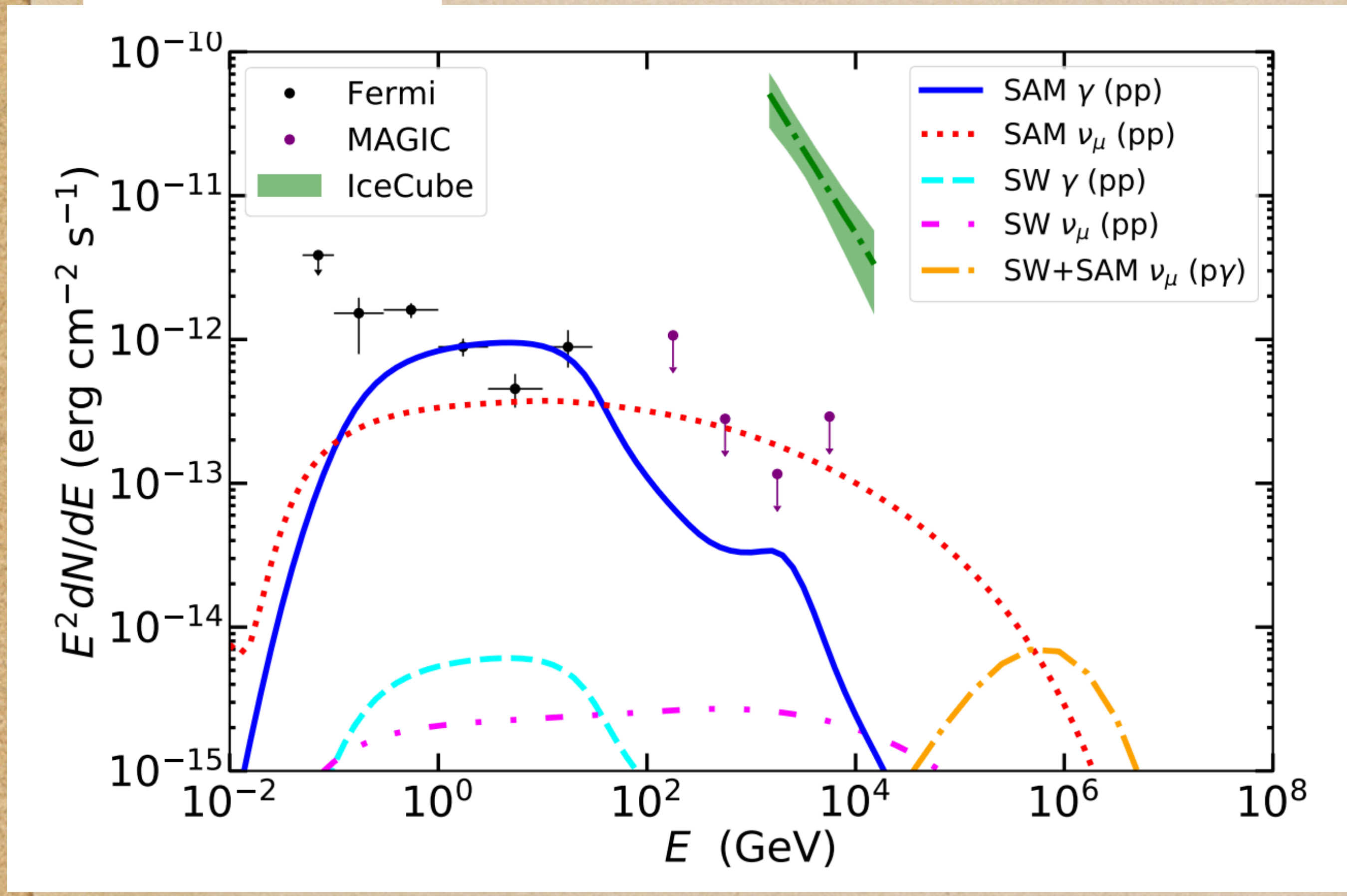


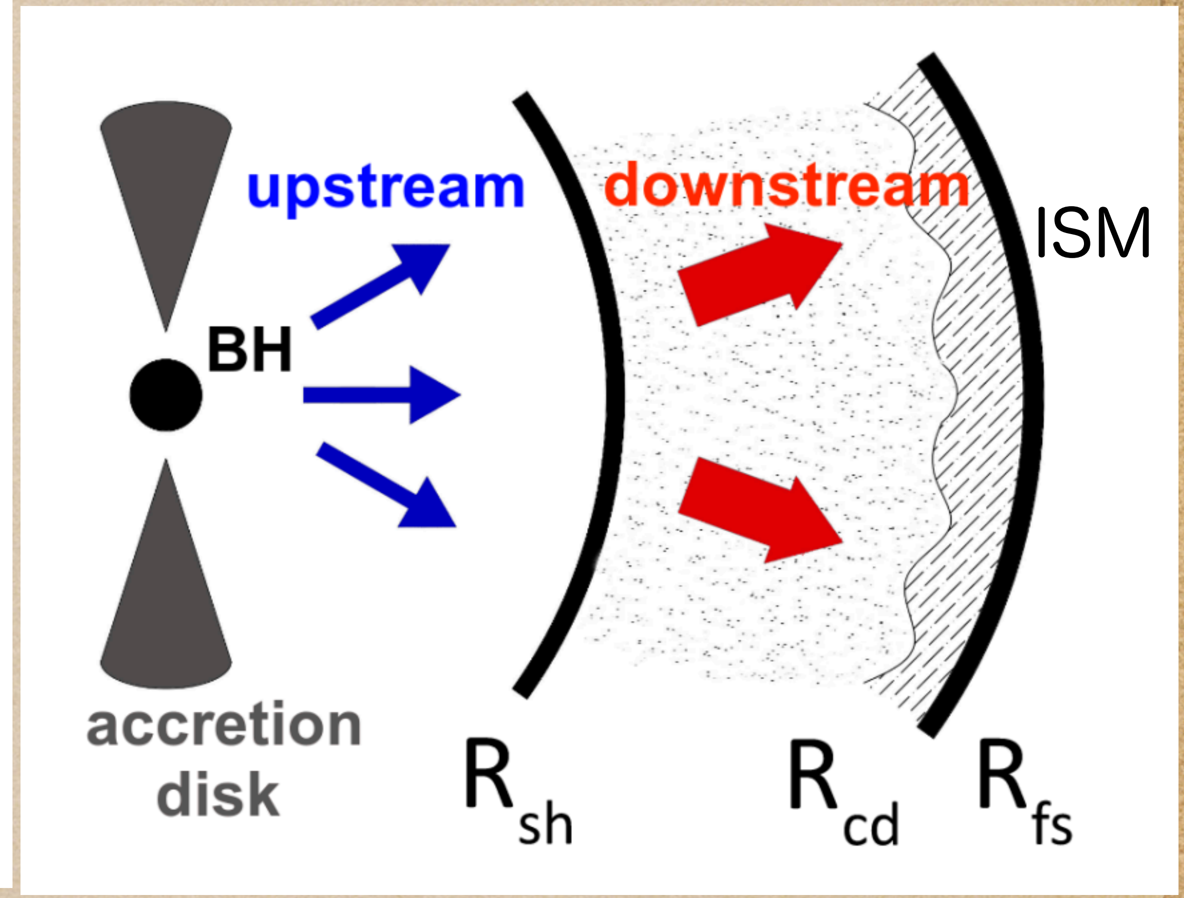
Credit: Kyoto Univ., MM

UFO x high energy physics

UFO shock can trigger particle acceleration?

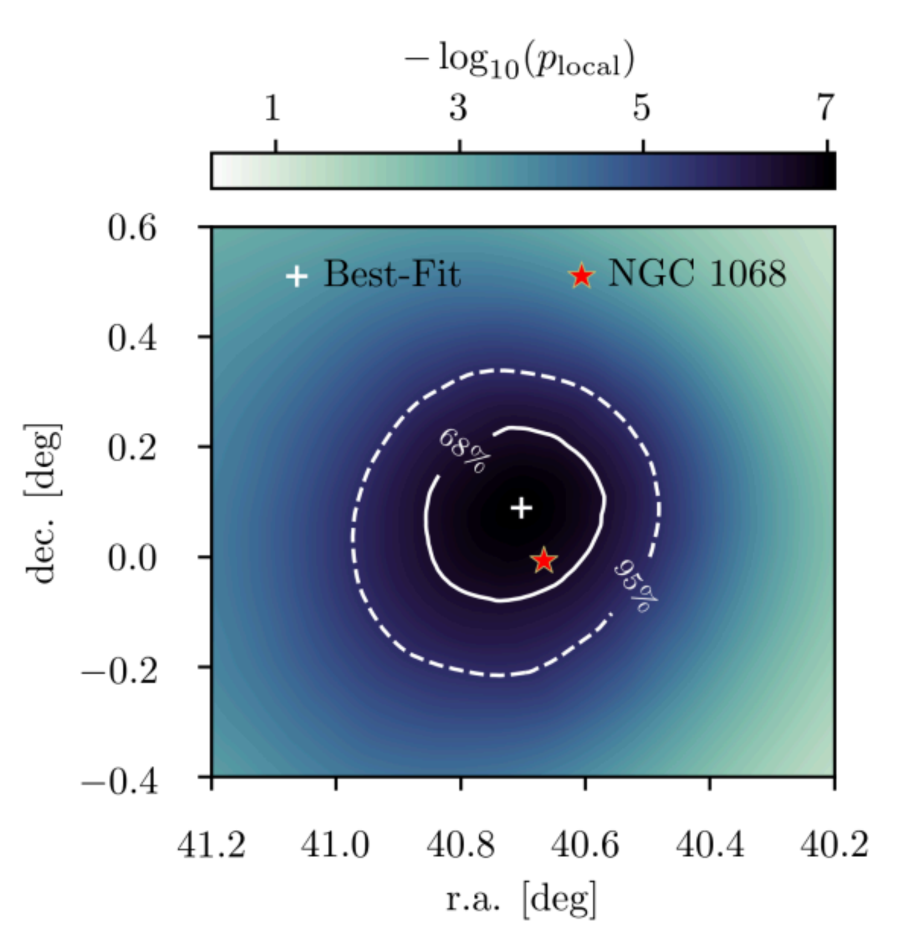
NGC 1068





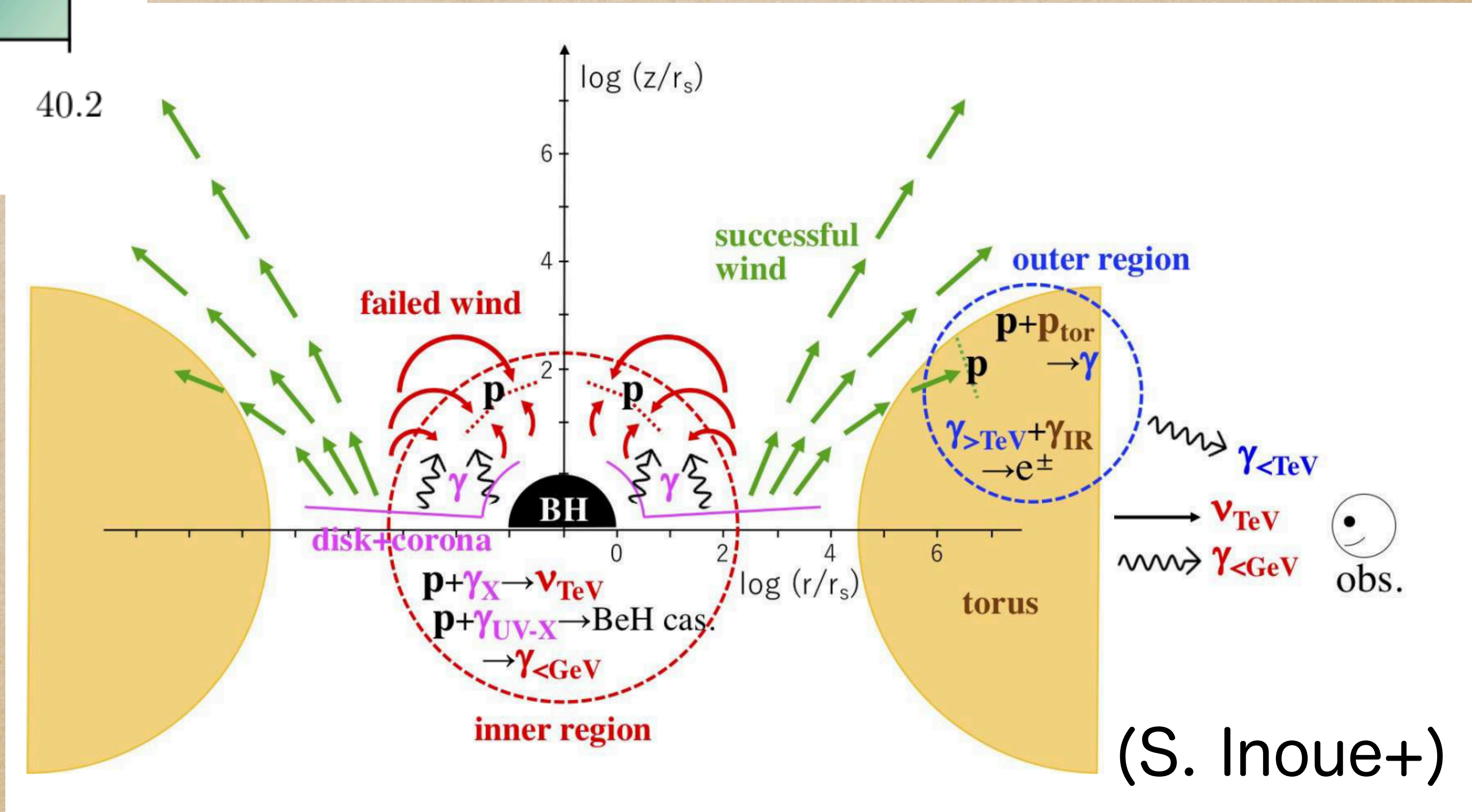
(Peretti+23)

UFO x high energy physics



Neutrino detection from NGC 1068 (Icecube collab. 2022)

UFO shock can explain neutrino?

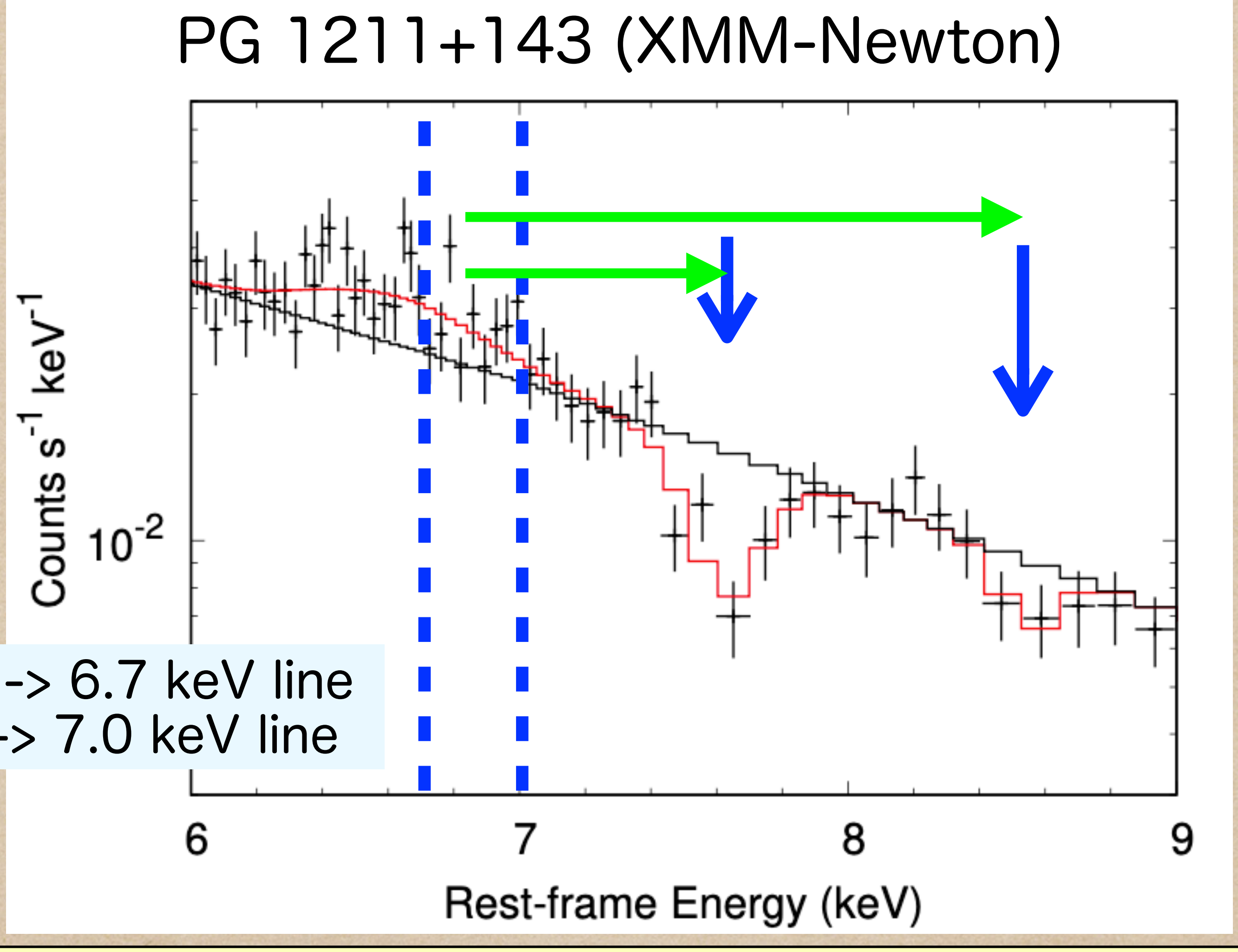


Scope of this talk

- (Honestly speaking, I am not familiar with the particle acceleration and neutrino observations...)
- I will provide you the material to discuss these issues.
- This talk has the following three sections:
    1. What is UFO? How is the UFO observed? What drives UFO?
    2. How does the UFO travel? (Interaction between UFO and the ambient matter)
    3. Our recent study on UFO (if time permits)

