降着円盤大研究会2015

京都大学, 2015年6月21-22日

MONACO
Calculation Framework of X-ray Radiation in Astrophysical Objects based on Monte Carlo Simulations

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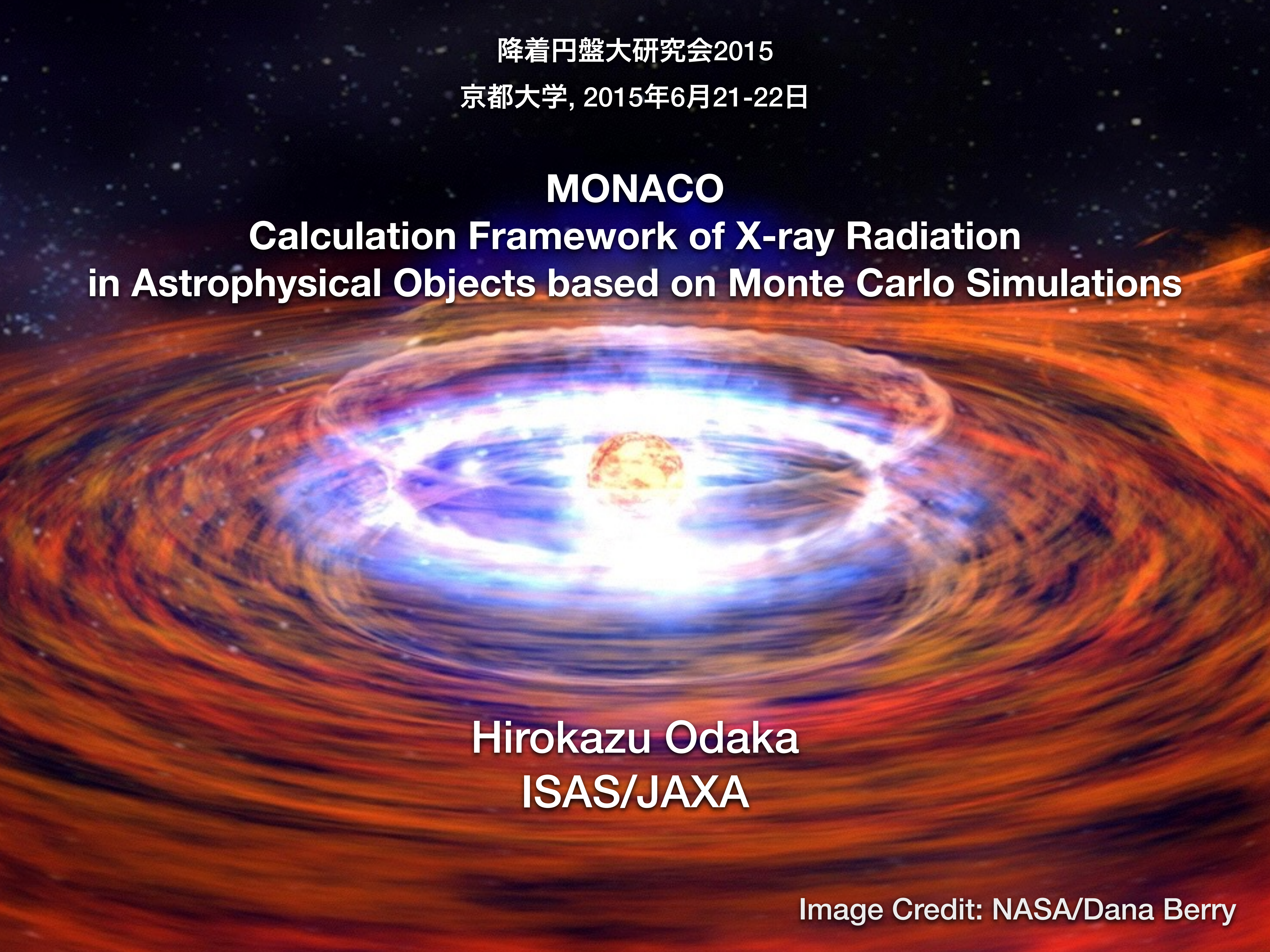
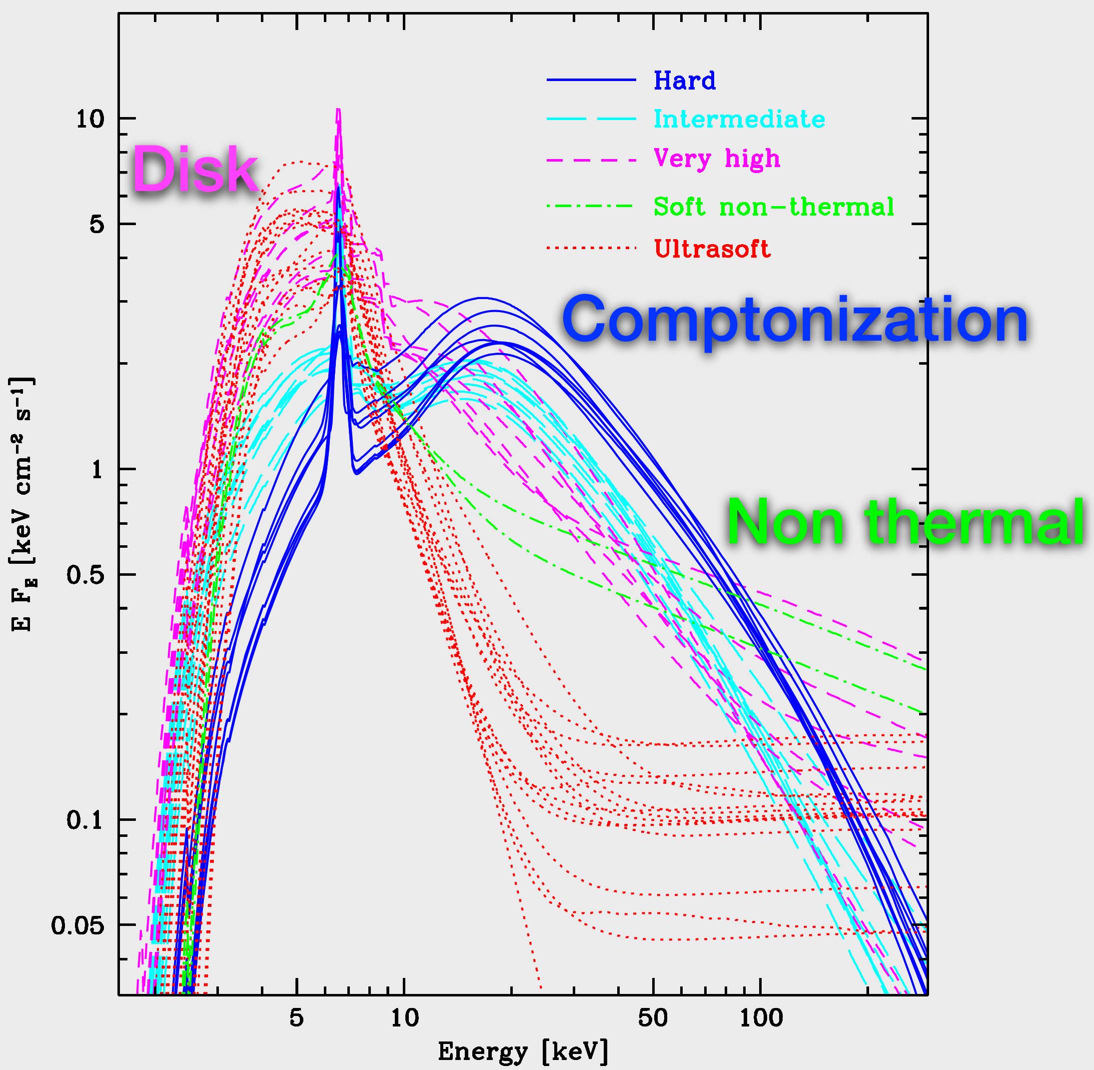


Image Credit: NASA/Dana Berry

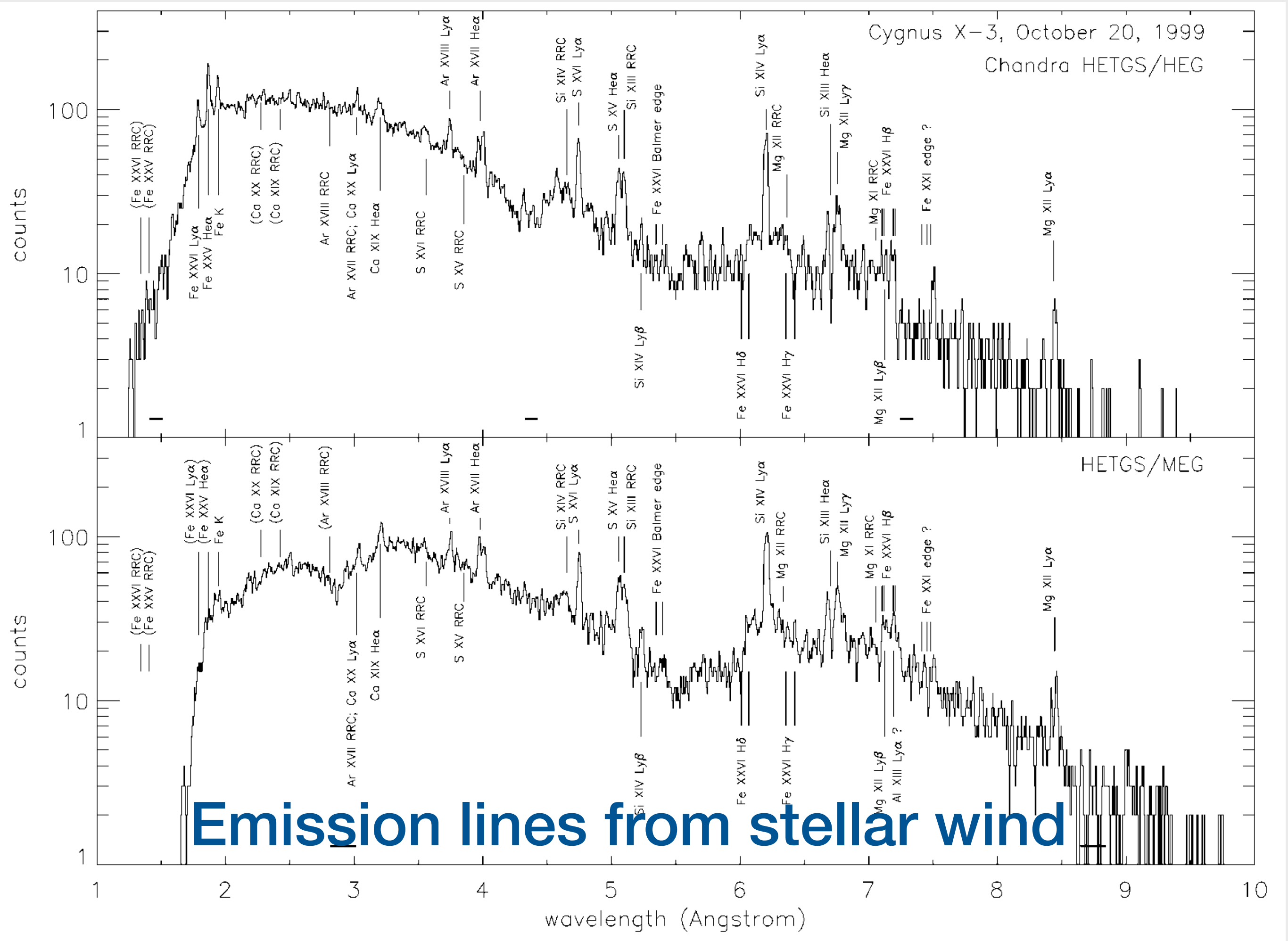
X-ray view of accreting objects

Cyg X-3 in a wide band (RXTE)



Hjalmarsdotter et al. 2009

Cyg X-3 in high resolution (Chandra-HETG)



Paerels et al. 2000

X-ray features emerging from Comptonization, disk black body, disk reflection, photoionized stellar wind, etc. tell us physical conditions of the system.

Radiative Transfer

Modern X-ray observations bring us high-resolution and high-statistics data. Interpretation of the high-quality data requires more precise astrophysical models.

optical thickness →

$\tau \ll 1$	$\tau \sim 1$	$\tau \gg 1$
Optically thin	***intermediate***	***Optically thick***

Reprocessing of X-ray photons

It is necessary to treat
- discrete processes of photons,
- competing processes,
- multiple interactions.

Moreover, it depends on geometry.

↓

Monte Carlo approach

easy

Statistical approach
continuous approximation
diffusion approximation
→differential equation

Black body if very thick
e.g. standard accretion disk

MONACO—Monte Carlo approach

We have developed a new multi-purpose calculation framework of X-ray radiation based on Monte Carlo Simulations for observational study.

MONACO:

Monte Carlo simulation for

Astrophysics and **Co**smology

Alphonse Mucha (1897)

MONACO—Monte Carlo approach

- Able to treat arbitrary geometry and gas motions.
- Several physical processes important in accretion-powered sources are implemented.

Physics	Applications
Reflection	X-ray reflection nebulae (Odaka et al. 2011) AGN molecular tori (Furui et al. in prep.)
Photoionization	Stellar winds in X-ray binaries (Watanabe et al. 2006) AGN outflows (Hagino et al. 2015)
Comptonization	Accretion flows onto NS (Odaka et al. 2014) Accretion flows onto BH (Odaka et al. in prep.)

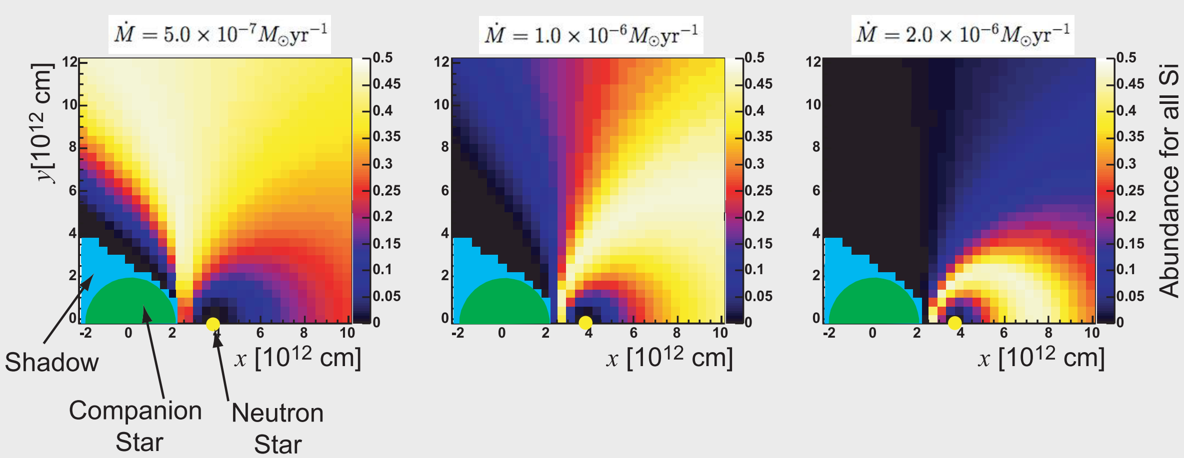
- Supports scattering cross section altered by a strong magnetic field.
- Able to treat polarization.
- General relativity is not included yet.

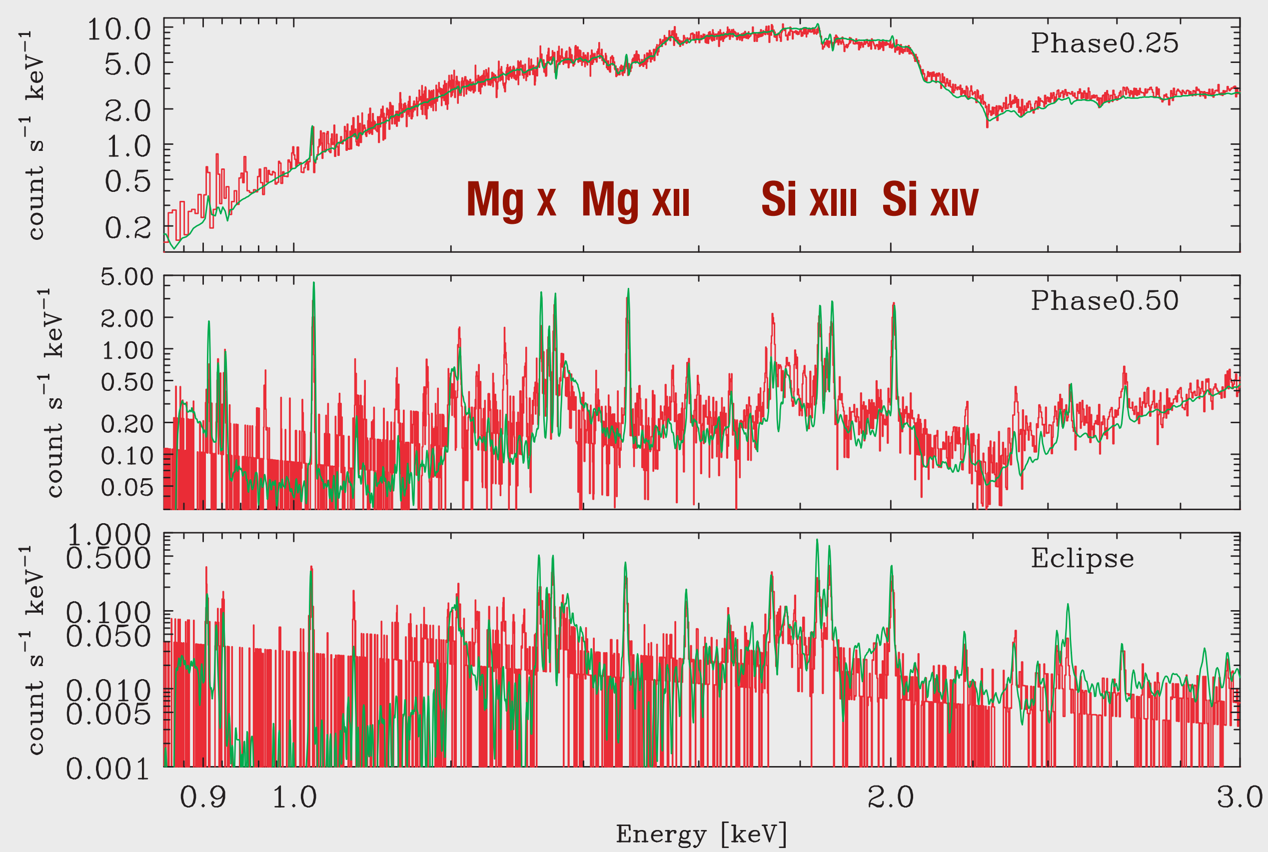
Photoionization

See also Astro-H White Paper “New spectral features” (arXiv:1412.1172v1)

- Stellar winds illuminated by neutron stars or black holes are best studied X-ray photoionized plasma. e.g. Vela X-1, Cyg X-3
- Watanabe et al. (2006) determined structure of the stellar wind of Vela X-1 including the wind mass-loss rate based on Chandra-HETG specta and detailed Monte Carlo modeling at different orbital phases.