1. What is UFO? How is the UFO observed? What drives UFO?

Observation of UFO



FeXXV (He-like Fe) -> 6.7 keV line
FeXXVI (H-like Fe) -> 7.0 keV line

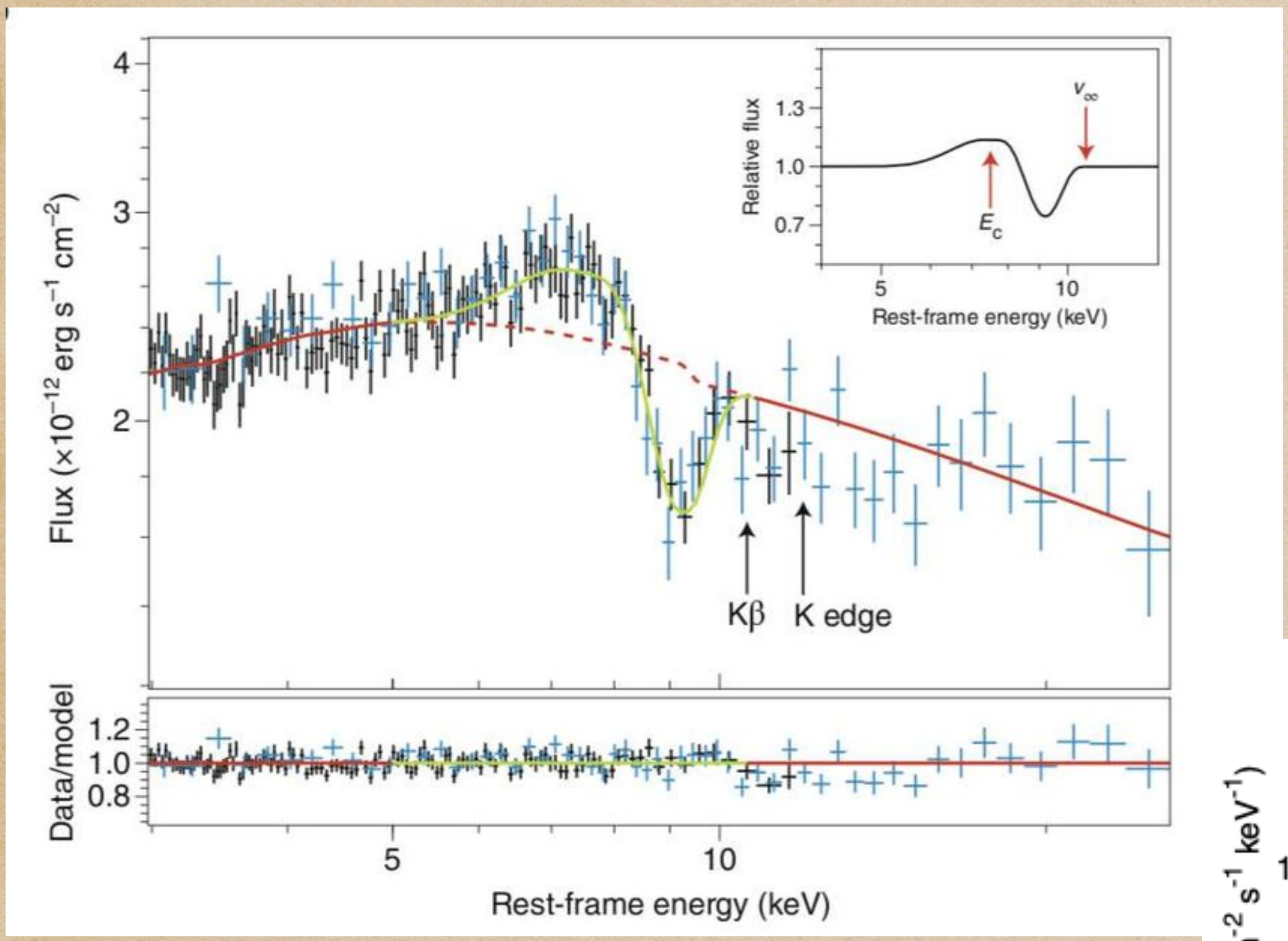
1. Very fast (velocity = 5-30% of the light speed)
2. Highly photo-ionized (He-like and/or H-like Fe-K lines)
3. High column density ($N_H = 10^{22}$-10^{24} cm^{-2})

UFO detection rate

35% (36/101; XMM-Newton; Tombesi et al. 2010)

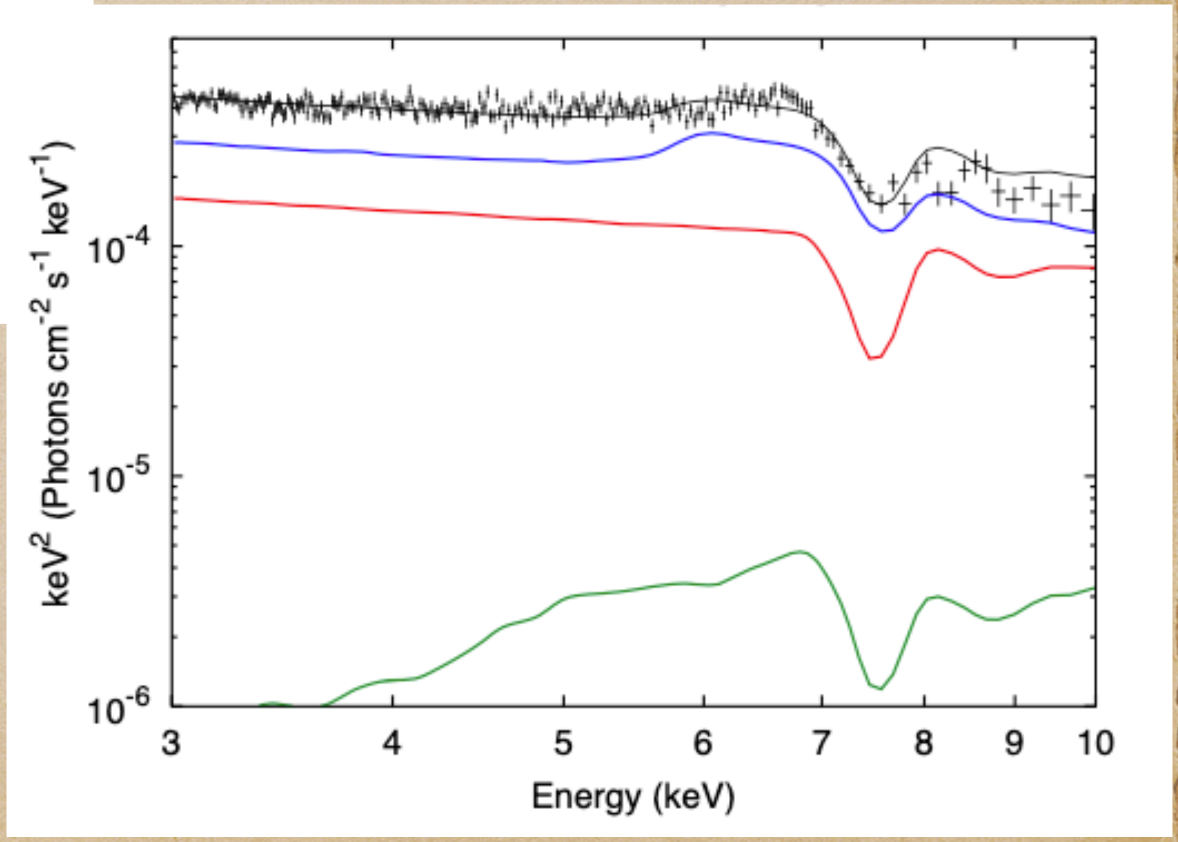
40% (20/51; Suzaku; Gofford et al. 2015)

Examples of UFO

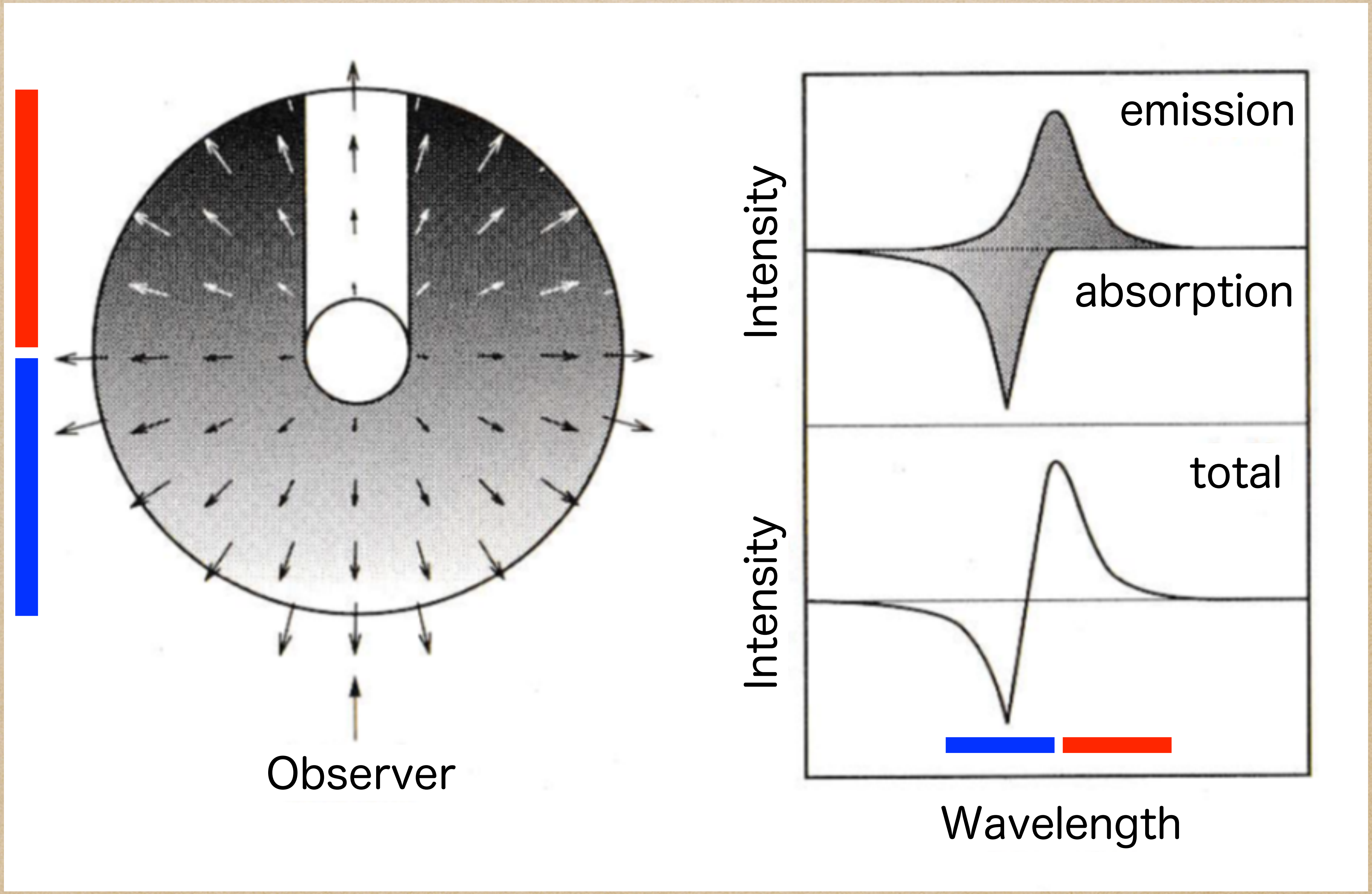


PDS 456 (Nardini+15)

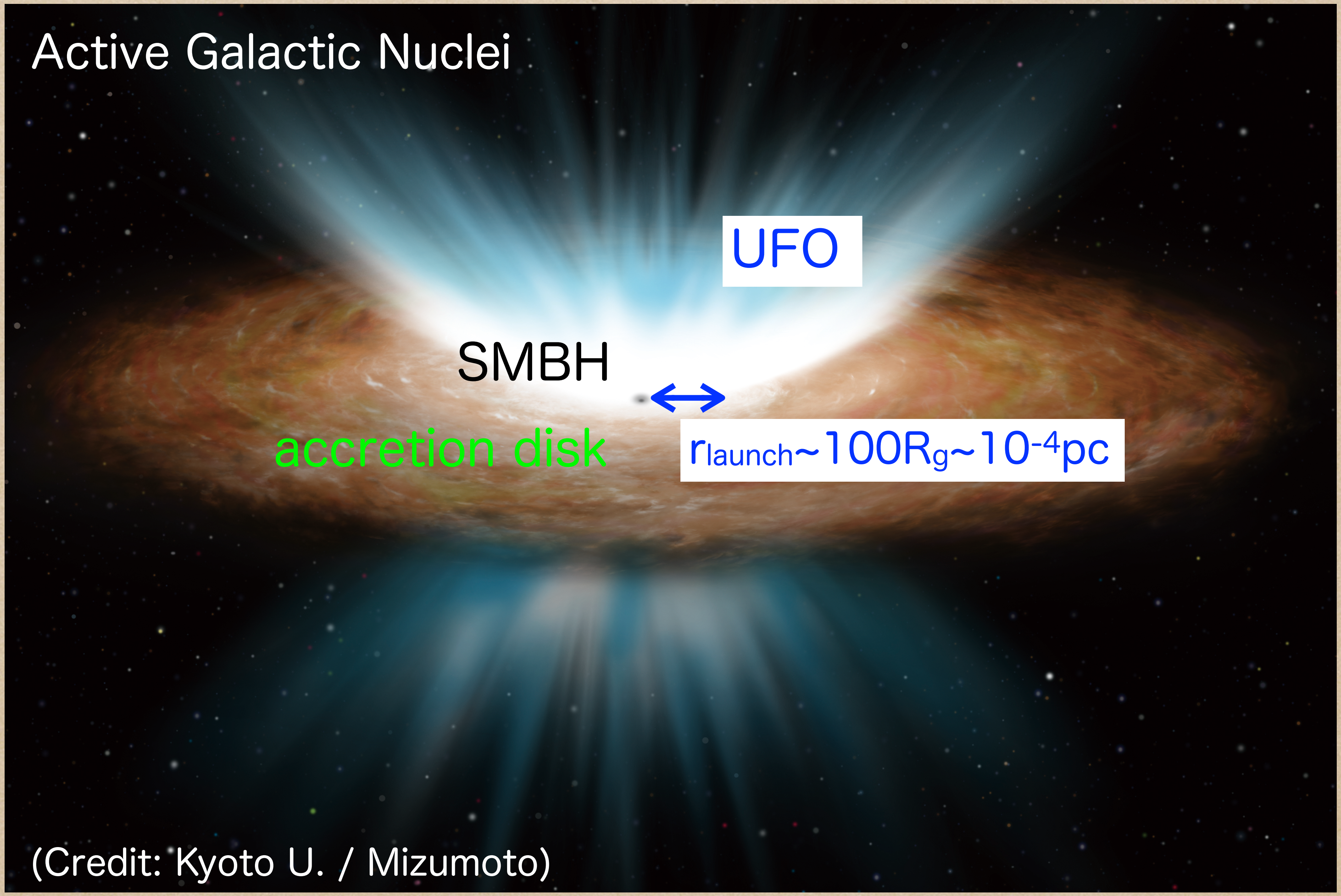
1H 0707-495 (MM+19)



P Cygni profile



Schematic picture of UFO

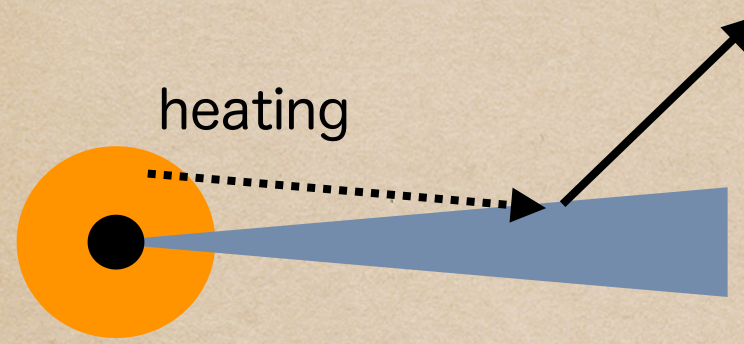


$r_{launch}=2GM_{BH}/v_{wind}^2$

↑ Assumption that wind velocity = escape velocity

UFO launching mechanism

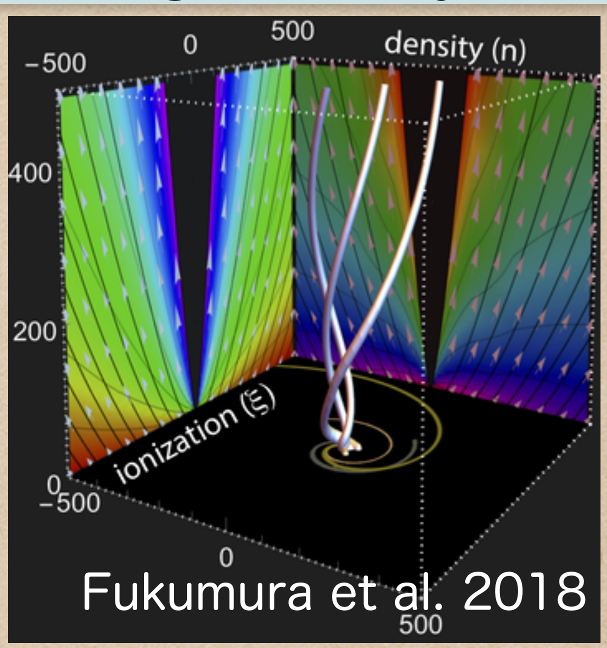
1. Thermally driven



However,
- Wind radius > disc outer radius
- Wind velocity (~500km/s) << UFO

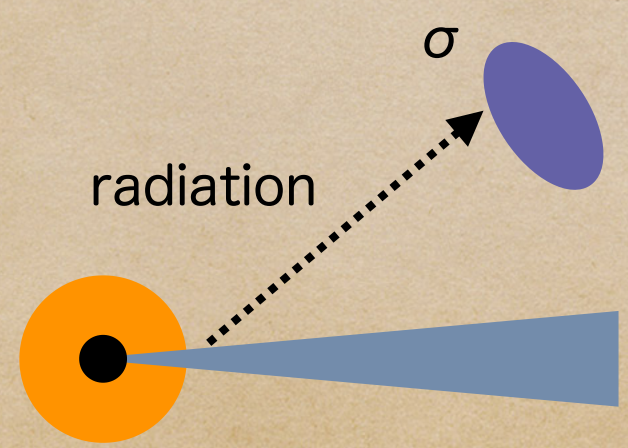
(may be at work for slower wind; MM+19a)

2. Magnetically driven



- can launch (almost) all kinds of wind
- depend on the (currently unknown) magnetic field configuration
- (Not covered in this talk)

3. Radiatively driven



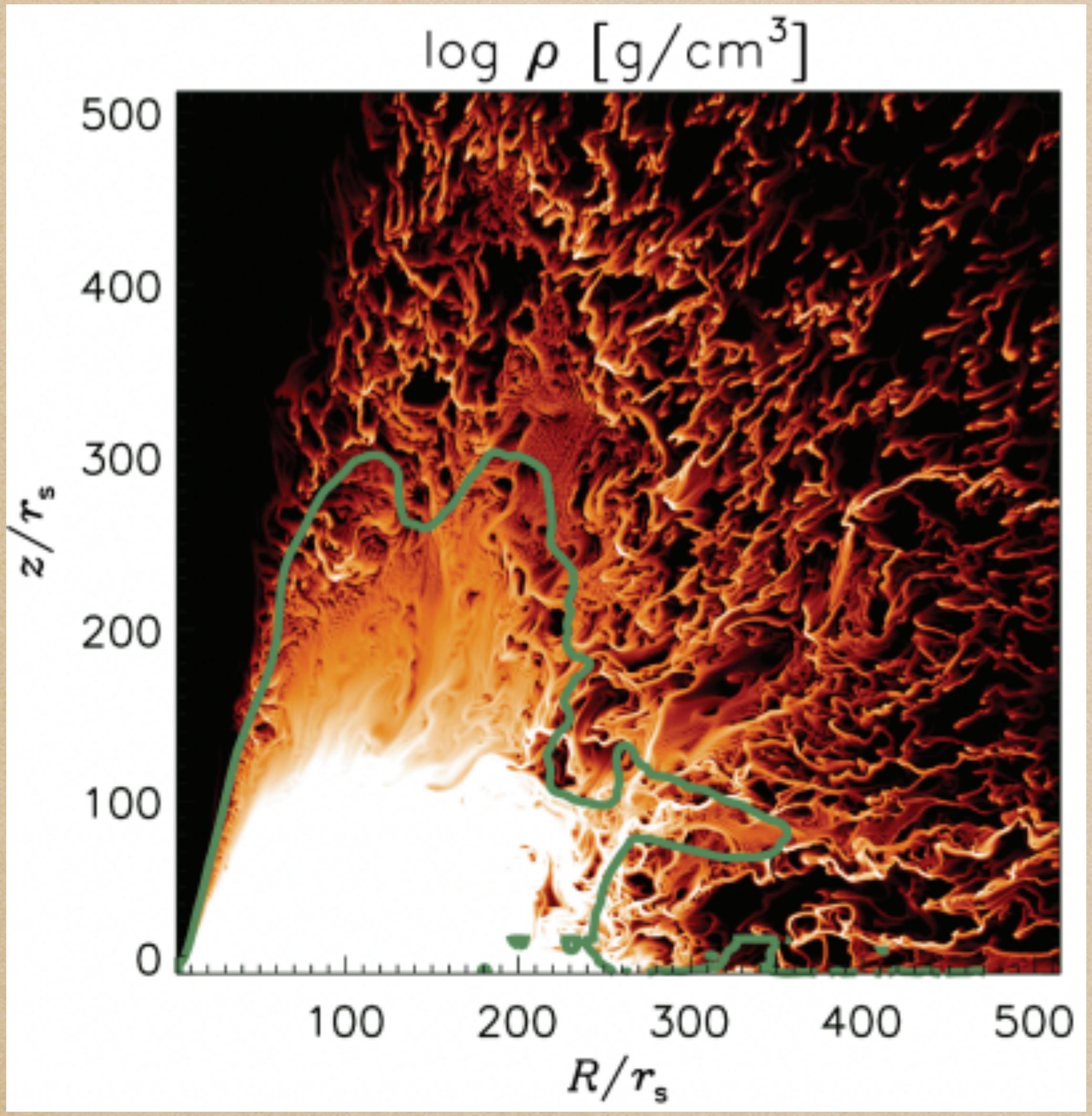
3a. continuum driven

$\sigma = \sigma_T$ only for super-Eddington

3b. line driven

$\sigma = \sigma_{line} >> \sigma_T$ can be at work for sub-Eddington

3a. continuum-driven wind



(Takeuchi+14)