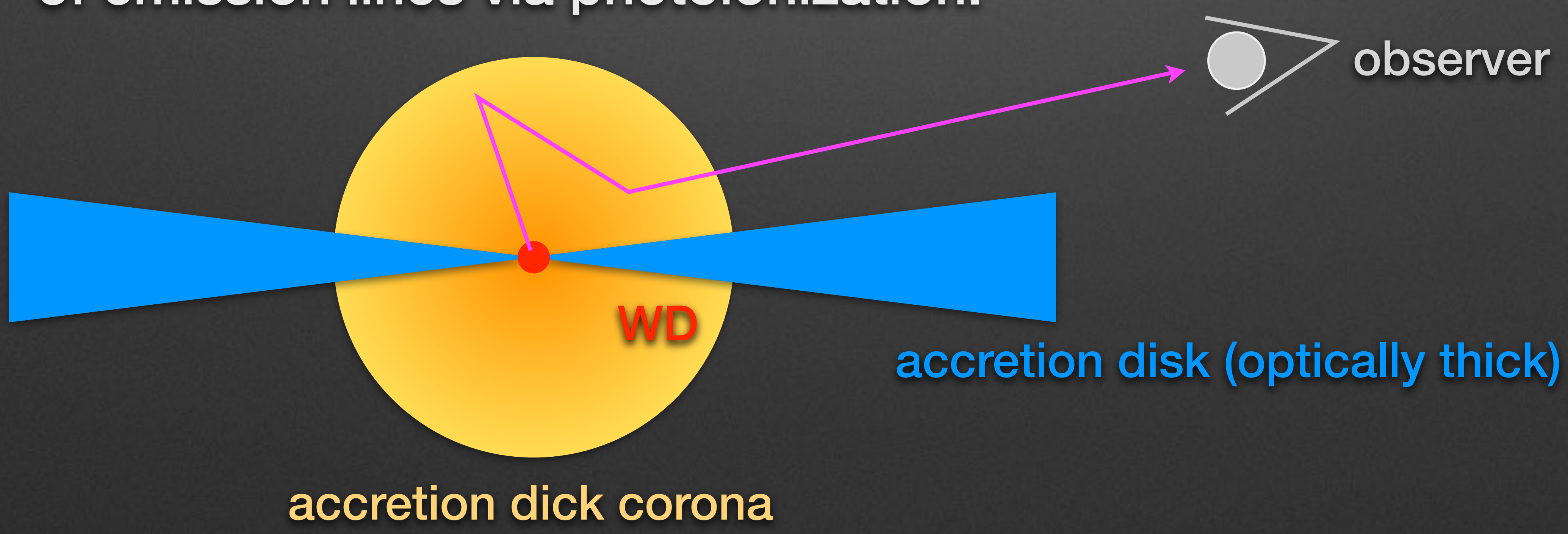
Fraction of hydrogenic ion of silicon
wind mass-loss rate dependence



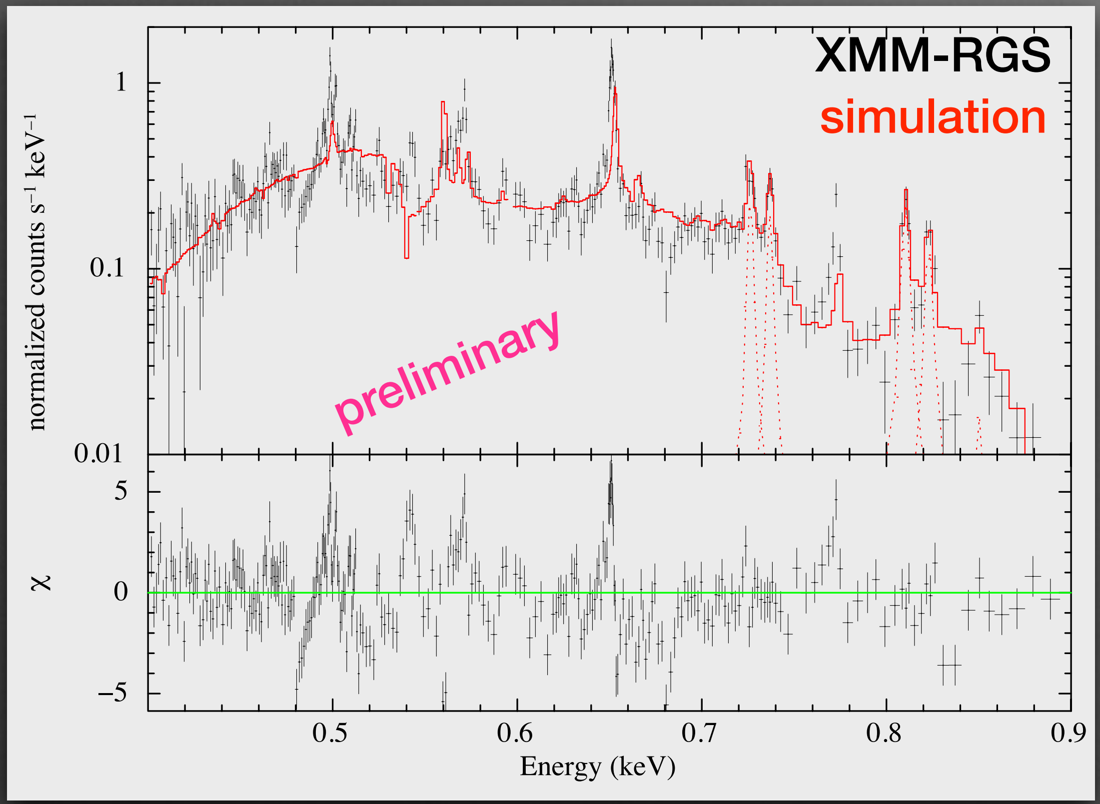


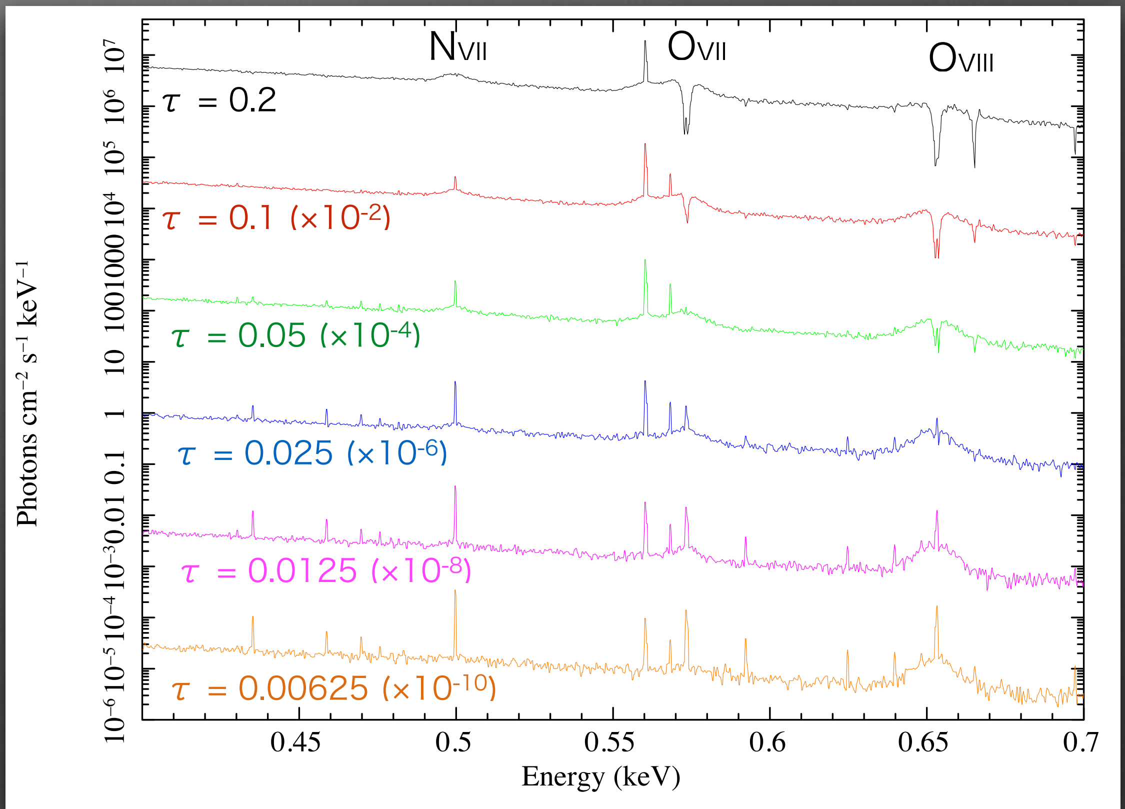
Super soft X-ray sources (SSS)

- Extremely bright in soft X-rays (below 0.8 keV)
- Thermonuclear burning continuously occurs on a white dwarf surface, radiating at close to the Eddington luminosity ~ 10^{38} erg s^{-1}.
- Very high accretion rate ~ $10^{-7}\ M_{\odot}\ yr^{-1}$.
- Possible progenitors of type Ia supernovae.
- There exists an accretion disk corona (ADC) which displays plenty of emission lines via photoionization.