- Eddington luminosity
- Radiation pressure = Gravity
- Assumption:
  - Spherically symmetric
  - optically thin

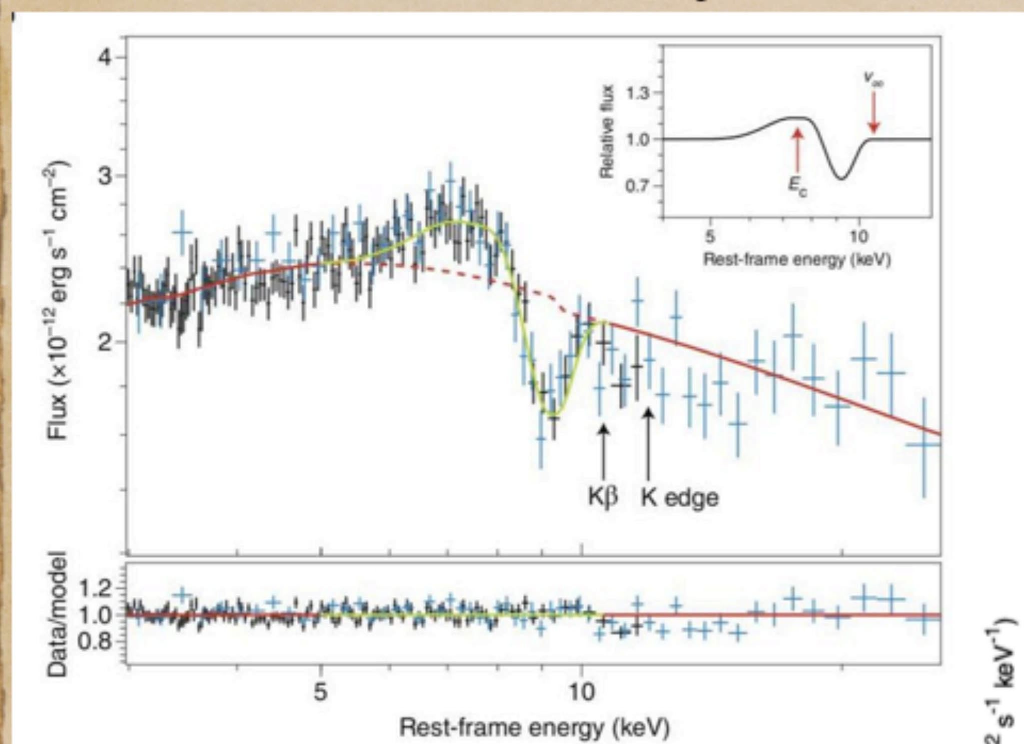
$$\frac{\sigma_T}{c}\frac{L_{Edd}}{4\pi r^2} = \frac{GM_{BH}m_H}{r^2}$$

$$\rightarrow L_{Edd} = \frac{4\pi cGM}{\sigma_T/m_H} = \frac{4\pi cGM}{\kappa_T}$$

If these assumptions do not hold, super-Eddington accretion flow can exist.
On the surface of the super-Eddington accretion disk, the continuum-driven wind can blow (i.e., radiation pressure > gravity).

3a. continuum-driven wind

Examples of UFO



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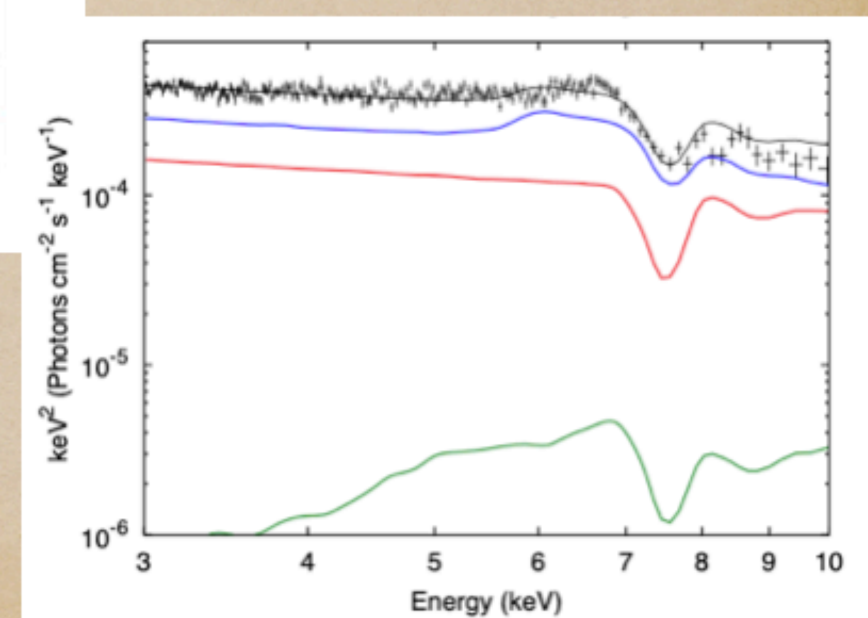
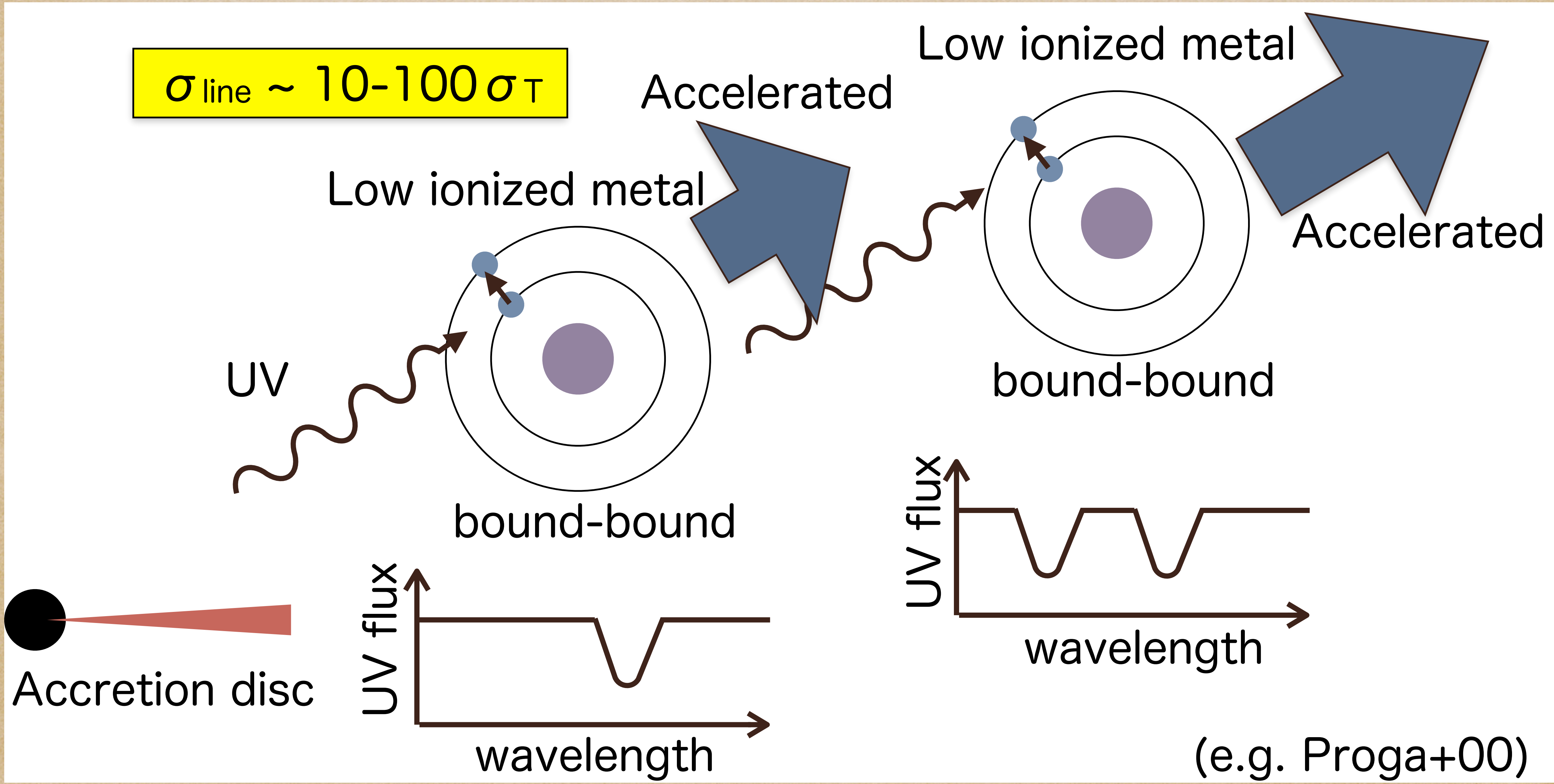


They have super Eddington luminosity -> continuum driven wind

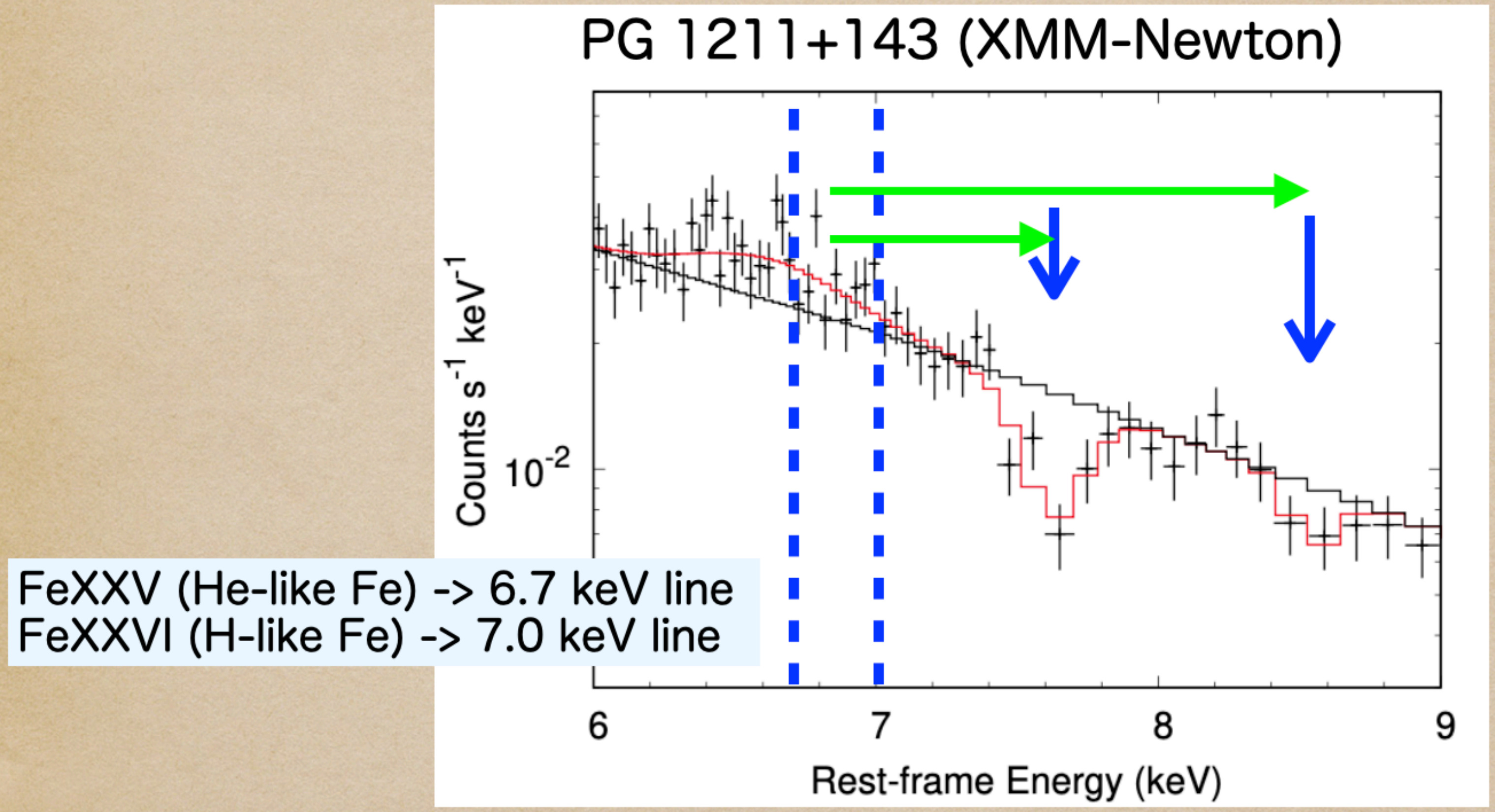
3b. UV line driven disk wind

Analogy to O-star wind and CV (Cataclysmic Variable) disk wind
(e.g. El Mellah et al. 2017)
and AGN has a UV-bright disk



3b. UV line driven disc wind

Observation of UFO



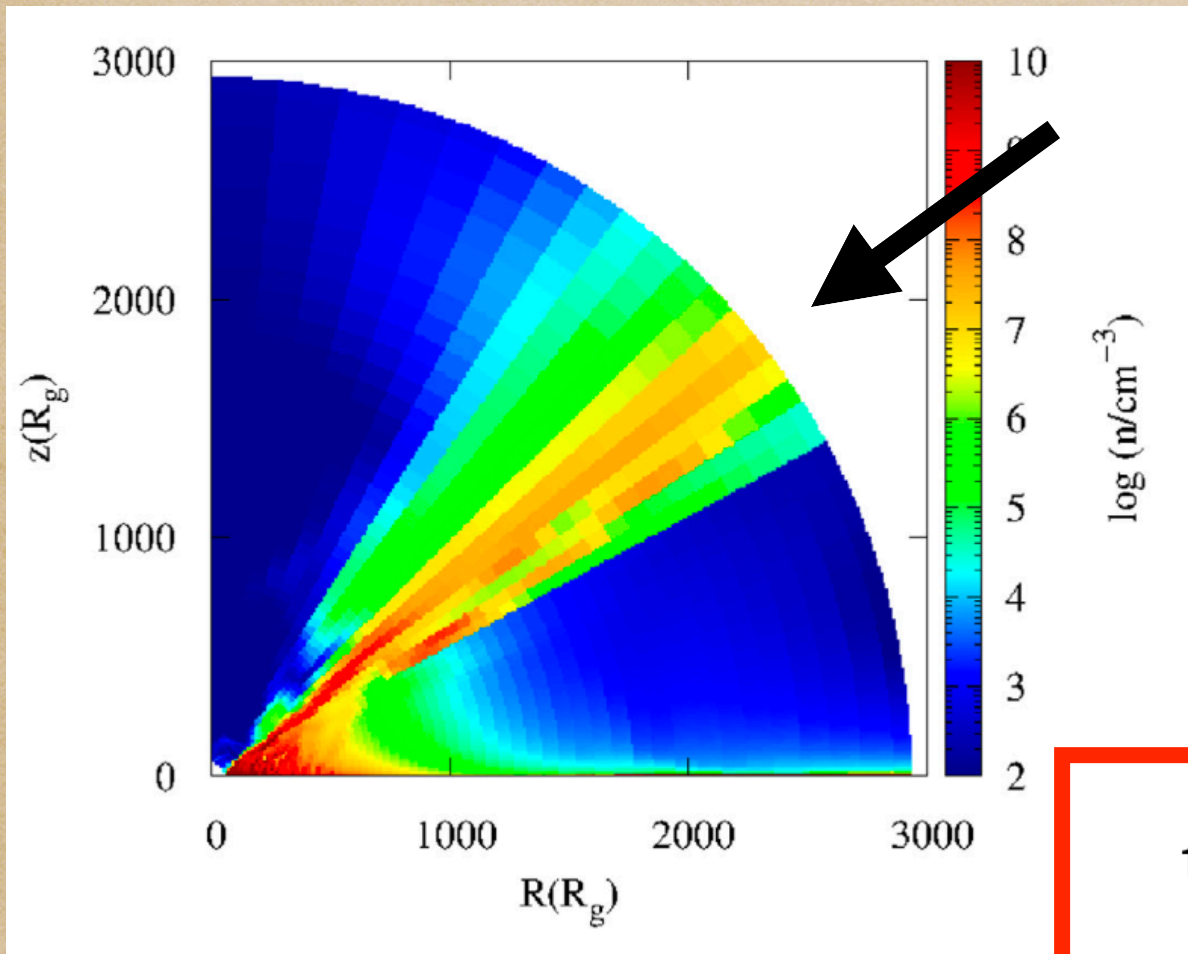
1. Very fast (velocity = 5-30% of the light speed)
2. Highly ionised (He-like and/or H-like Fe-K lines)
3. High column density ($N_H=10^{22}$-$10^{24}cm^{-2}$)

UFO detection rate

35% (36/101; XMM-Newton; Tombesi et al. 2010)

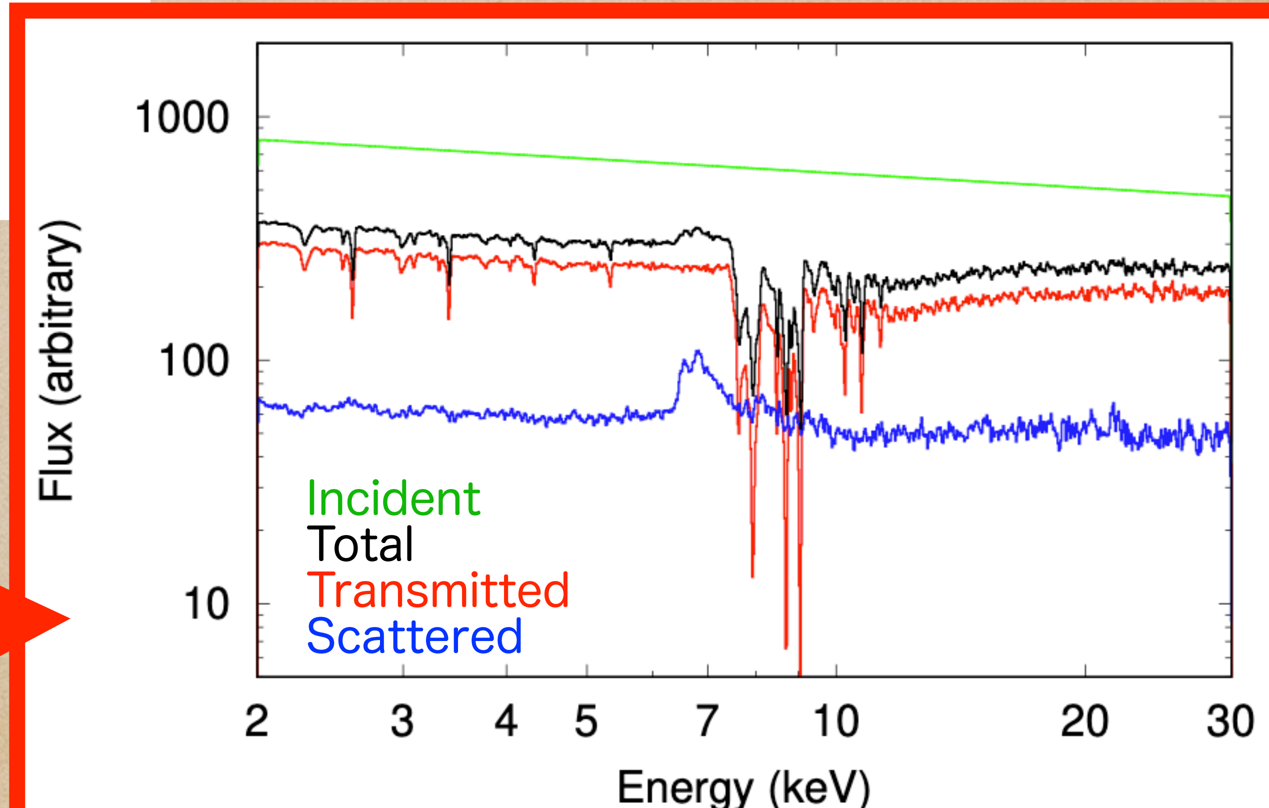
40% (20/51; Suzaku; Gofford et al. 2015)

Hydro simulation vs observation

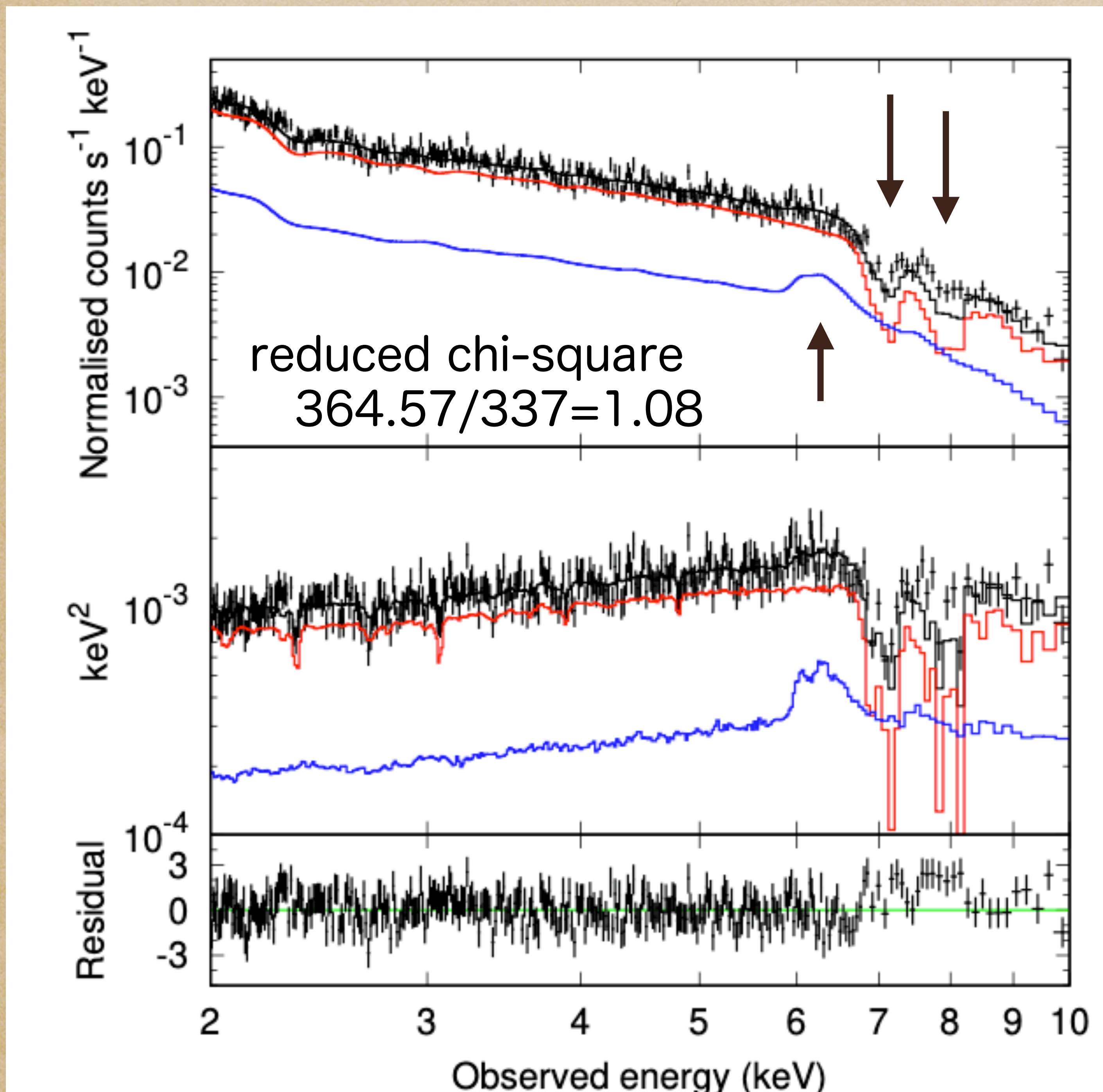


(Nomura et al. 2020)

MM+21



To reproduce UV line-driven UFO



PG 1211+143

Can explain the emission/absorption lines

— Primary

— Scattered

MM+21

XRISM

X-Ray Imaging and Spectroscopy Mission

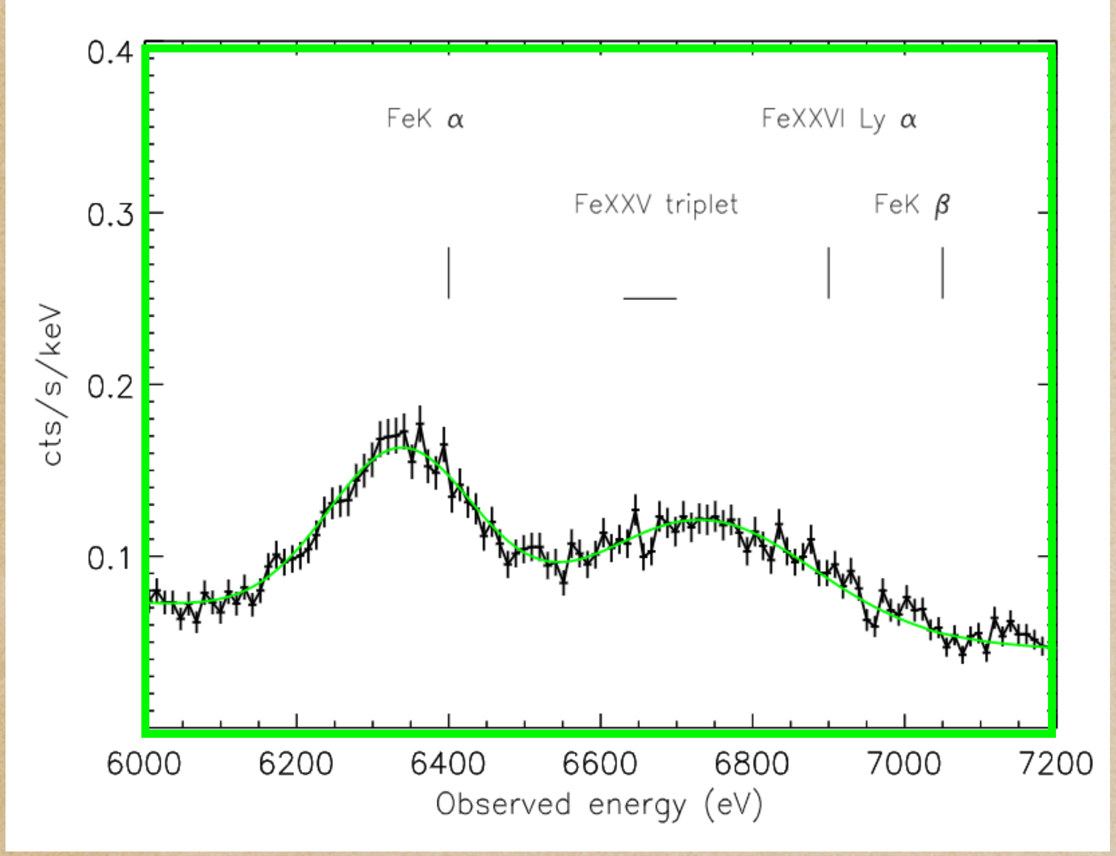
- launched on 2023 Sep 7th
- Micro-calorimeter is on board

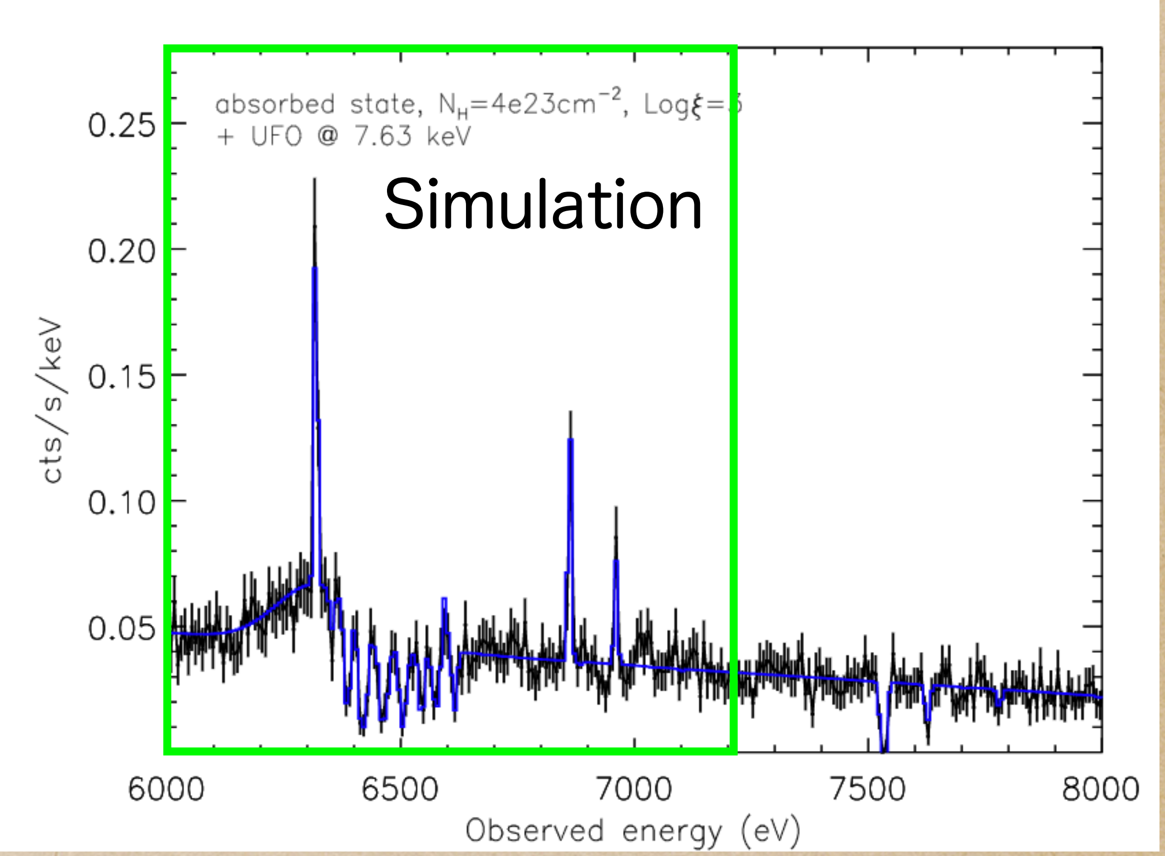
XRISM simulation

Mrk 766 (AGN)

CCD detector (ΔE=140eV @7keV)

XRISM/Resolve (ΔE=5eV @7keV)

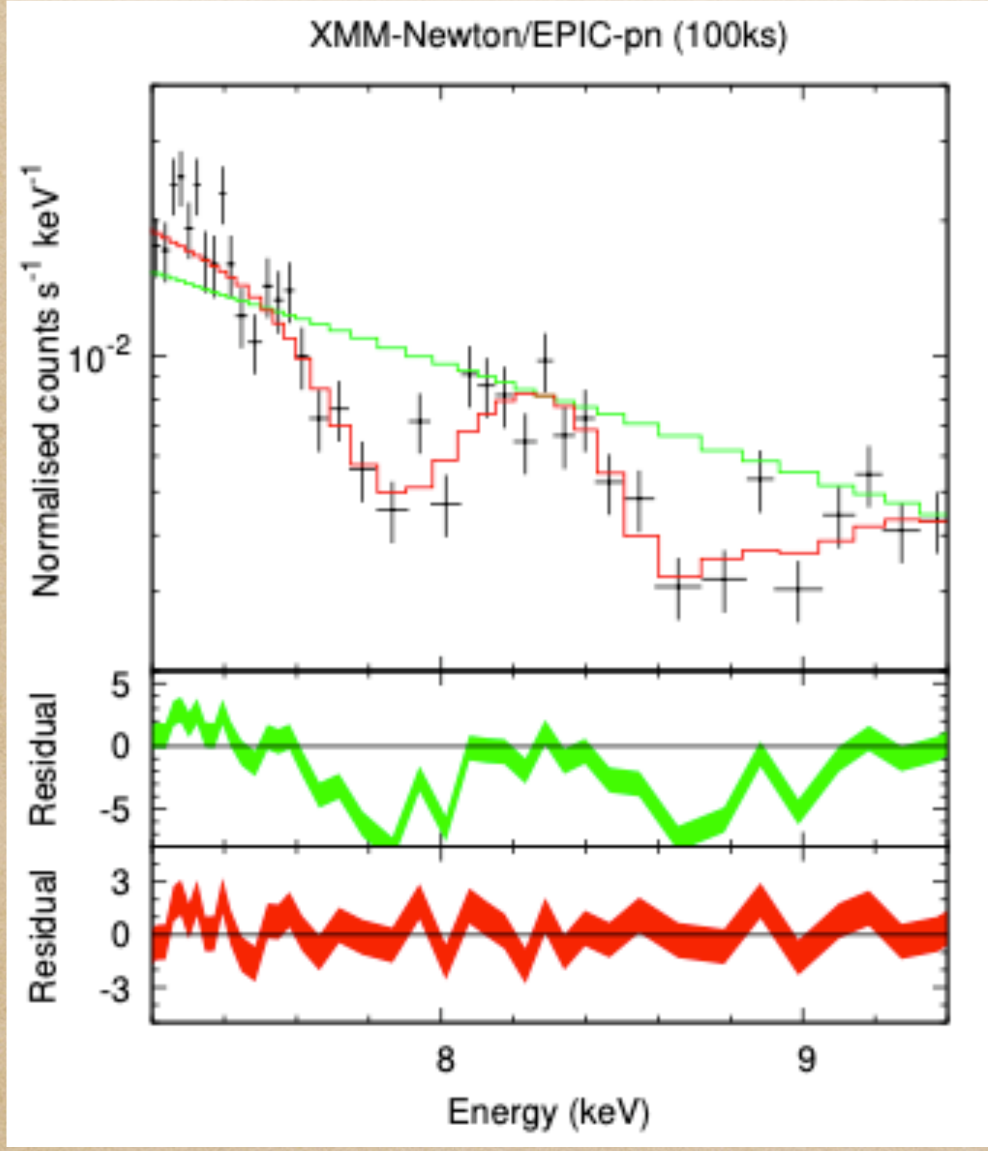




(Costantini et al. 2020)

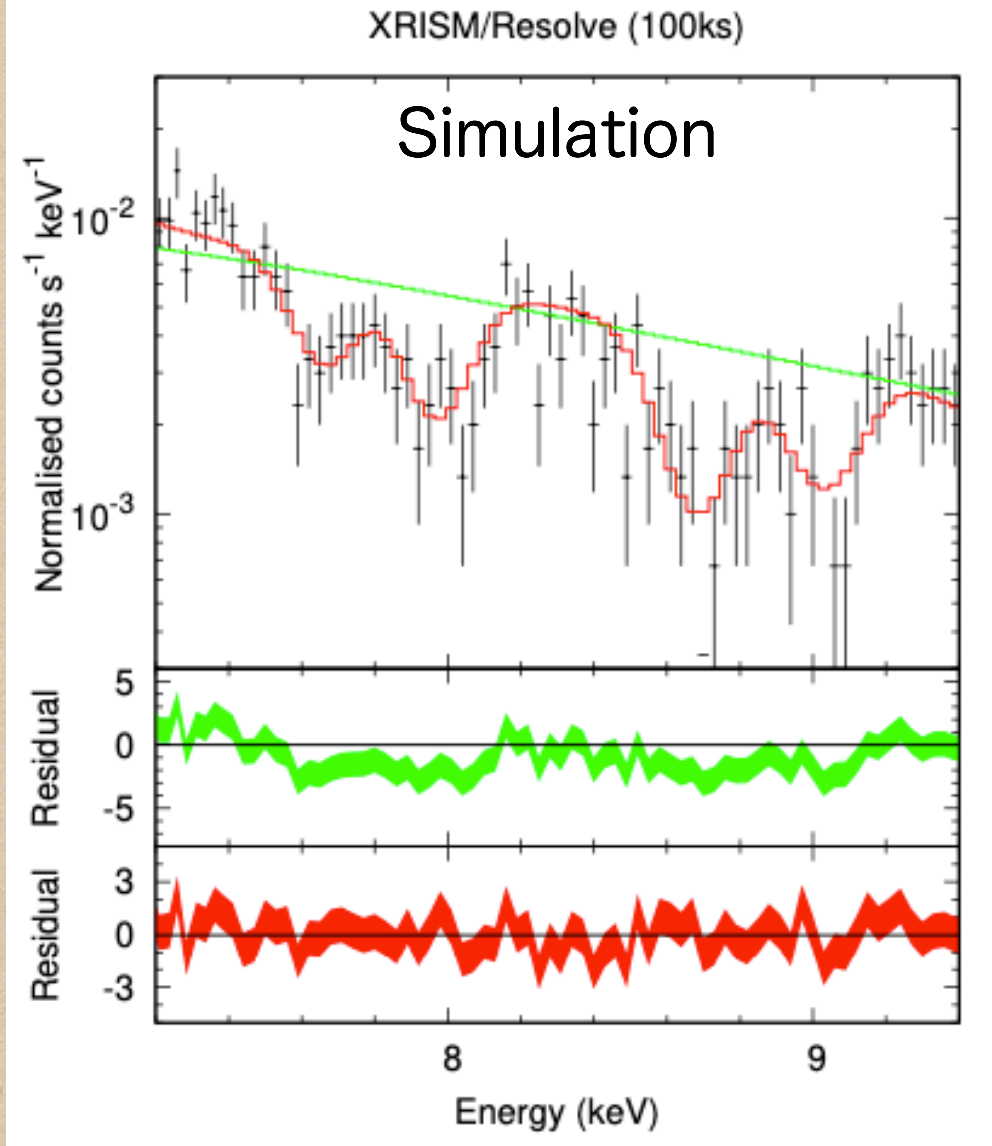
UFO with XRISM

XMM-Newton (100ks)