Accretion Disk Corona in SSS



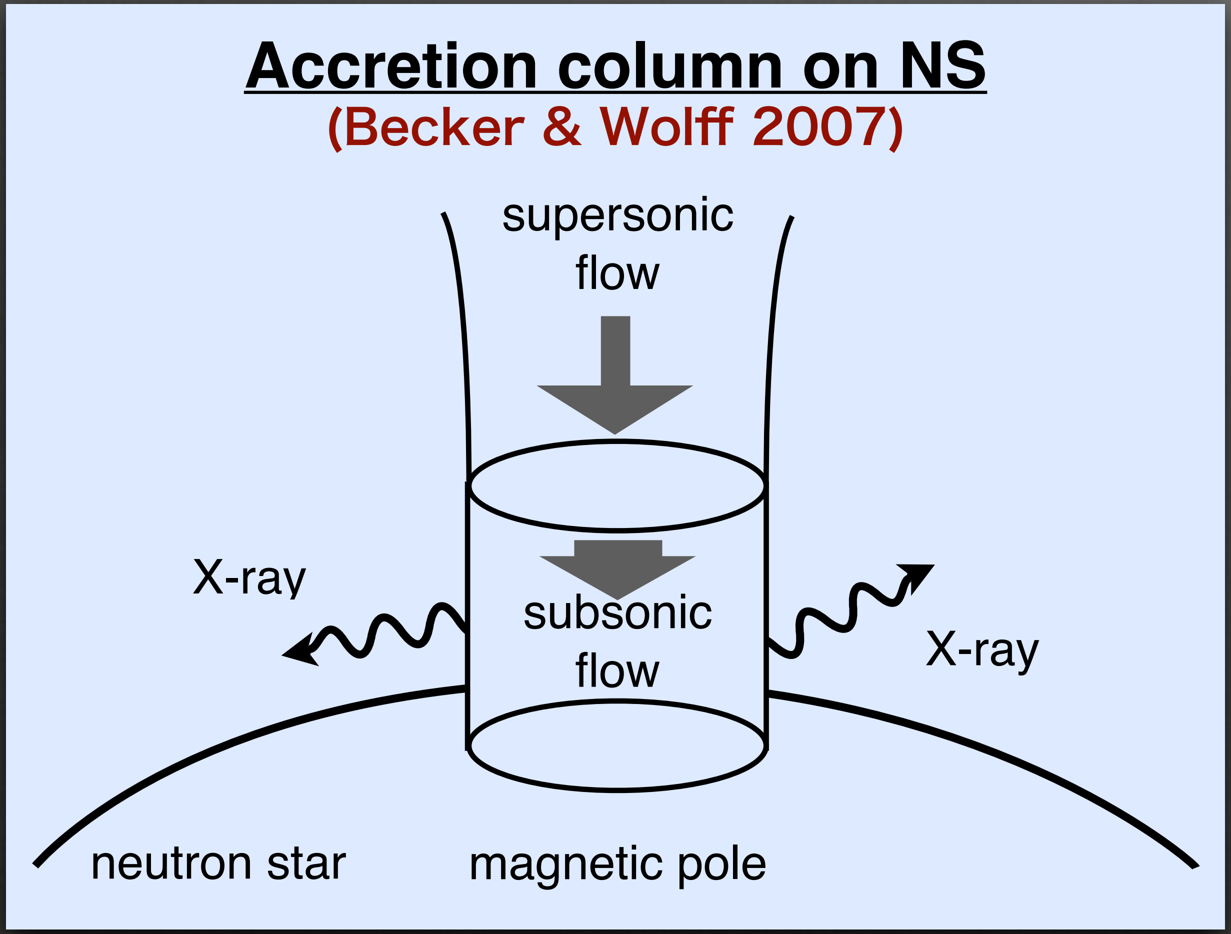


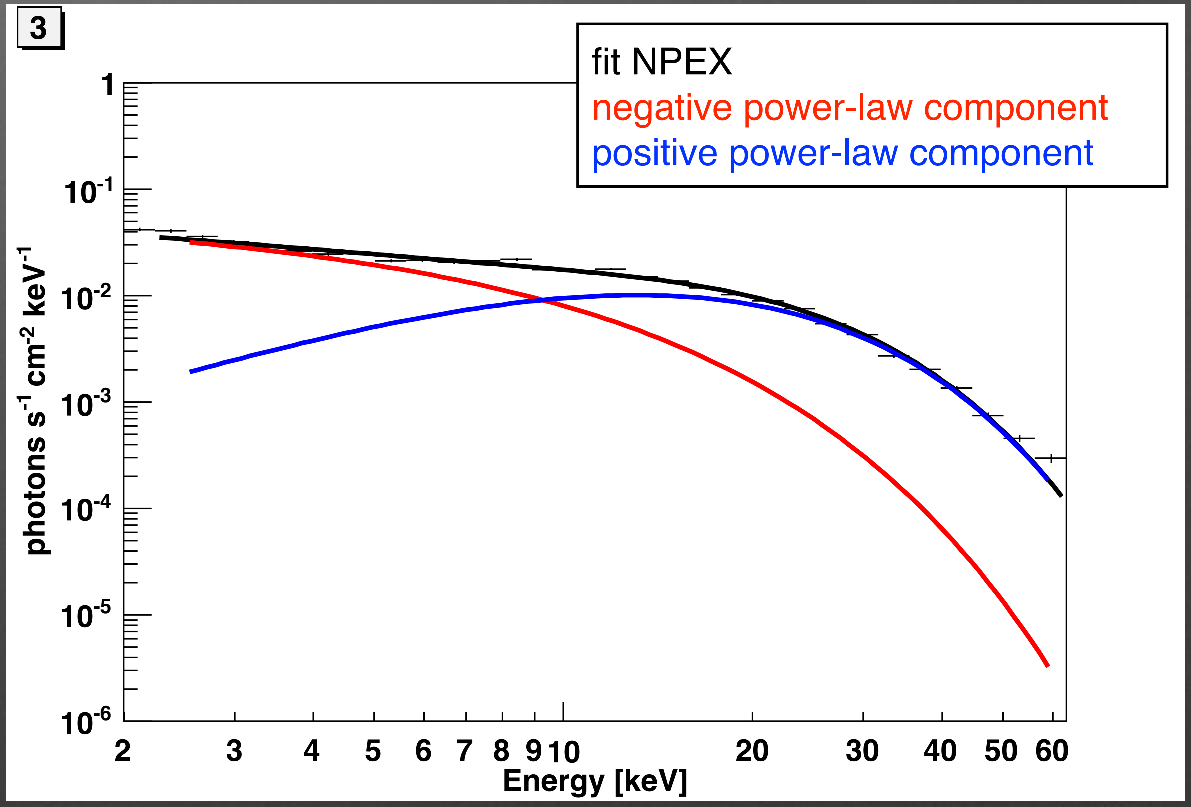
- We attempt to reproduce the high-resolution X-ray spectrum of CAL 87 (SSS in LMC) in the context of accurate photoionization modeling.
- Line red shifts imply that the corona is outflowing.
- Absence of features by resonance scattering suggests that optical depth is even thinner than reported by previous studies.

Wada et al. in prep.

Comptonizaton

Optically thick	Analytical/numerical methods are efficient.
Not optically thick Complicated geometry High energy band	The process is essentially discrete. →Monte Carlo approach is suitable.



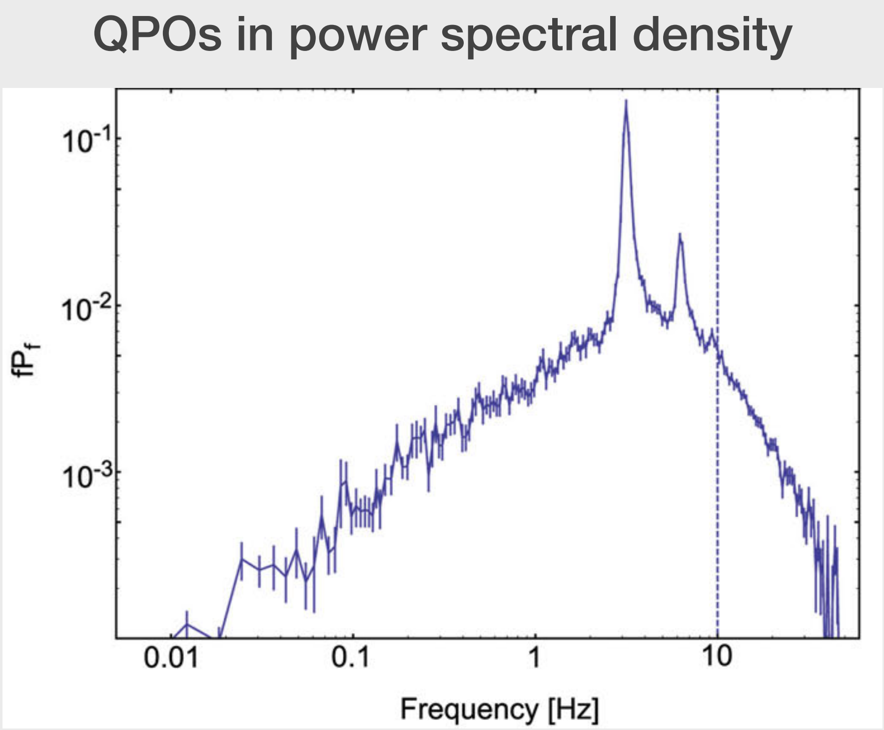


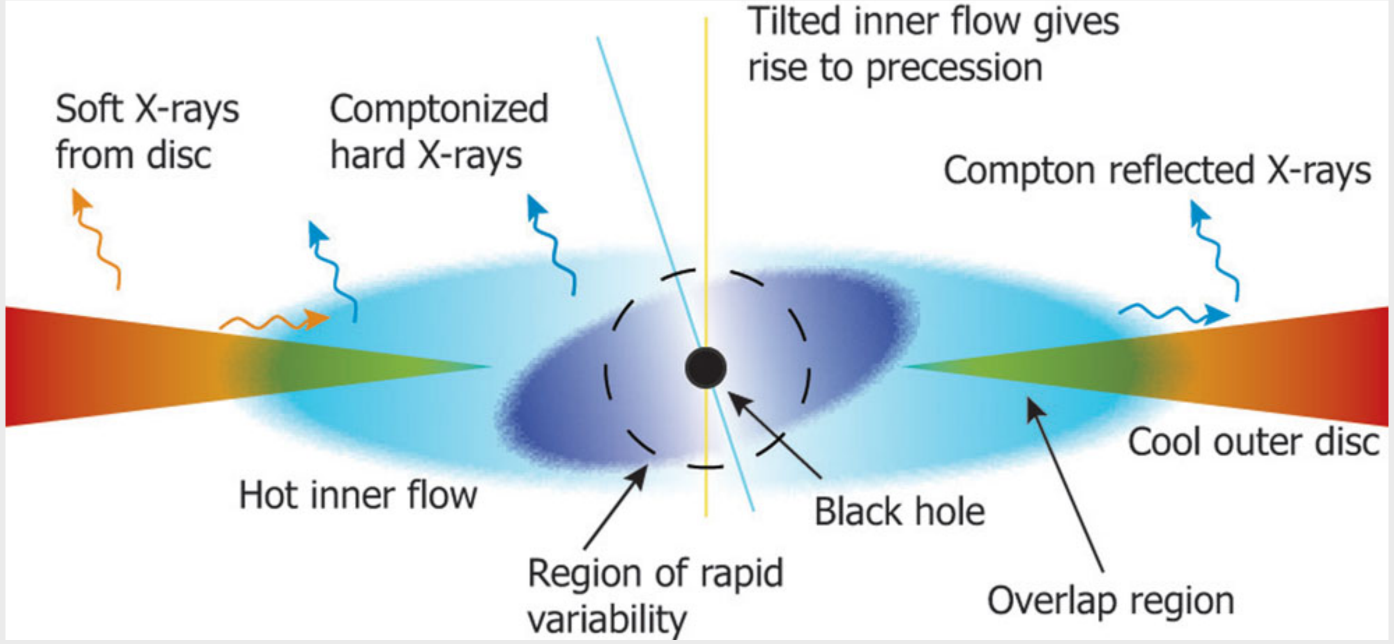
Odaka et al. 2013, 2014

We found a set of self-consistent solutions that agree with the observations of accreting NS Vela X-1 and have reasonable model parameters.
column radius = 200 m, kTe = 6 keV, B field=2×10^{12} G

Accretion flow onto black holes

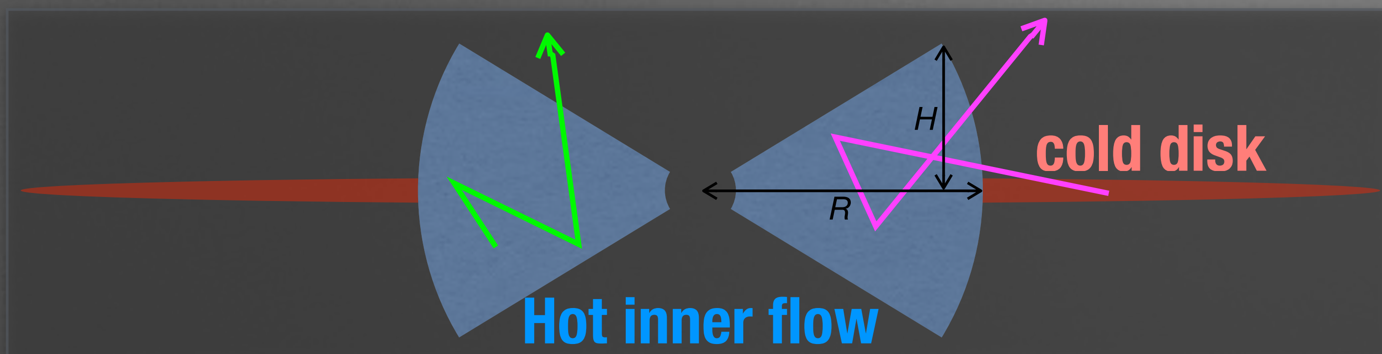
- The scattering process would be much simpler than the NS case. No need to consider the strong B-field and the bulk motion.
- However, the properties of the accretion flow are highly uncertain.
- We investigate Comptonized radiation of microquasar XTE J1550–564 on its rise to outburst in 1998.
- The source showed strong low frequency QPO, which can be explained in the context of a precessing inner hot flow.

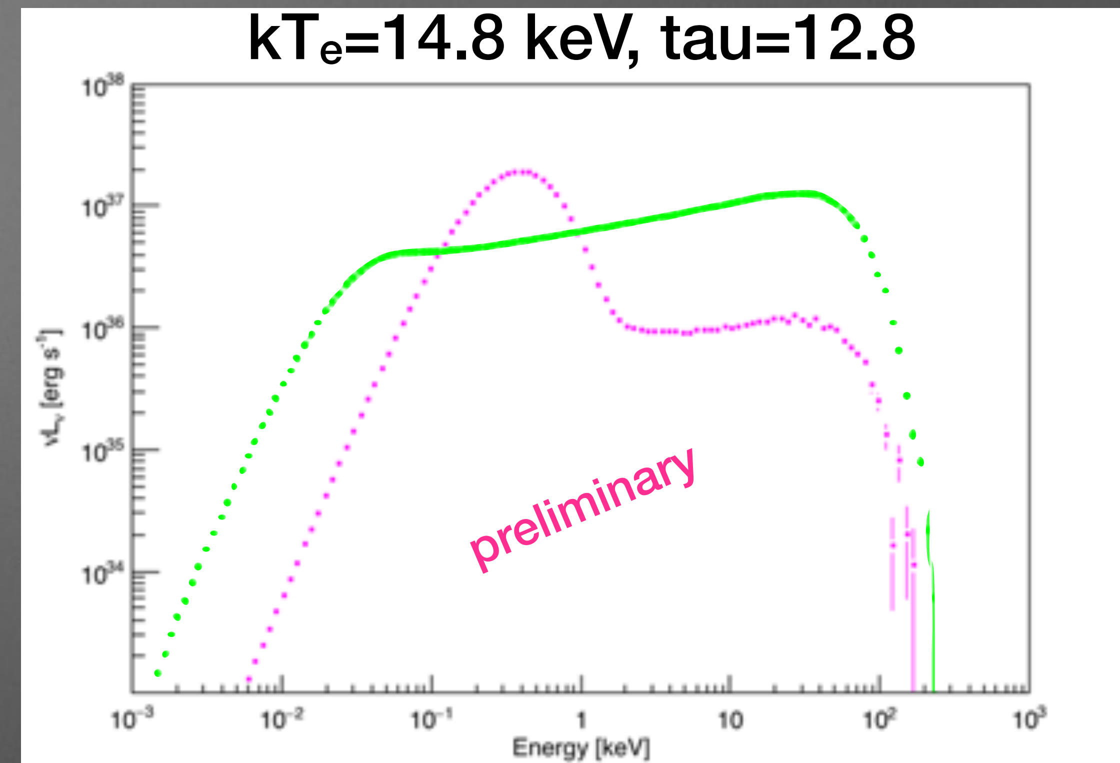




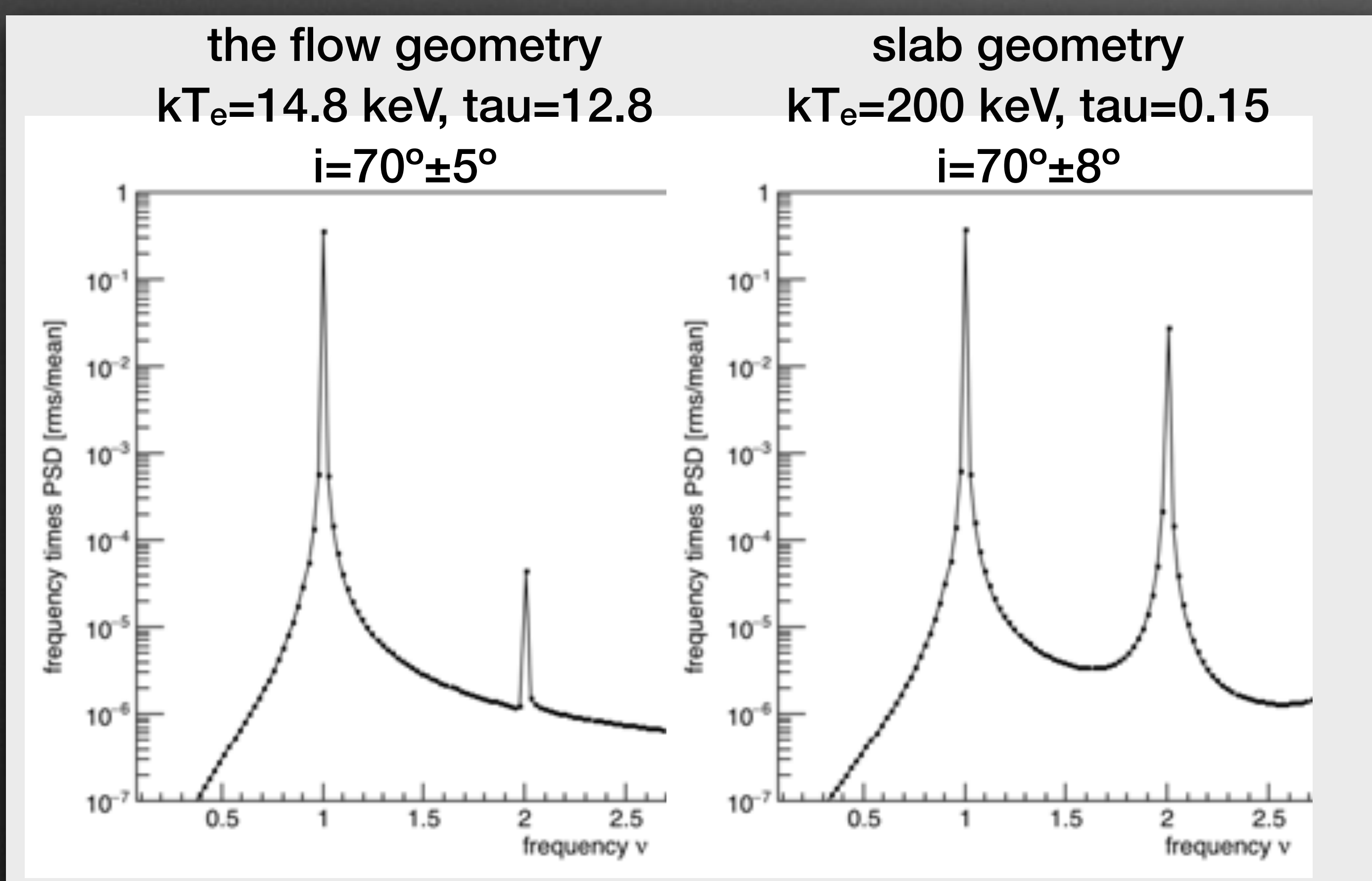
Axelsson et al. 2013

Comptonization model





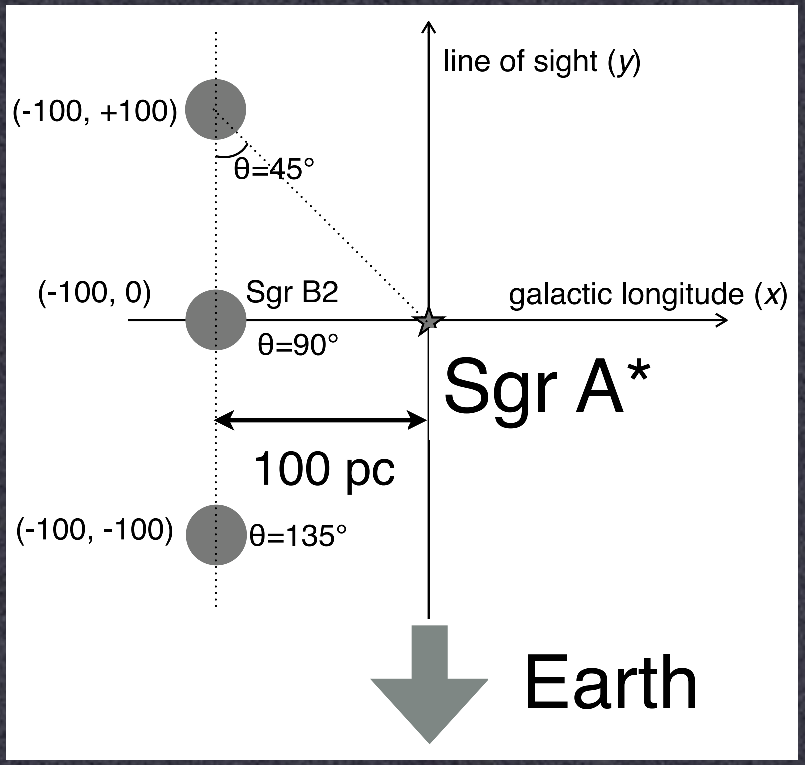
We assume cyclo-synchrotron (CS) origin of the seed photons as well as disk black body. CS can have a significant role in cooling the hot inner flow (e.g. Di Matteo et al. 1997).