Cannot resolve H-like and He-like

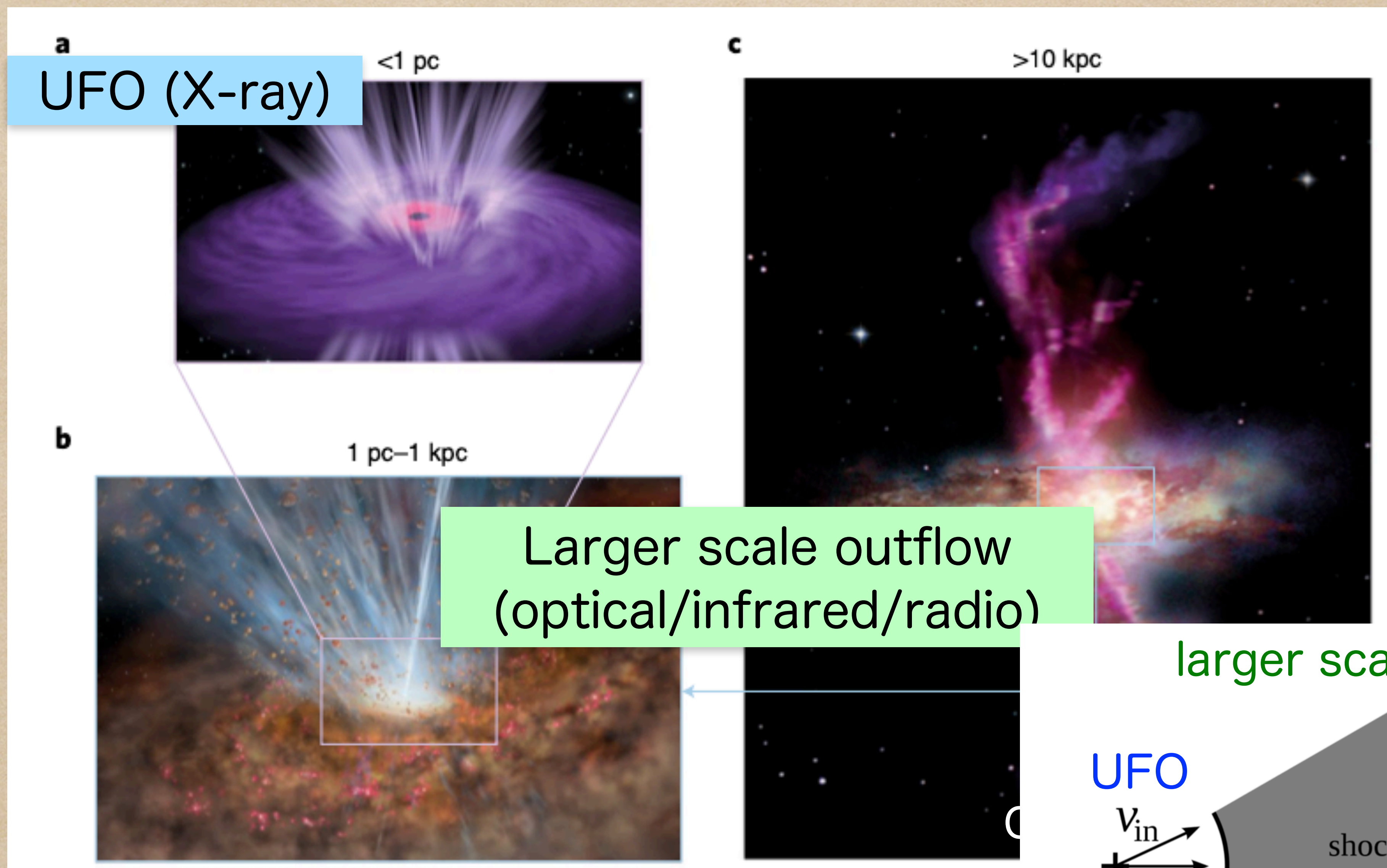
XRISM (100ks)

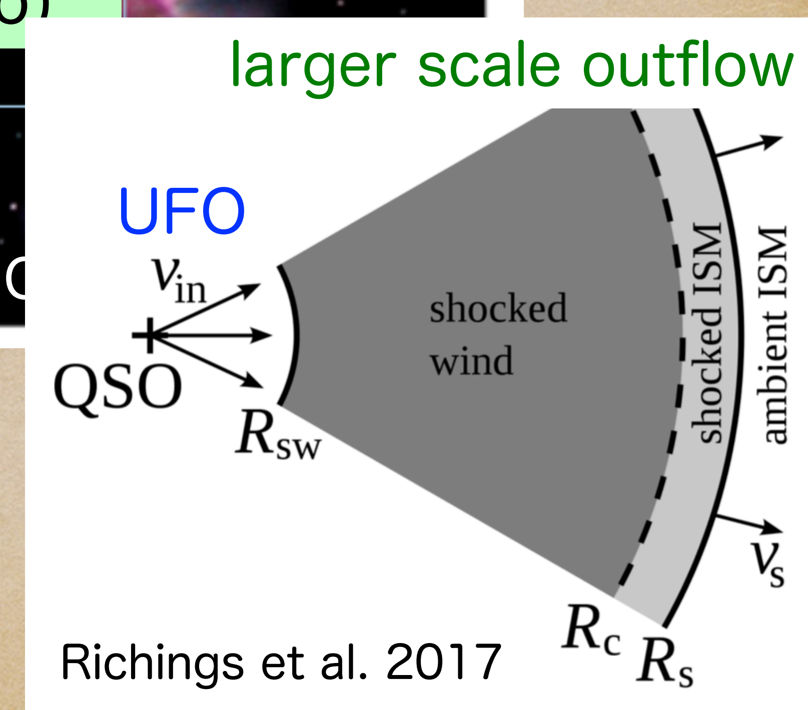


Can measure the velocity turbulence
Can resolve H-like and He-like

2. How the UFO travels? (Interaction between UFO and ambient matter)

Multi-phase AGN outflow





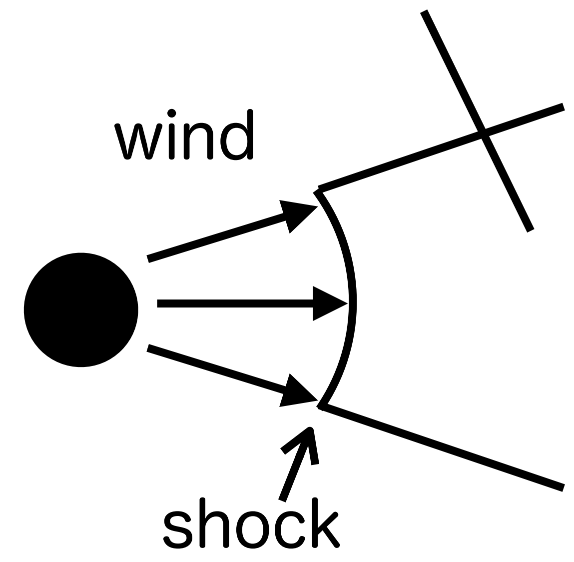
UFO can sweep up the ISM and create the larger-scale outflows

(Theoretical -> King 2003, Riching et al. 2017)

(Observational -> Tombesi et al. 2015, MM+19)

UFO -> hot bubble

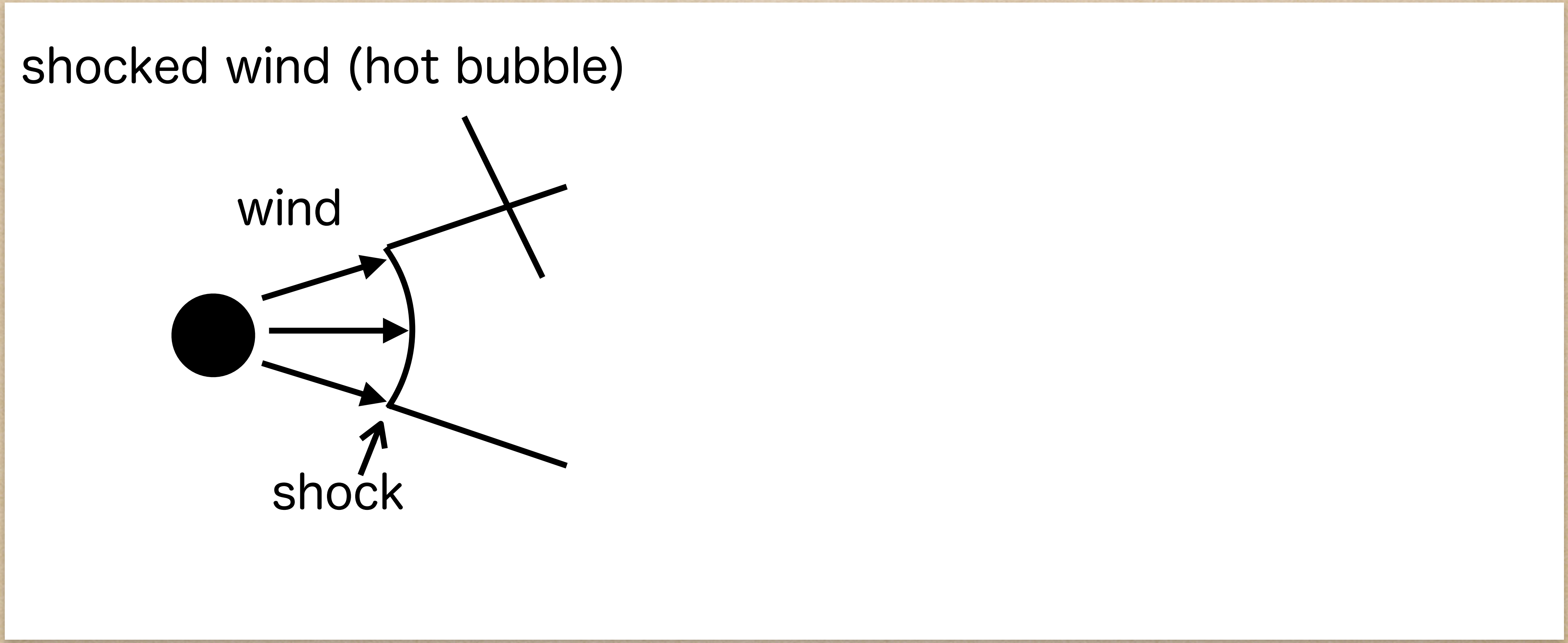
Zubovas & King (2012, 2019)



- UFO velocity >> ISM sound speed -> Strong shock develops.
- $T_{\rm shock} = \dfrac{2\mu m_{\rm p} v_{\rm wind}^2}{16k} \simeq 10^{10}\,{\rm K}$
- UFO kinetic energy -> thermal energy of the hot bubble

Cooling of hot bubble

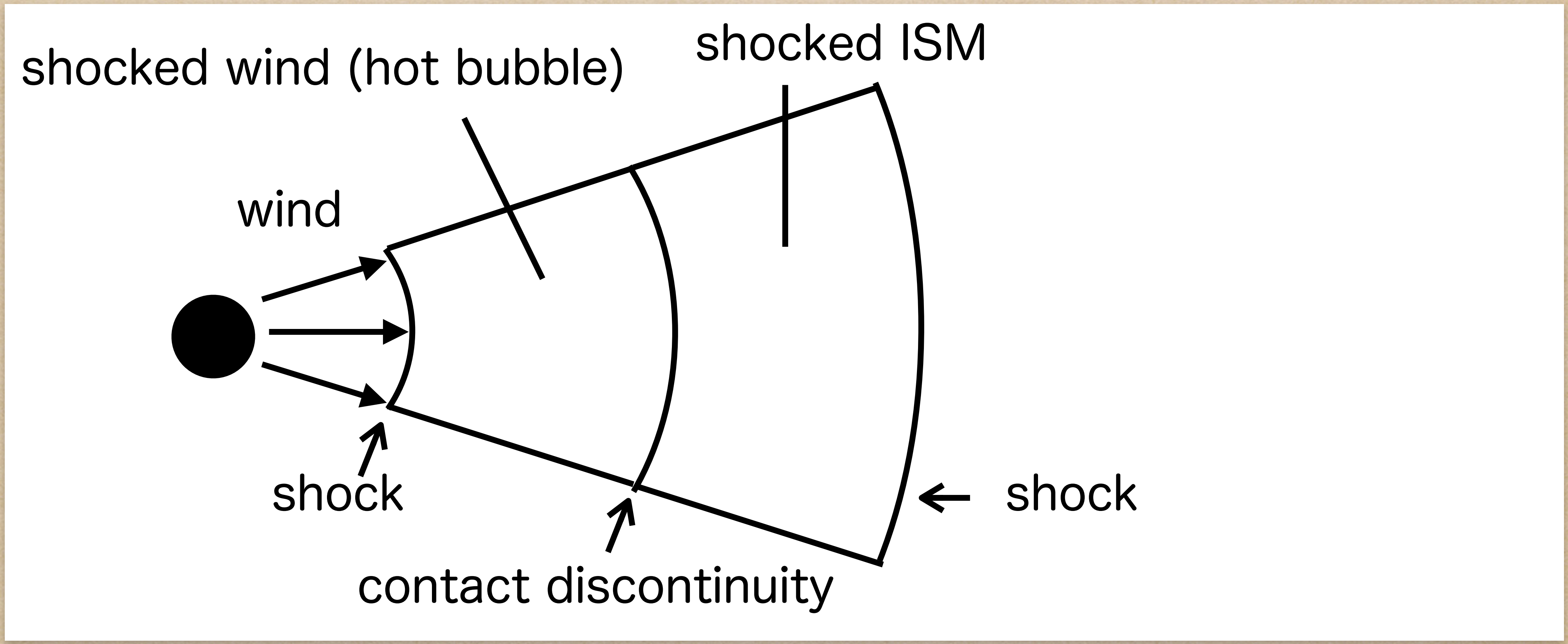
Zubovas & King (2012, 2019)



- Compton cooling (interaction between AGN photons and hot electrons)
- The Compton cooling timescale $\propto n^{-1} \propto R^2$
- The expansion timescale = R / (sound speed) $\propto$ R
- The cooling is inefficient beyond a certain radius (R_{cool}). In this case the bubble becomes adiabatic.
- R_{cool} is typically ~500 pc

Energy-conserved flow

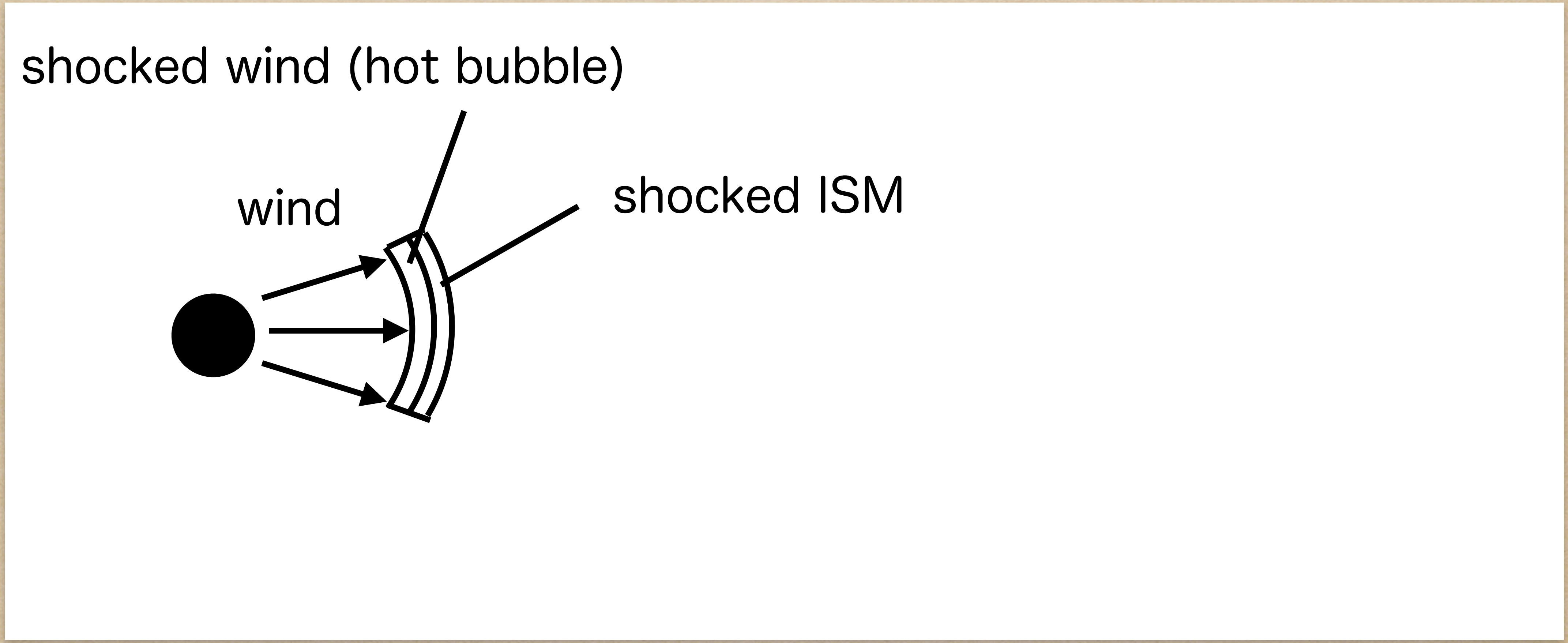
Zubovas & King (2012, 2019)



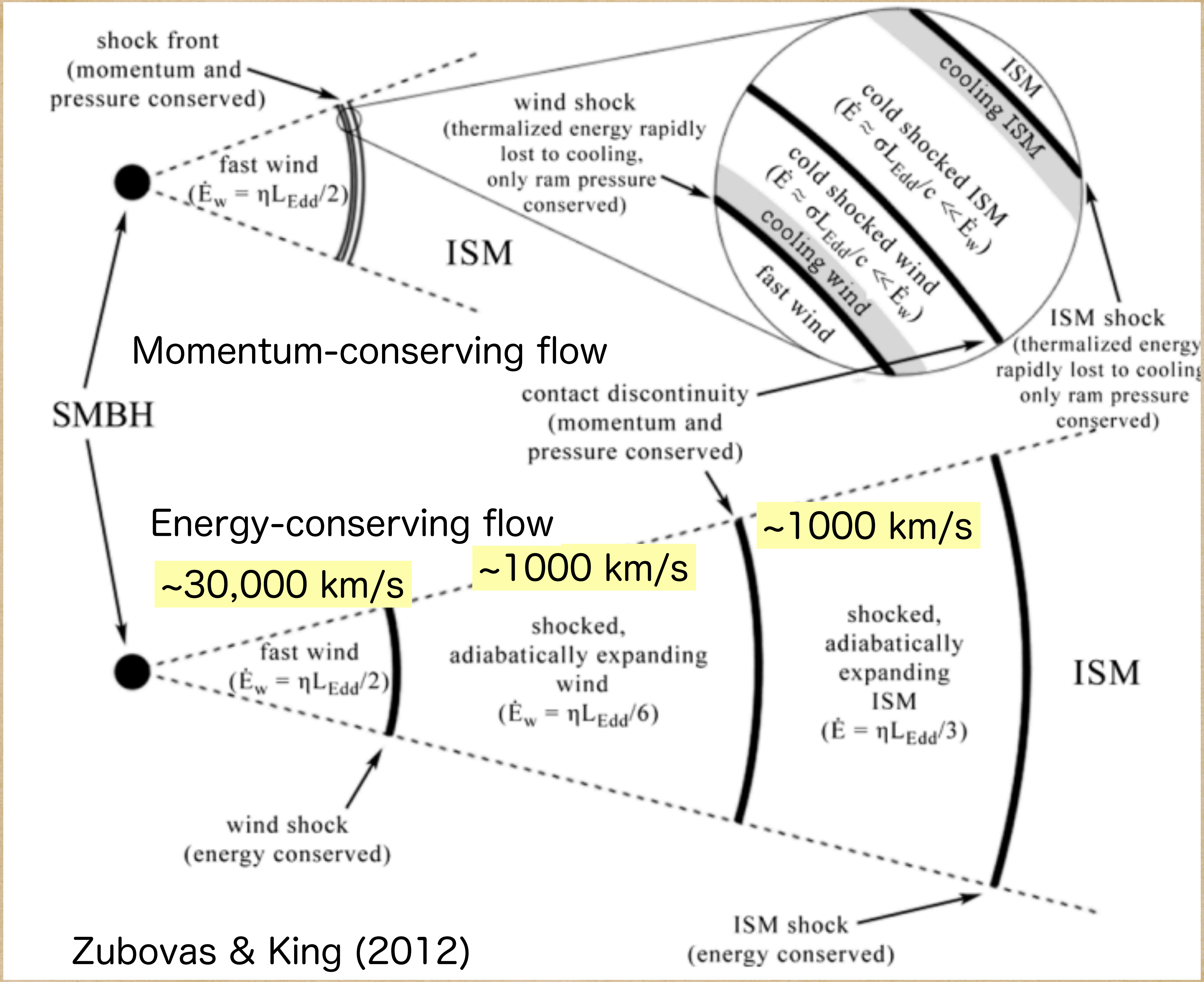
- When cooling is inefficient, the hot bubble expands beyond R_{cool}.
- UFO kinetic energy -> thermal energy in the hot bubble -> shocked ISM
- The "energy-conserved" flow exists.