- Assuming the vertical precession of the flow (i=70°±5°), we successfully reproduced the observed level of QPO. But the first harmonic was significantly weaker than observed.
- This may implies that the flow has inhomogeneous structure with higher kTe or nonthermal electrons.

Odaka et al. in prep.

Diagnostics of Molecular Clouds

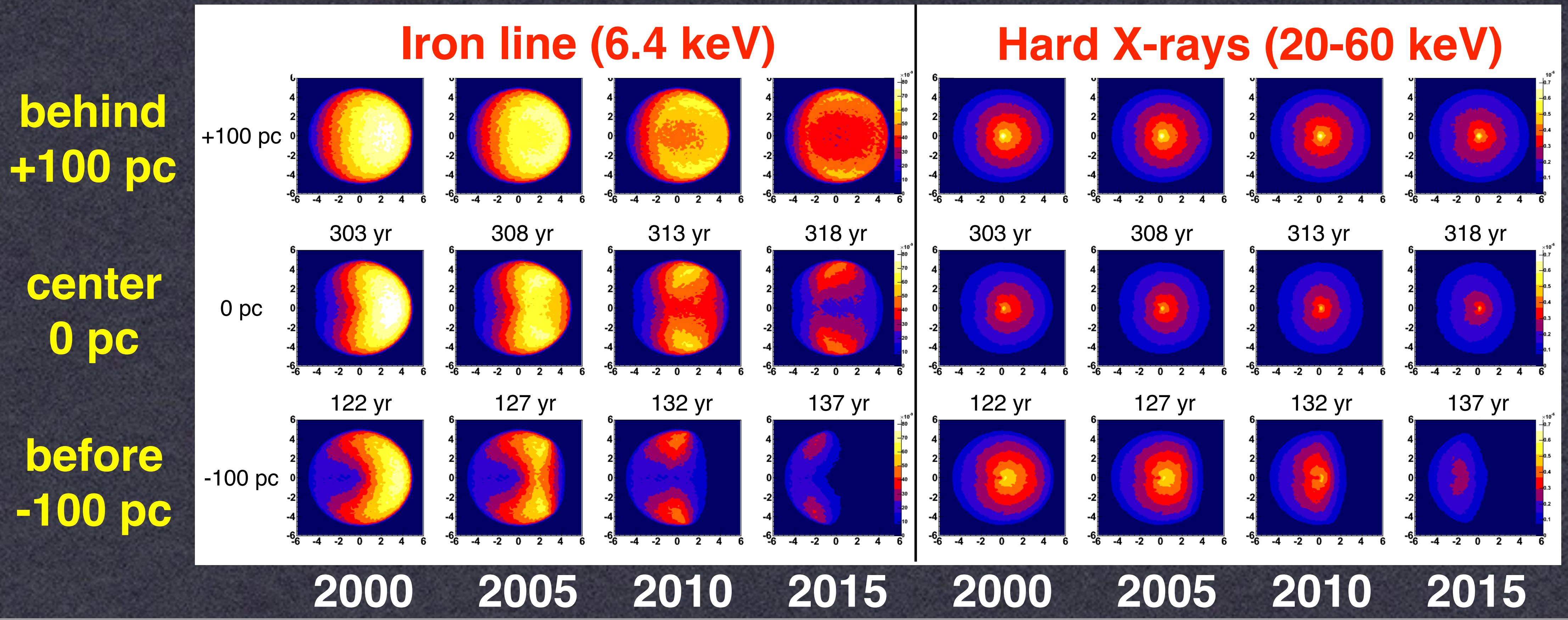


Odaka et al. 2011

Parameters:

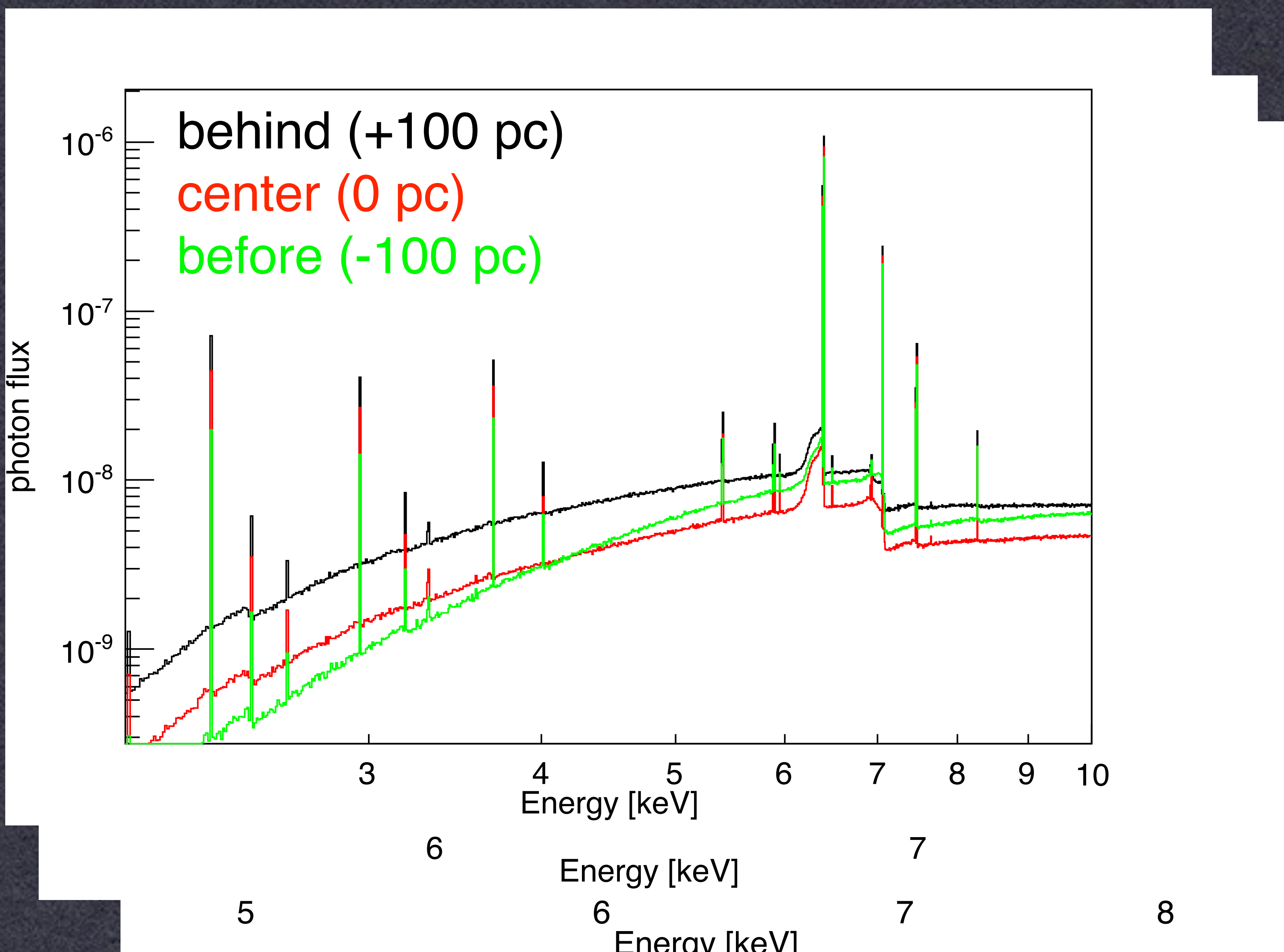
- line-of-sight position of the cloud
- mass
- density profile
- chemical composition

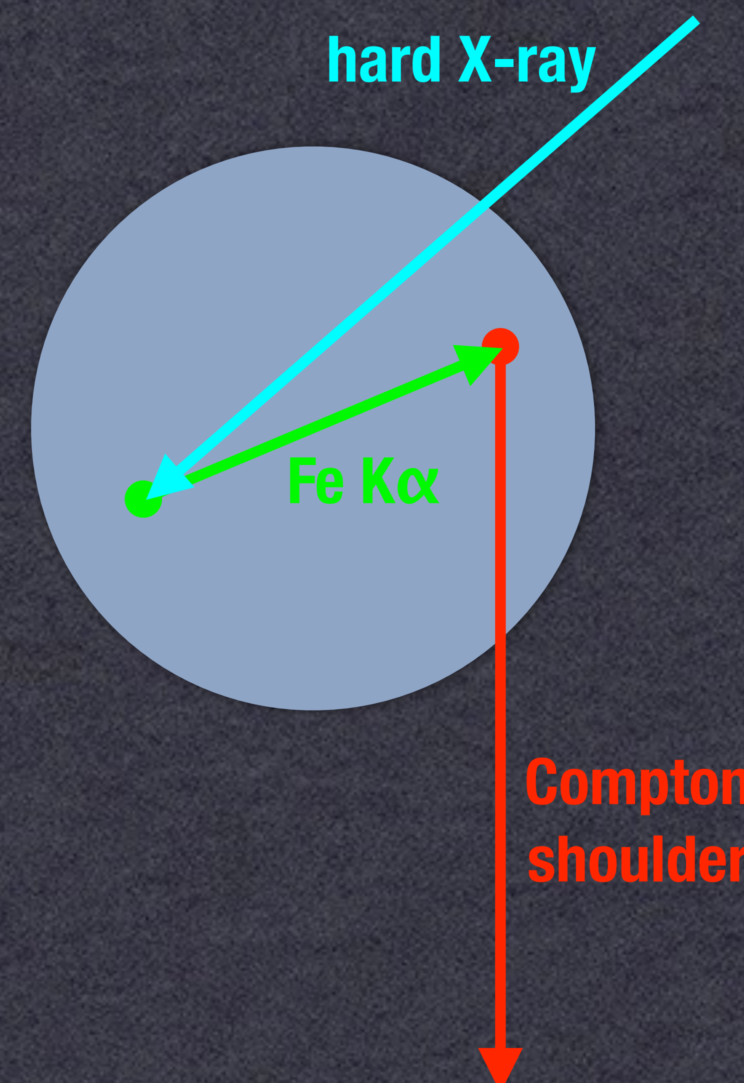
Imaging results show very different between the iron line and hard X-rays.



Compton Shoulder

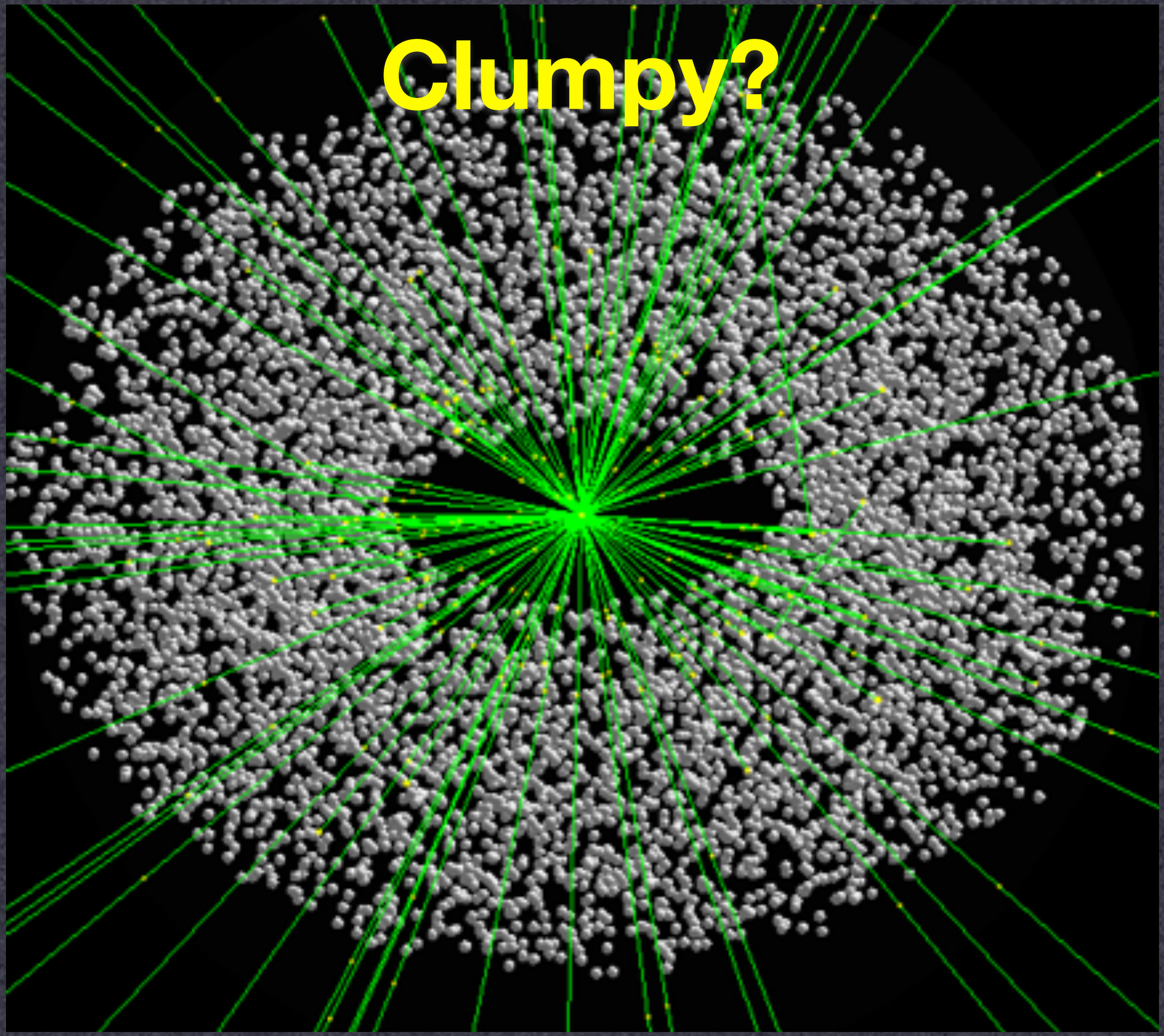
Compton shoulder, which is produced by Compton down-scattering of strong fluorescence lines (e.g. Fe Kα), has a potential diagnostic power.

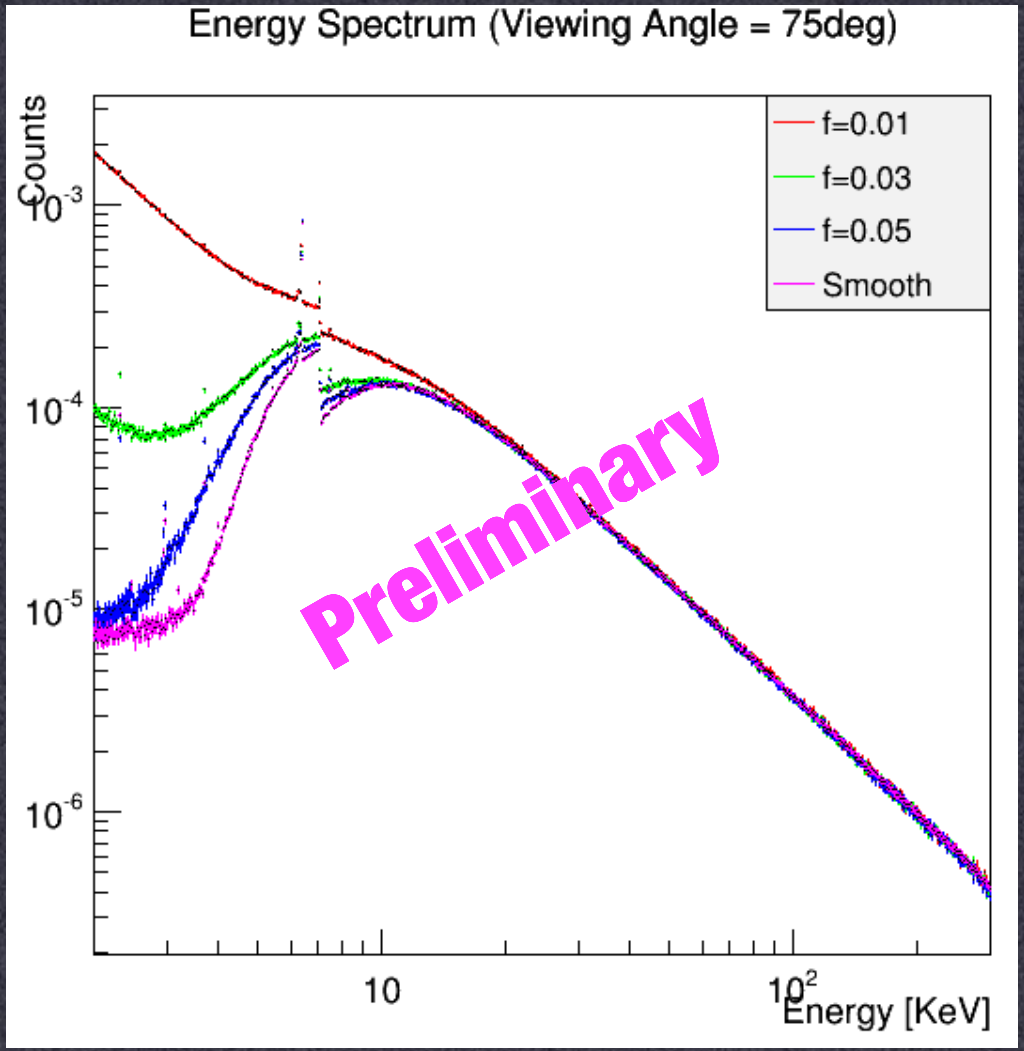




AGN Dusty Torus

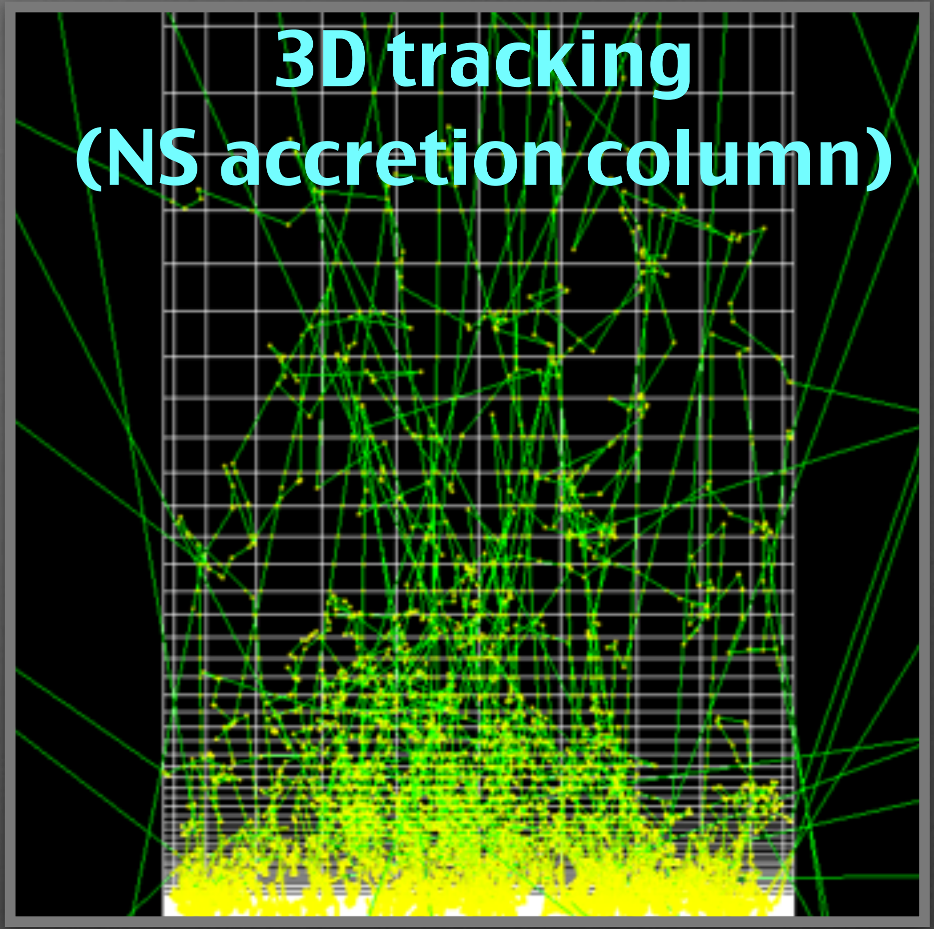
The nature of AGN dusty torus is also investigable with MC simulations. MYTorus model is available to XSpec users (Yaqoob 2012).