Momentum conserving flow

Zubovas & King (2012, 2019)

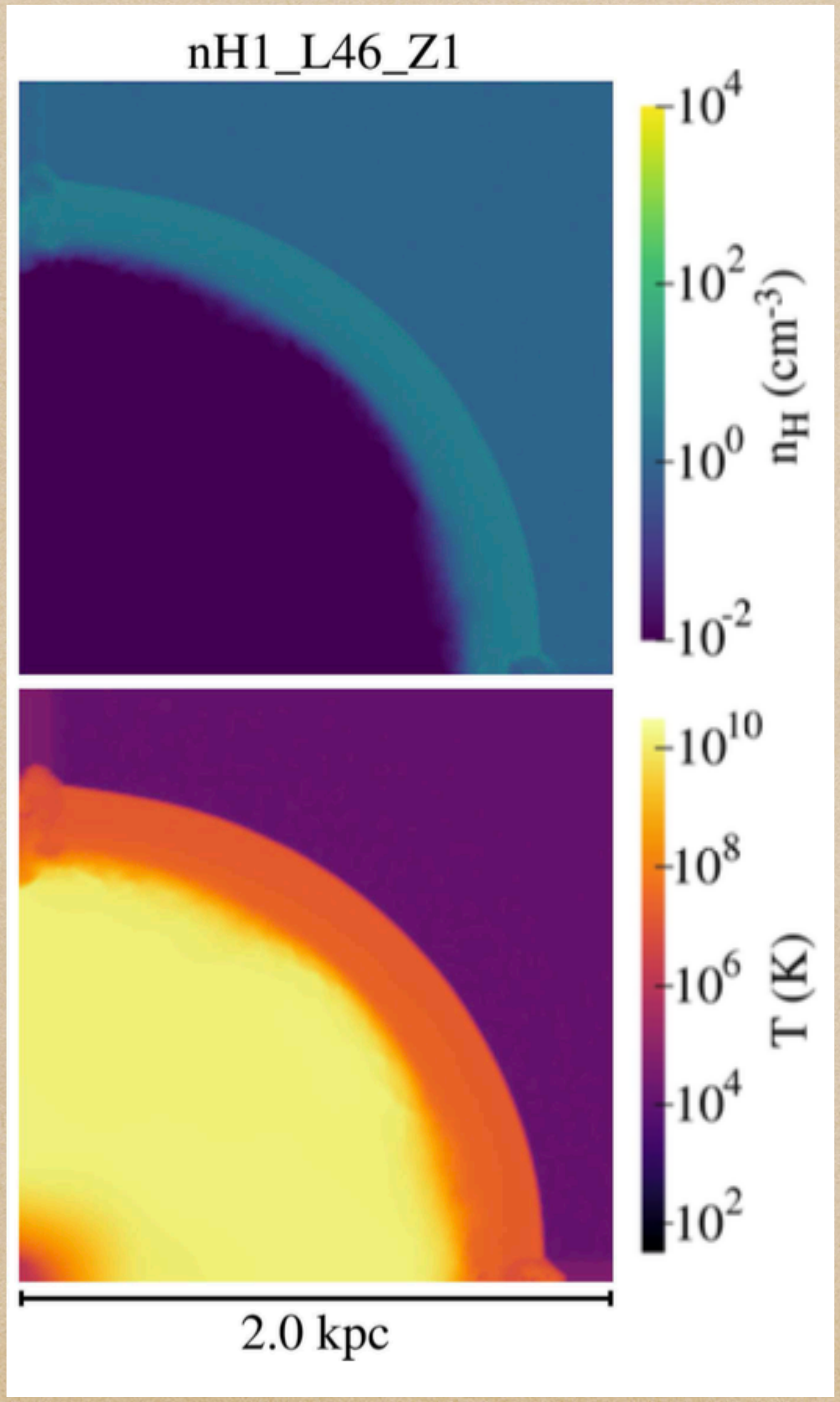


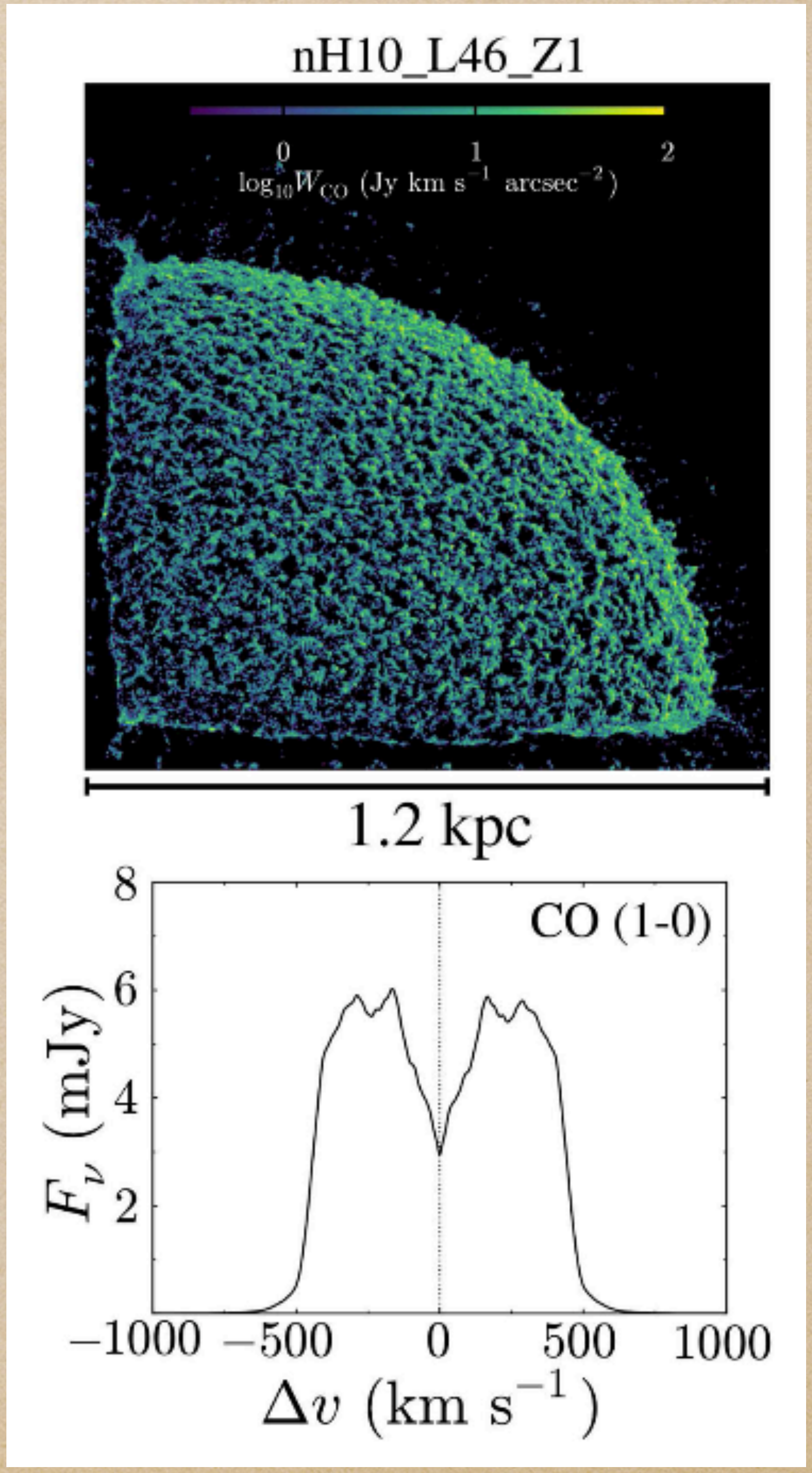
- When cooling is efficient, the shocked wind is rapidly cooled and becomes isothermal.
- Only the ram pressure can push the wind.
- The "momentum-conserving" flow.


shock front
(momentum and
pressure conserved)
fast wind
($\dot{E}_w = \eta L_{Edd}/2$)
wind shock
(thermalized energy rapidly
lost to cooling,
only ram pressure
conserved)
ISM
ISM
cooling ISM
cold shocked ISM
($\dot{E} \approx \sigma L_{Edd}/c \ll \dot{E}_w$)
cold shocked wind
($\dot{E} \approx \sigma L_{Edd}/c \ll \dot{E}_w$)
cooling wind
fast wind
ISM shock
(thermalized energy
rapidly lost to cooling
only ram pressure
conserved)
Momentum-conserving flow
SMBH
contact discontinuity
(momentum and
pressure conserved)
Energy-conserving flow
~30,000 km/s
~1000 km/s
~1000 km/s
fast wind
($\dot{E}_w = \eta L_{Edd}/2$)
shocked,
adiabatically expanding
wind
($\dot{E}_w = \eta L_{Edd}/6$)
shocked,
adiabatically
expanding
ISM
($\dot{E} = \eta L_{Edd}/3$)
ISM
wind shock
(energy conserved)
ISM shock
(energy conserved)
Zubovas & King (2012)

Simulation of the shocked ISM

Riching+18



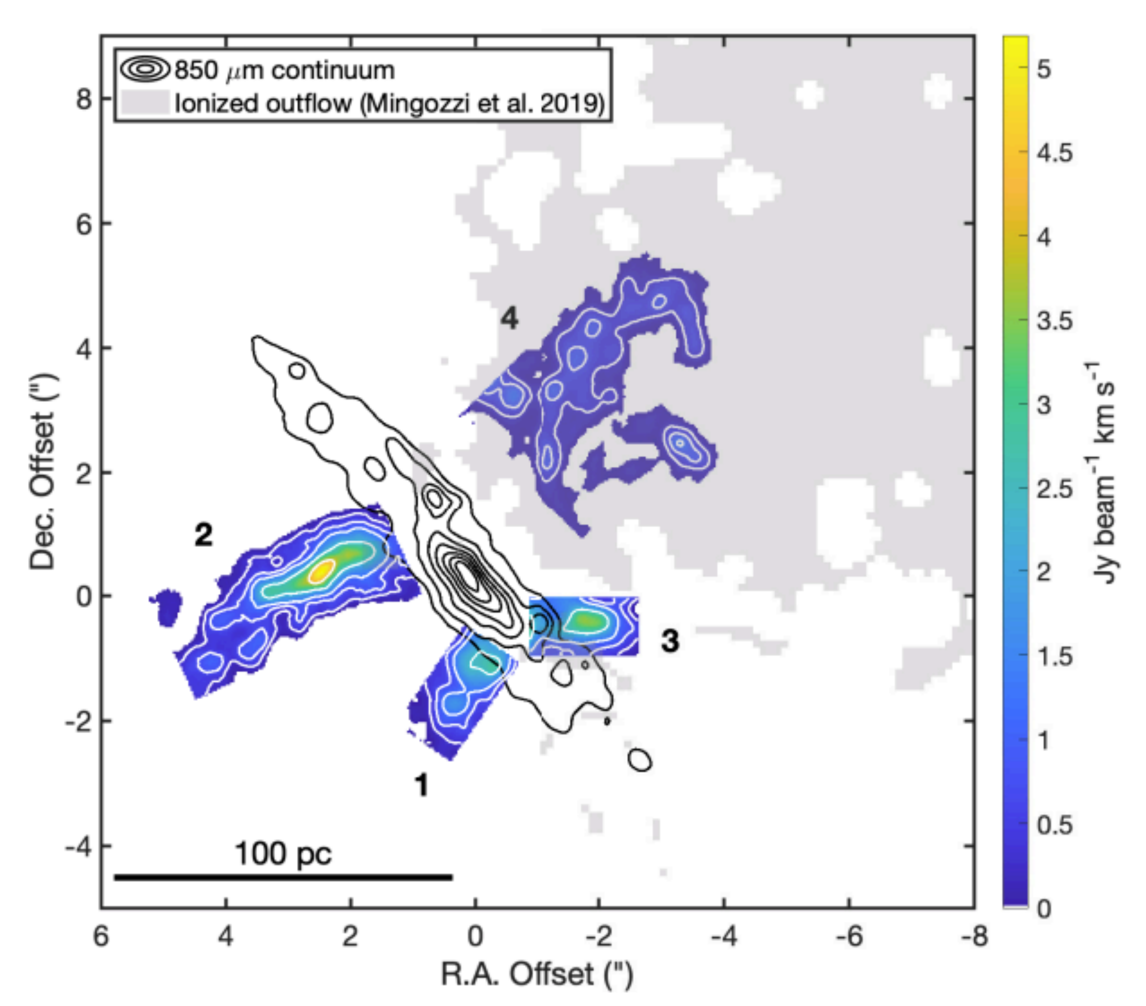


Seen as cold gas, such as CO molecules

Observation of the shocked ISM?

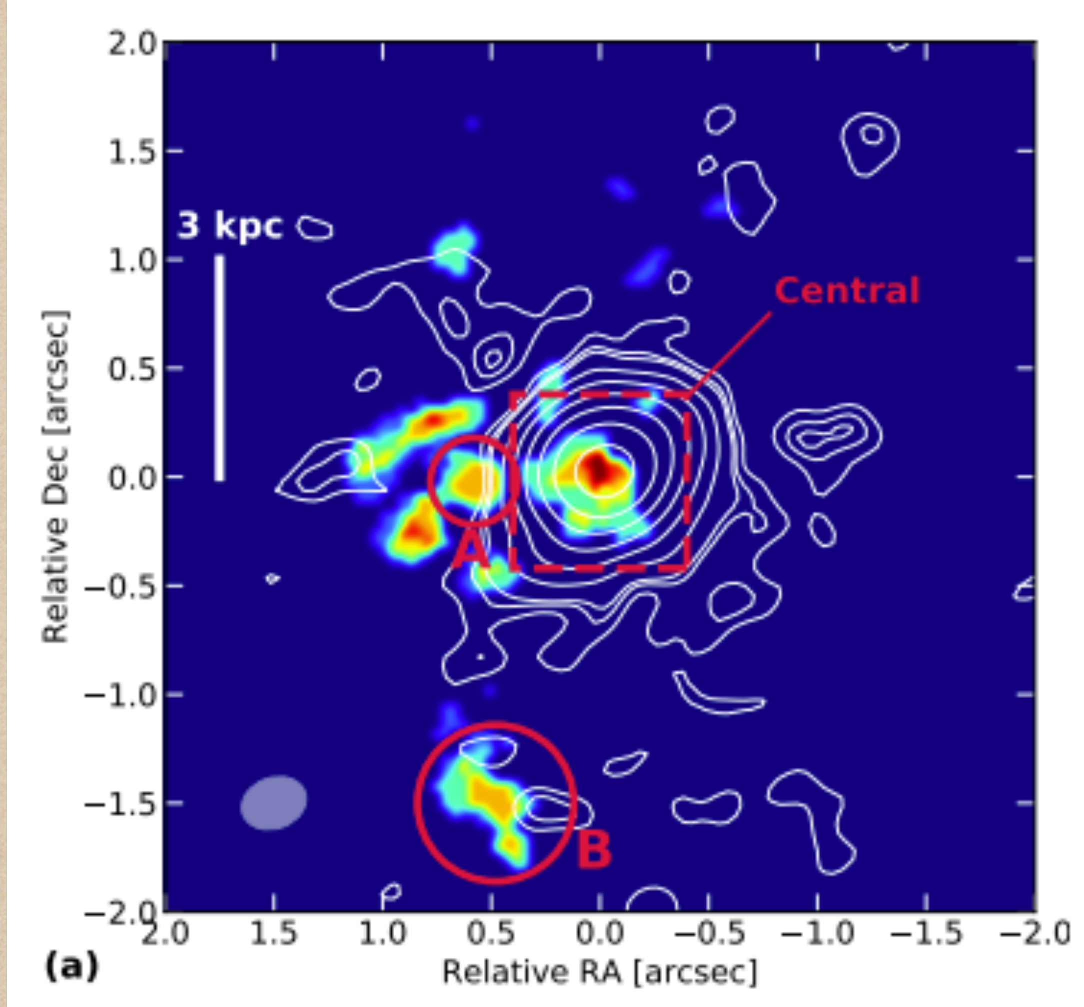
CO emission (larger scale outflow)

NGC 4945 (Bolatto+21)



100 pc, 600 km/s

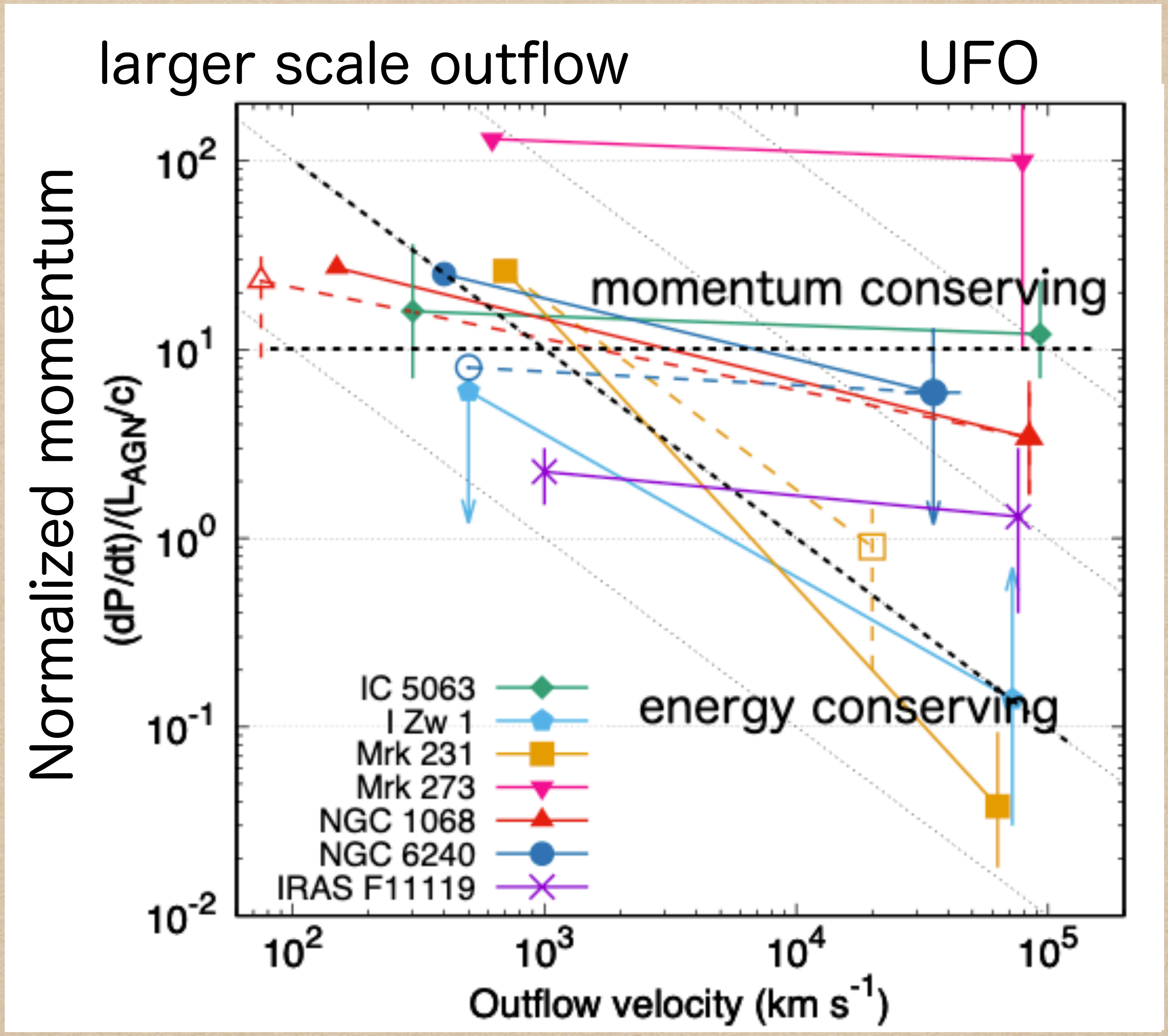
PDS 456 (Bischetti+19)



1-5 kpc, 500-1000km/s

(NOTE: It is still under debate how to produce these larger scale outflows.)

Energy conserving vs Momentum conserving

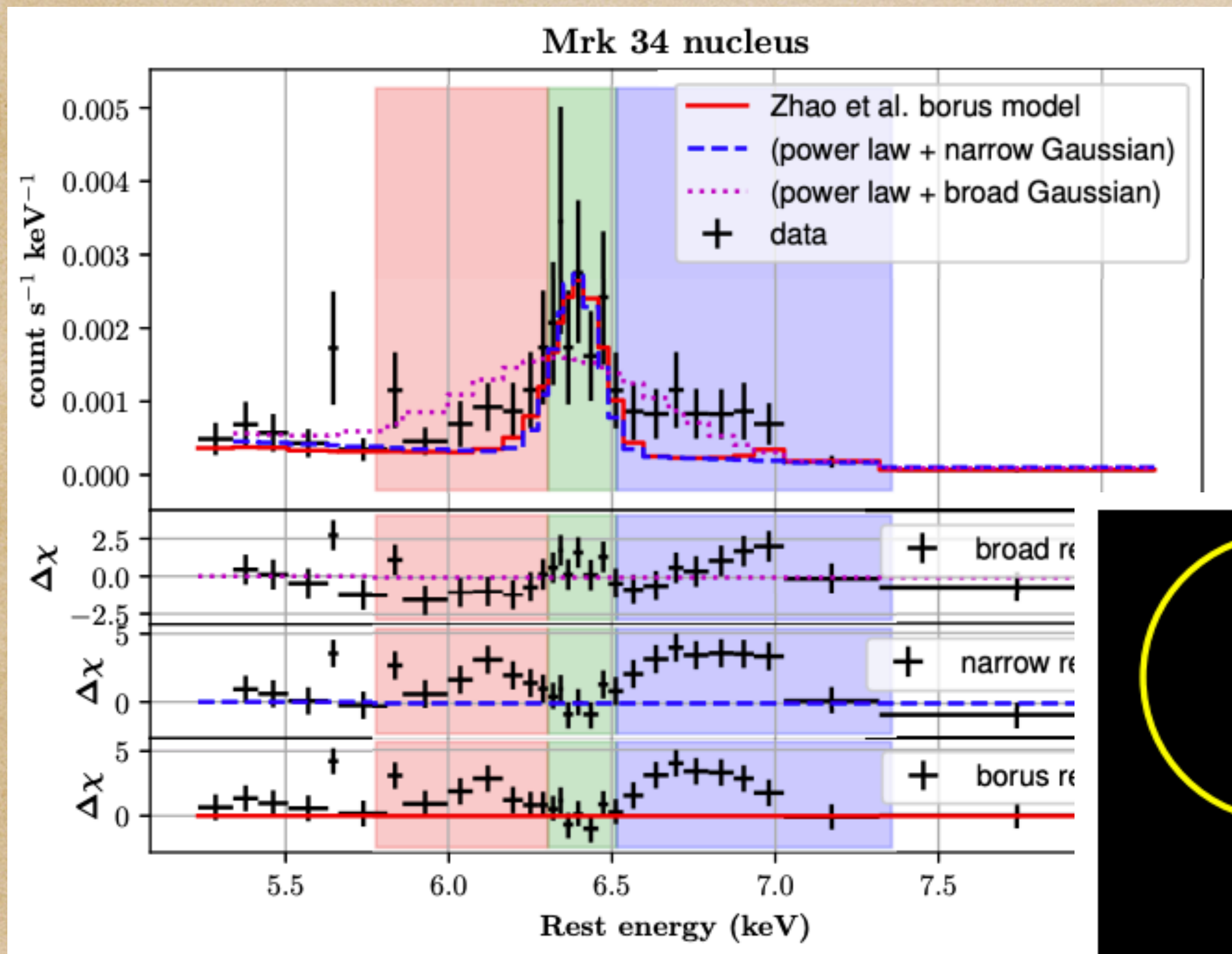


MM+19b

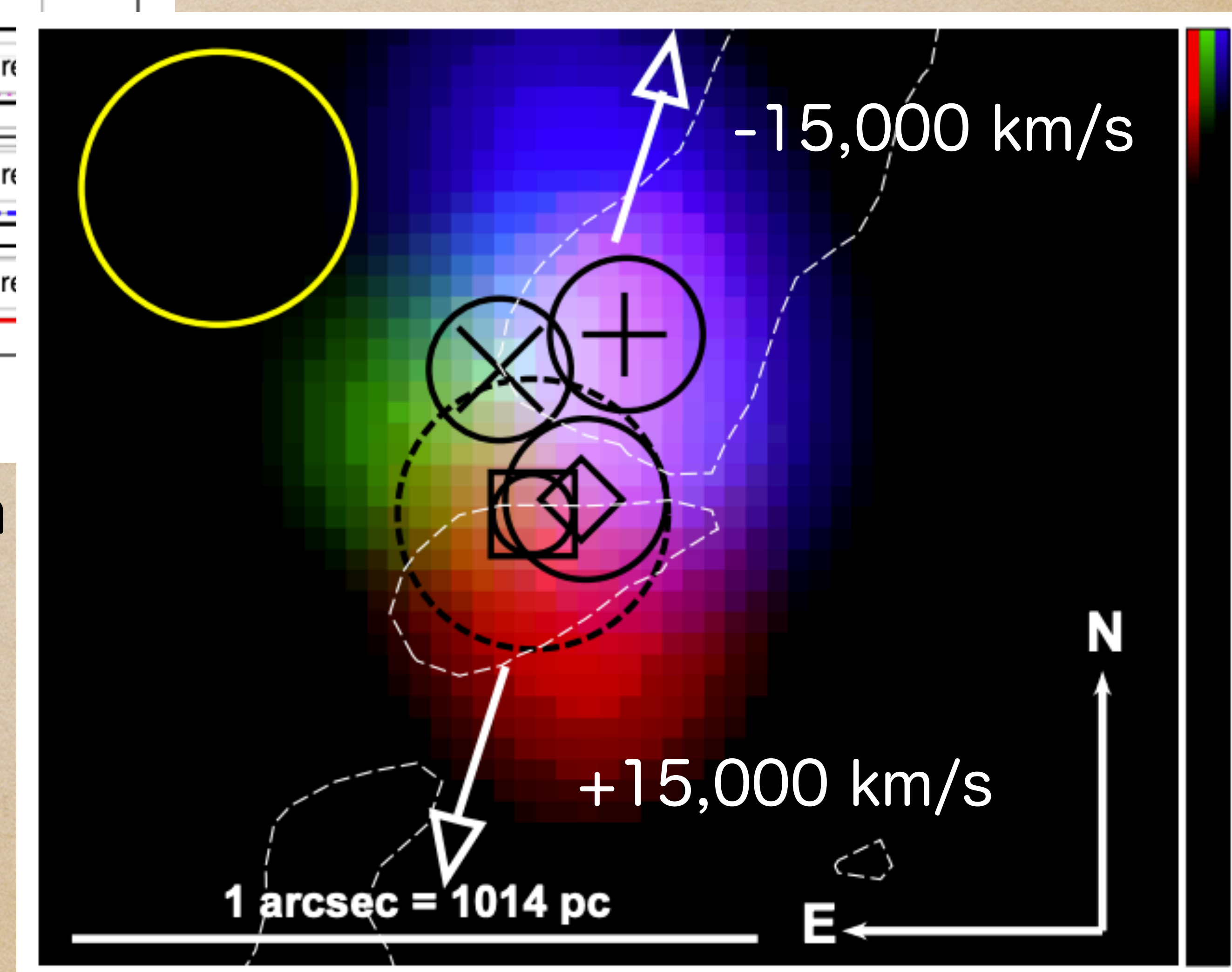
NOTE: The timescale that UFO reaches the larger scale outflow is > 1 kpc / 0.3c = 10^4 yr, but UFO's variability timescale is less than 1 yr.

Direct observation of the shocked flow?

- Mrk 34 (Seyfert 2)
- 6.4 keV line from the neutral Fe scattering
- a spatially-resolved outflow

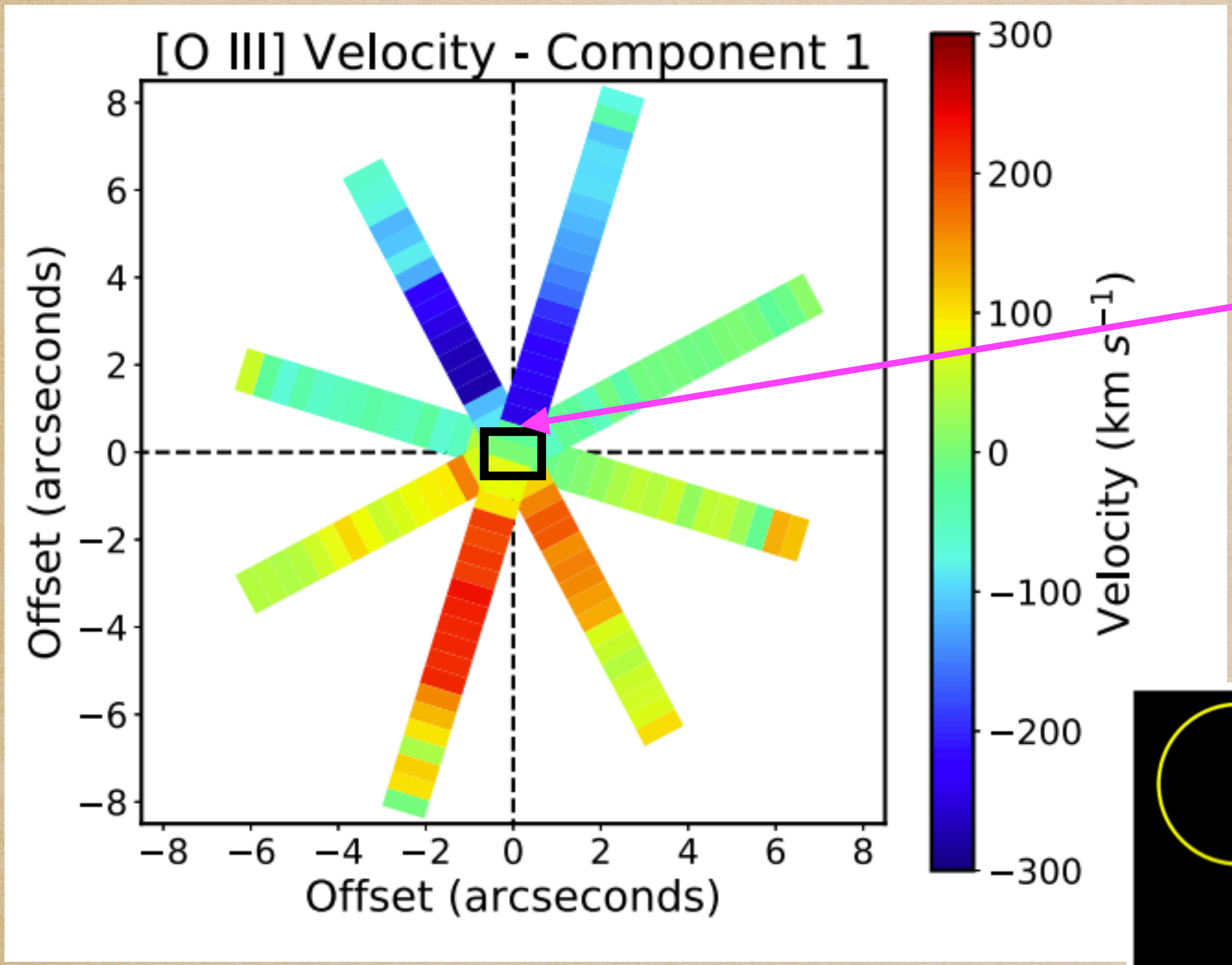


Chandra observation



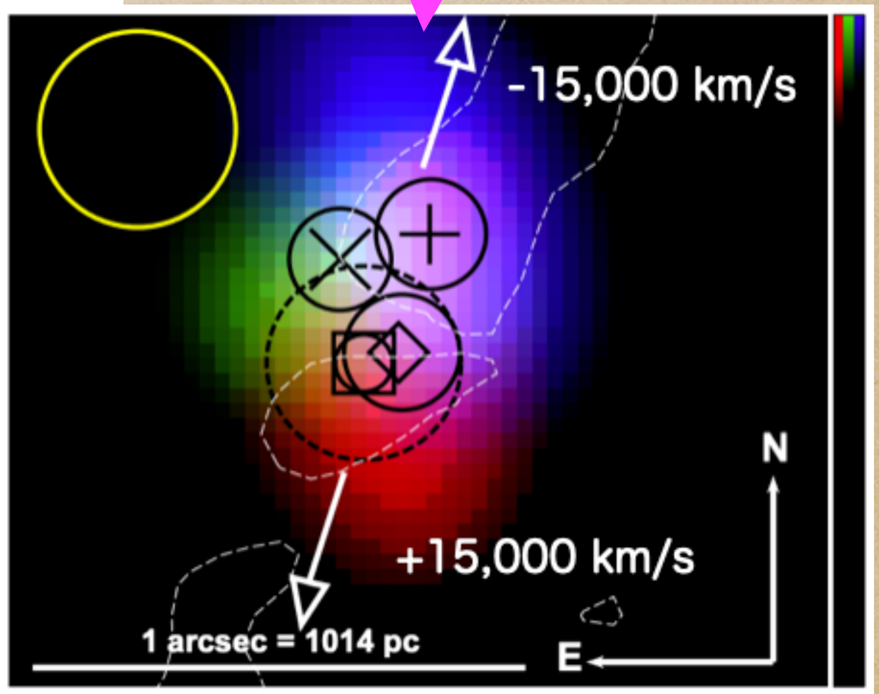
(Maksym+23)

Direct observation of the shocked flow?



HST data (Revalski+19)

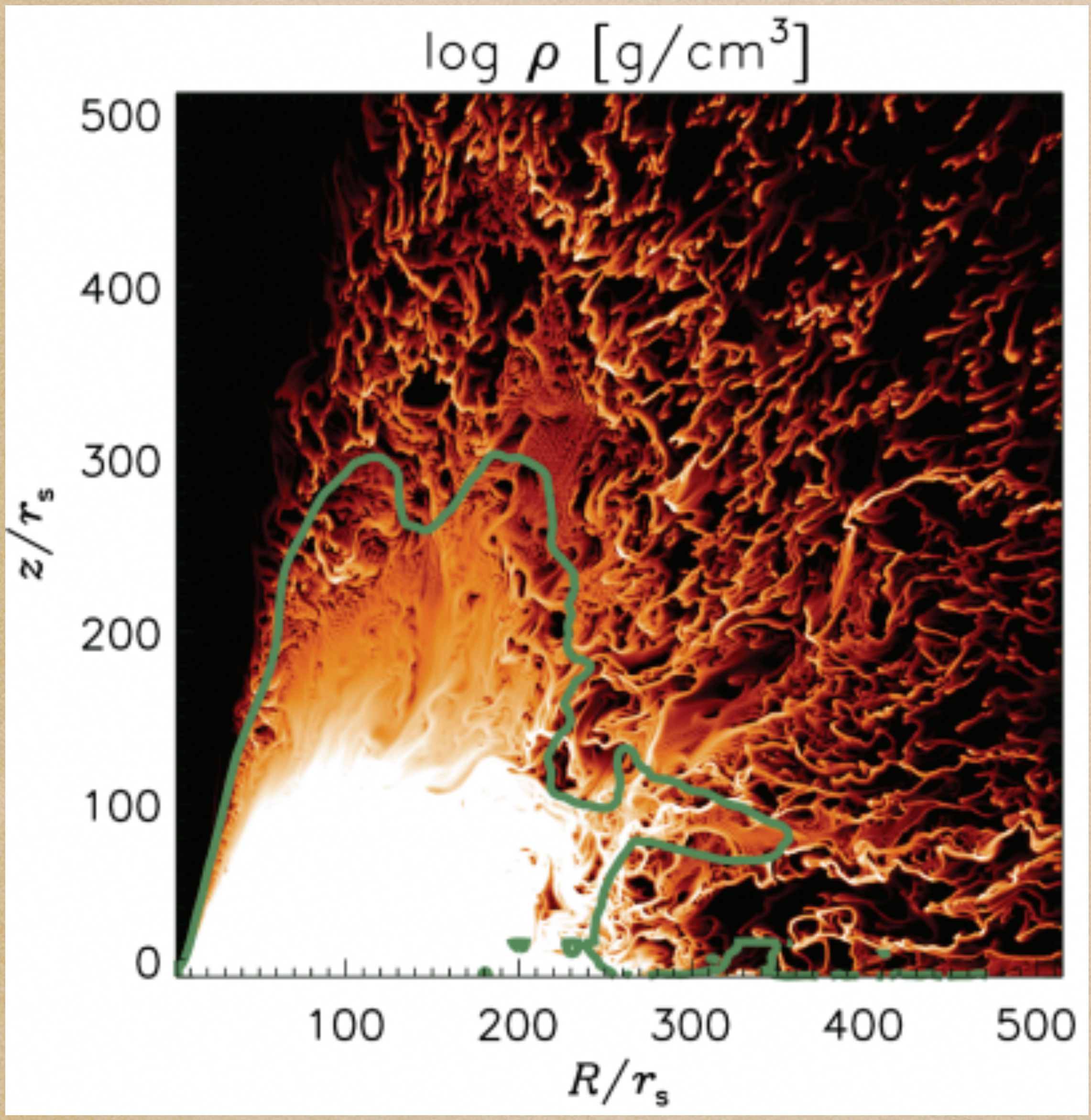
Shock front??
(R~1kpc)



3. Our recent study on UFO (if time permits)

(Based on our recent studies, Midooka MM+22, 23, in prep.)