Furui, Fukawaza, Kawaguchi & Odaka

Conclusions



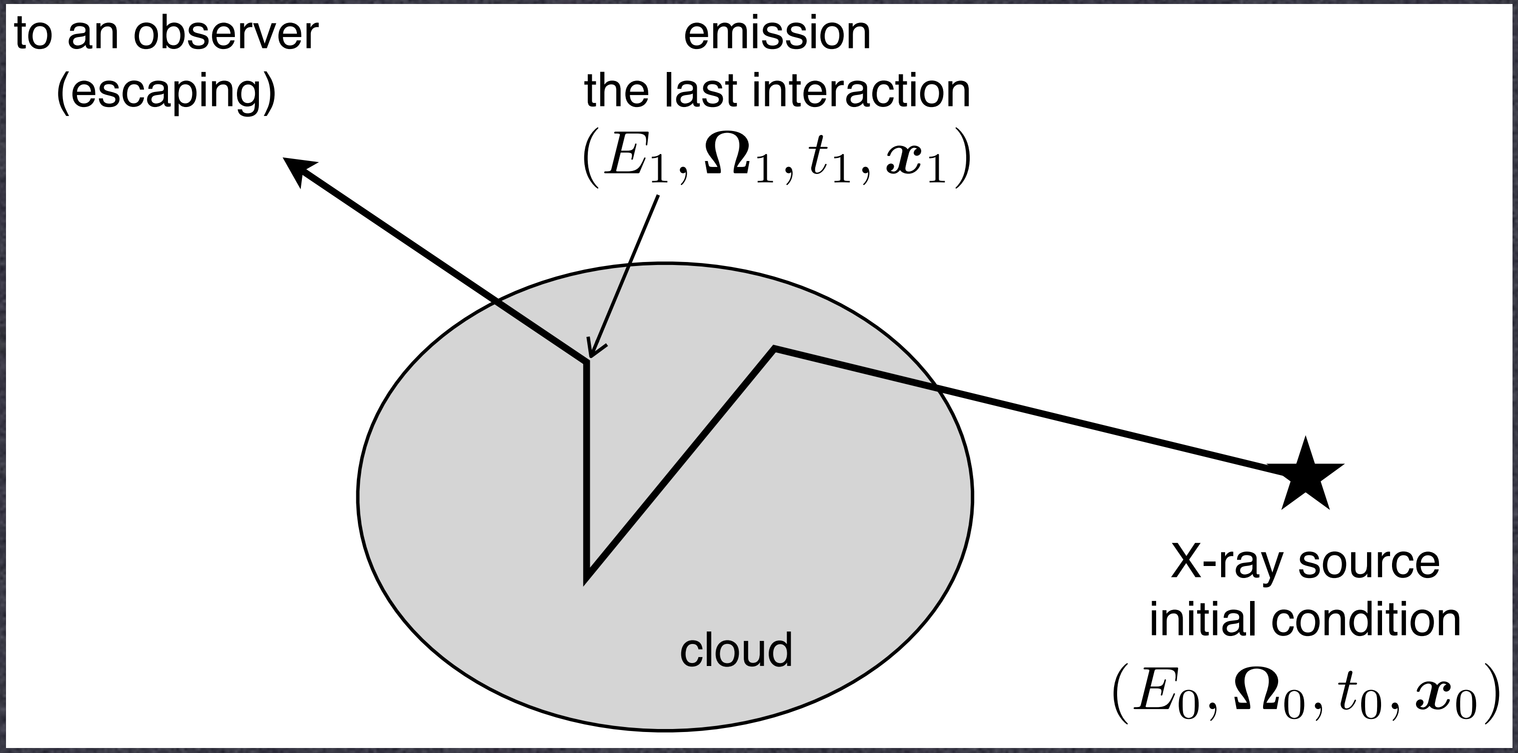
ASTRO-H衛星（今年度軌道投入予定）
宇宙物理学も精密定量科学の時代

モンテカルロ計算による正確な天体放射モデルをデータ解析に用いることが必要になってくる。

Collaborators of the MONACO project
Framework: Shin Watanabe, Tadayuki Takahashi
Reflection from molecular clouds: Felix Aharonian, Dmitry Khangulyan
AGN torus: Shunya Furui, Yasushi Fukazawa, Toshihiro Kawaguchi
Photoionized stellar winds: Shin Watanabe, Masao Sako
AGN outflows: Kouichi Hagino, Chris Done, Poshak Ghandi
Super soft X-ray sources: Kazuya Wada, Ken Ebisawa, Masahiro Tsujimoto
Accretion onto NS: Dmitry Khangulyan, Yasuyuki Tanaka, Kazuo Makishima
Accretion onto BH: Chris Done
Polarization: Paolo Coppi

Monte Carlo Simulation

The simulation tracks photons by calculating their propagation and interactions based on Monte Carlo method.

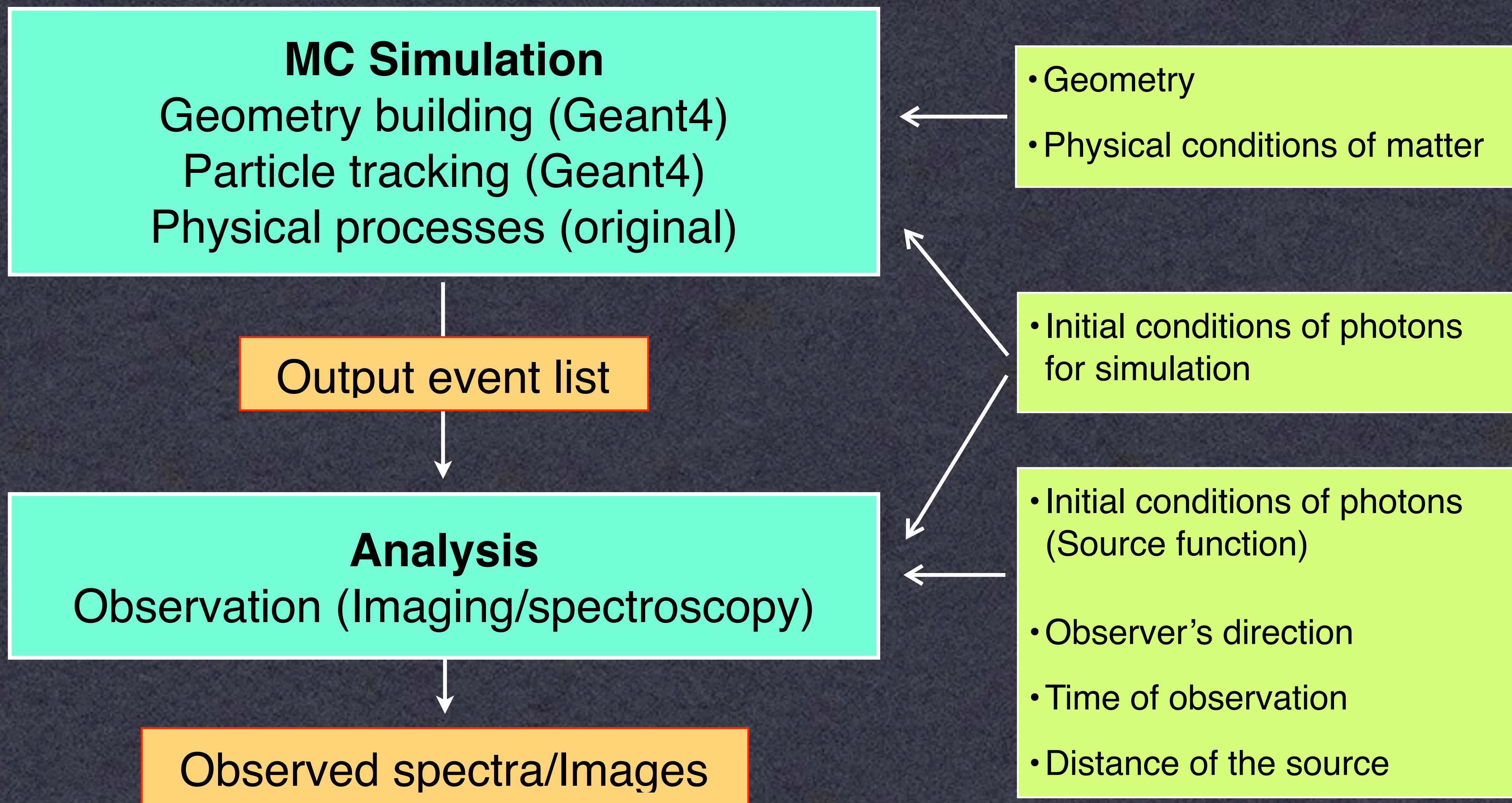


Process of one event

1) generate a photon, record initial conditions
2) calculate the next interaction point
3) invoke the interaction, reprocess photons
4) repeat 2-3
5) record the last interaction information if a photon escapes from the system.

A MC simulation generates a list of events which have information on a response of the system to the photon irradiation.

The MONACO Framework



- Building geometry and tracking particles: Geant4 toolkit library
  ←Sophisticated treatment of complicated geometry (e.g. radiation detector simulation)
- Physical processes: original implementation.
  ←Existing codes have been inadequate to treat binding effects of atoms and gas motion (Doppler effect of thermal/bulk/micro-turbulent motions).
  We also extend the Geant4 geometry builder for astrophysical objects.