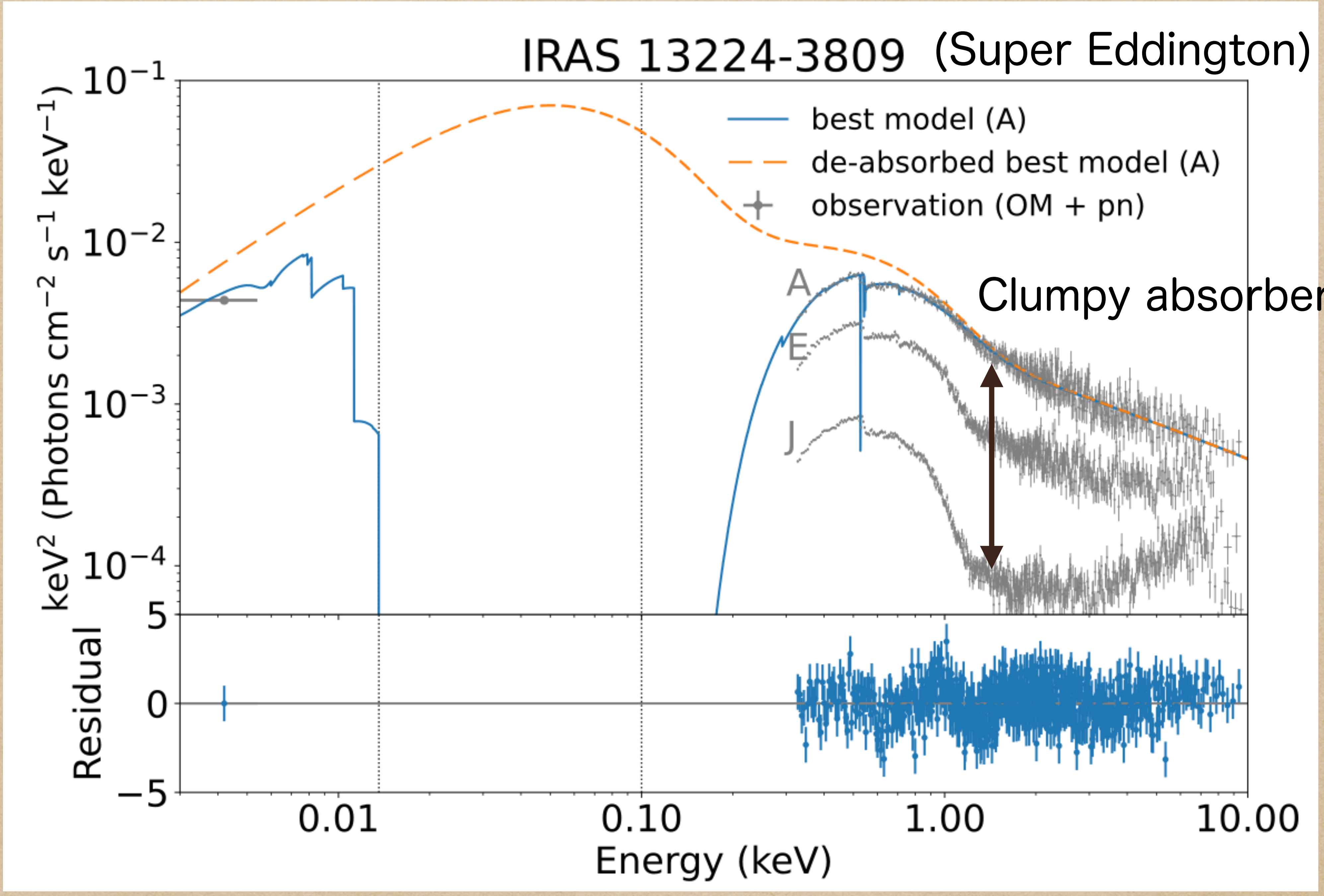
Clumpy wind



(Takeuchi+14)

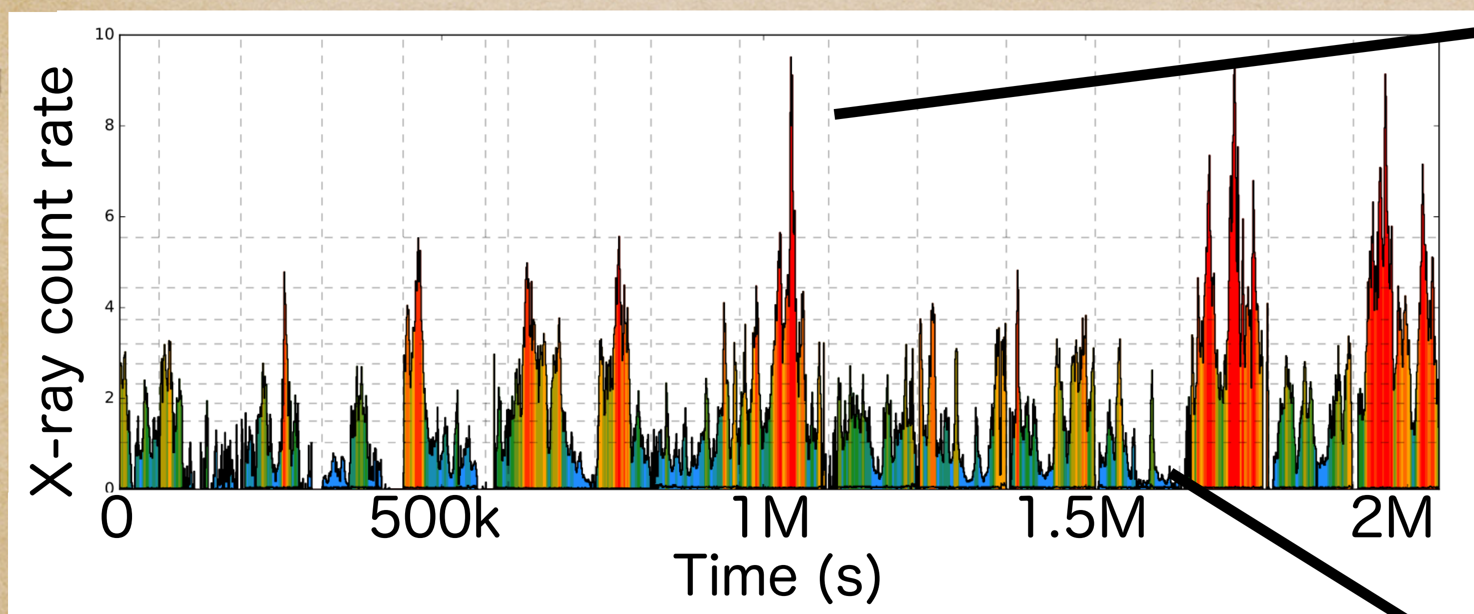
Super Eddington wind
-> Radiation pressure > Gravity
-> The density is higher on the upper stream
-> Rayleigh-Taylor instability
-> Clumpy wind

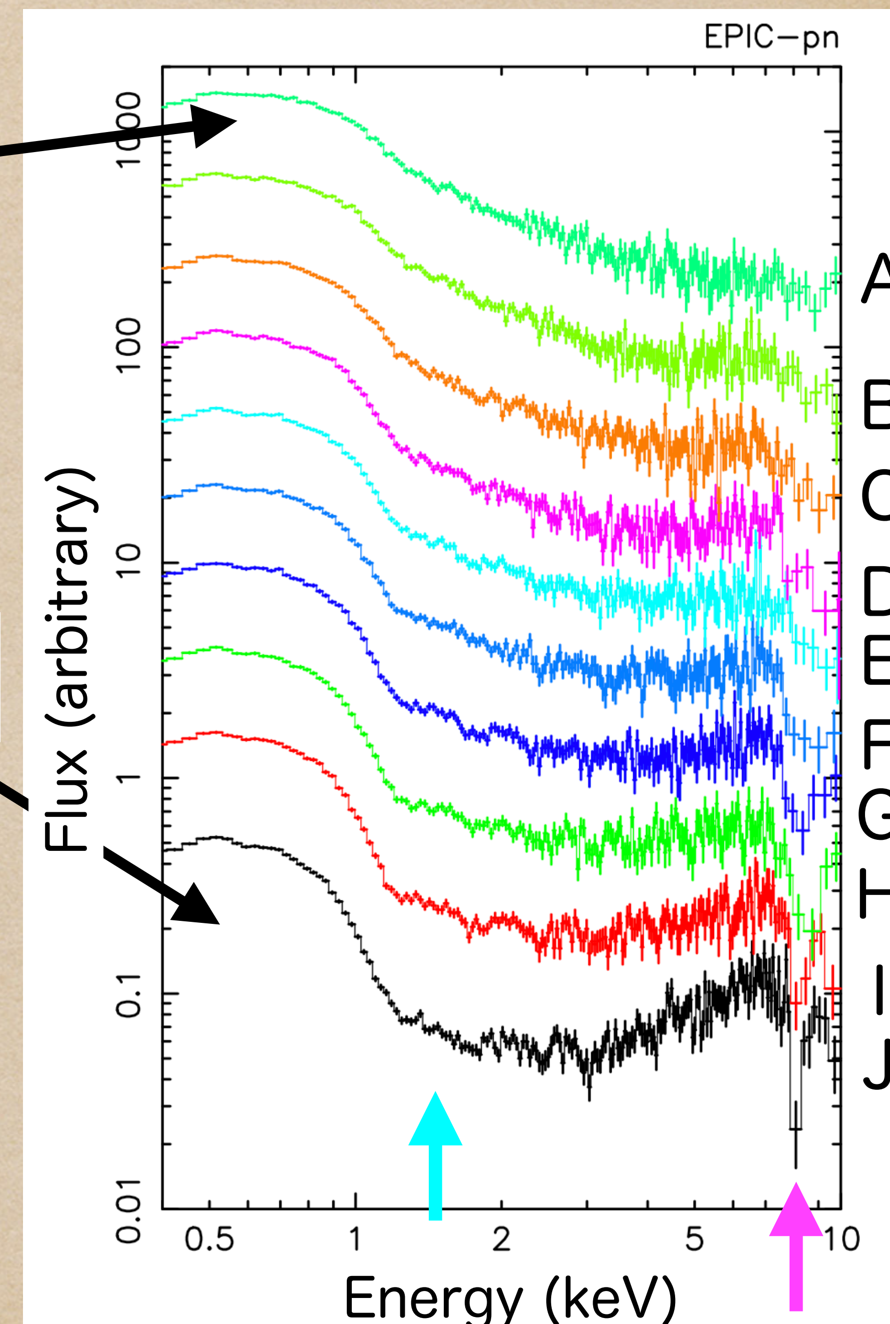
Clumpy absorber in X-ray spectrum



Intensity-sliced spectra

IRAS 13224-3809

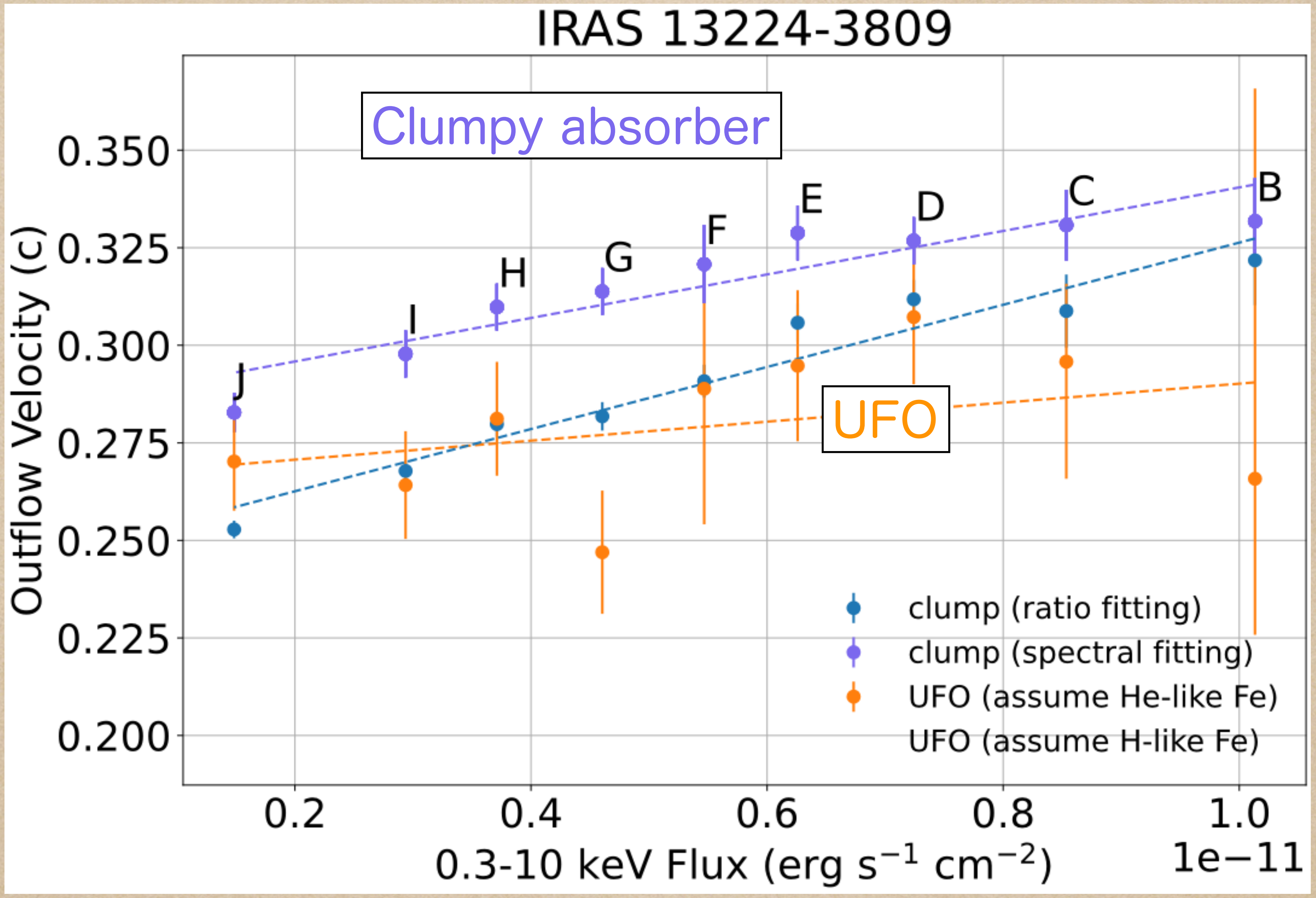




(Pinto+18)

- ✦ Clumpy absorber
- ✦ UFO (especially in fainter spectra)

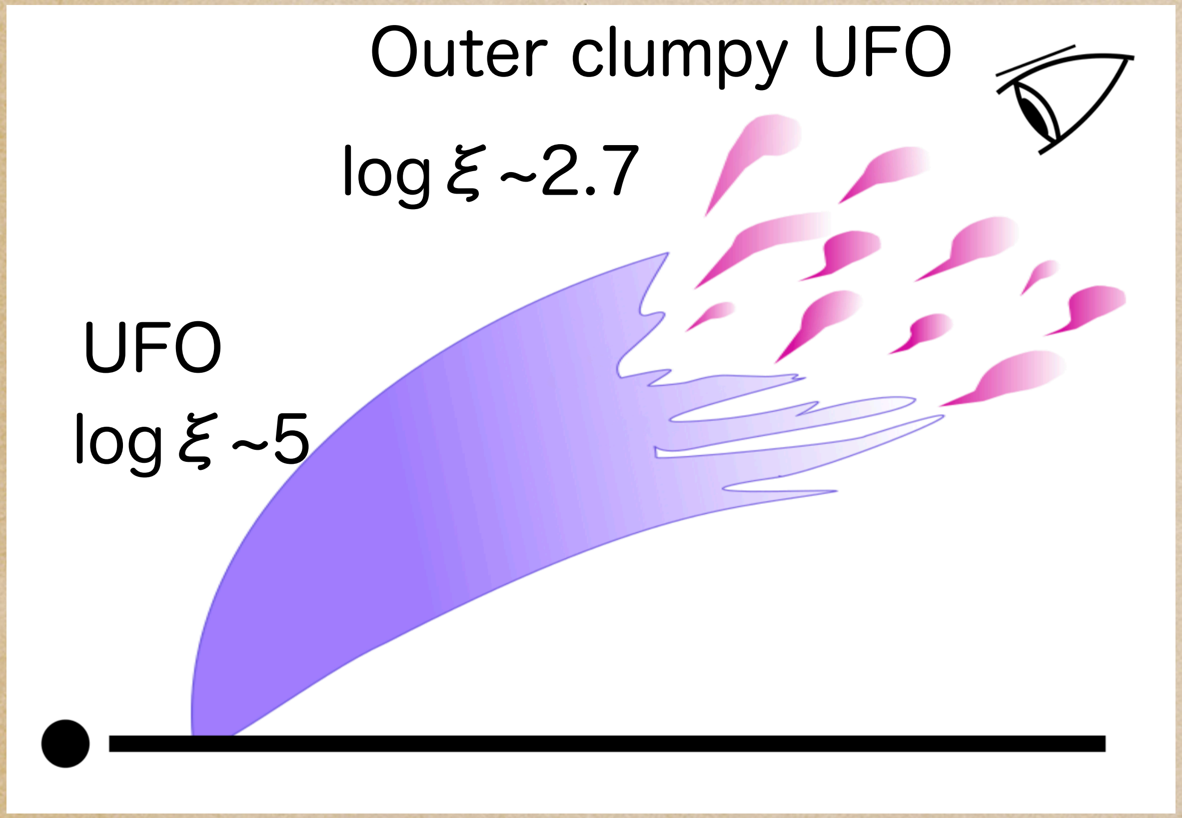
Comparison of outflow velocity



- Clumpy absorber velocity > UFO velocity

"Outer clumpy UFO"

Why Faster than UFO?



Super-Eddington accretion flow
-> Continuum driven wind

Once the wind becomes clumpy, the (local) number density becomes larger.
-> The ionization becomes lower.
-> UV line driven acceleration additionally works.
-> Faster than UFO

Summary

- UltraFast Outflow (UFO) is launched from a close vicinity of the central BH, with fast velocity (v=5-30% of the light speed) and enormous kinetic power.
- One of the plausible mechanism for UFO is a radiatively-driven wind.
  - Continuum driven: pushed by Thomson cross section (super-Eddington source)
  - UV line driven: pushed by UV bound-bound transition (sub-Eddington source)

- UFO may interact with ISM, create shocks, and sweep up the ISM.
  - Energy-conserving flow: Cooling is inefficient.
  - Momentum-conserving flow: Cooling is efficient.
- Shocked ISM = cold molecular outflow?
- Shocked UFO = will be seen in Mrk 34?