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Geant4 Applications to High Energy Astrophysics

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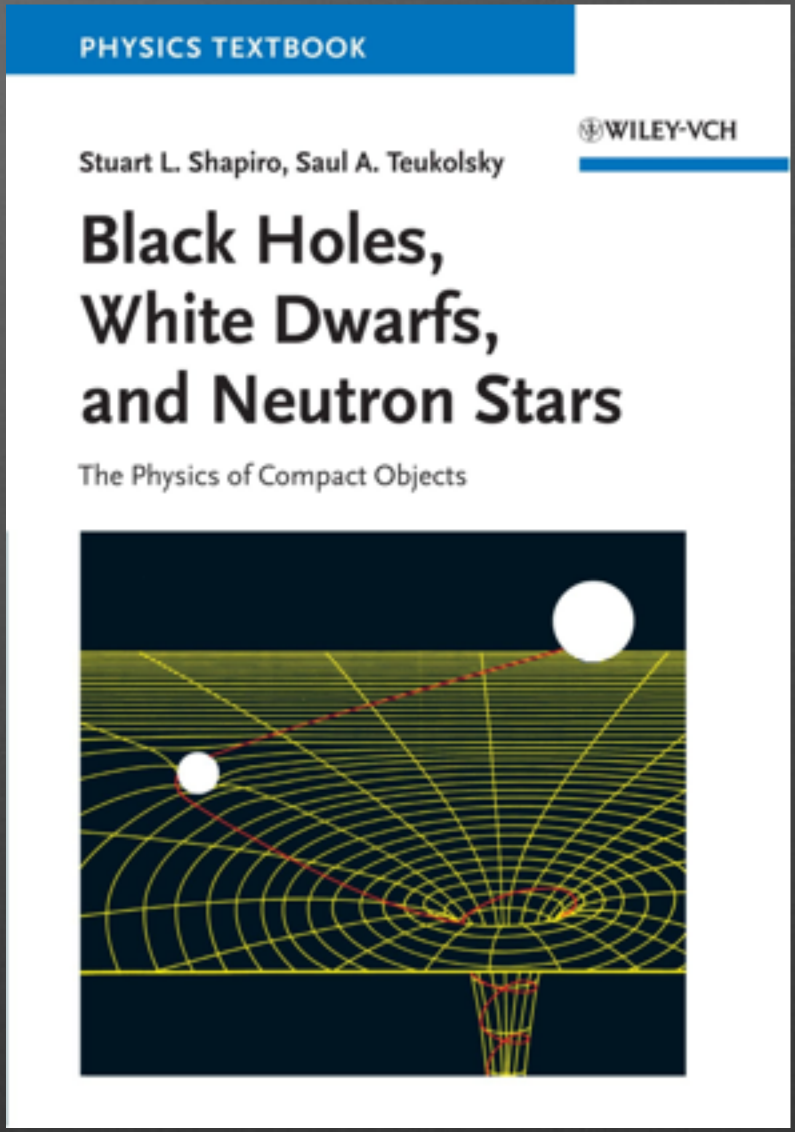
Image Credit: NASA/Dana Berry

Accretion power in compact objects

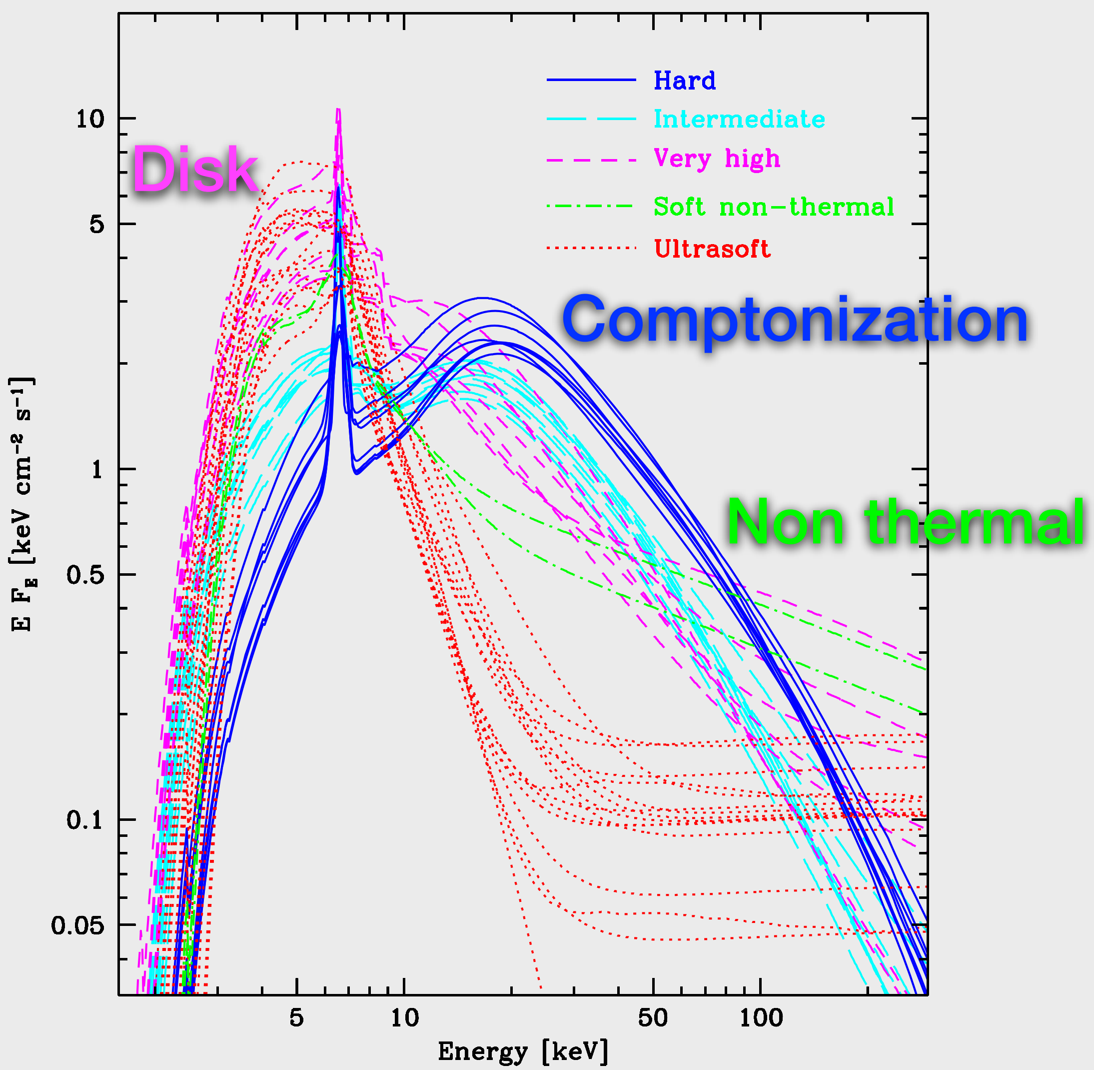
- Black hole: one of the most mysterious objects in the universe.
- Neutron star: composed of the densest material (super-nuclear density).
- Accretion onto a deep gravitational potential is one of the most efficient energy release mechanisms in the universe.
- Binary stars harboring a black hole or a neutron star can be the brightest X-ray emitters (known as X-ray binaries) with luminosities up to 10^{31} W.
- White dwarfs in binary systems can also be bright X-ray sources powered by accretion or thermonuclear burning.
- The energy is released via various forms: radiation, energetic particles, wind, and/or relativistic jet.

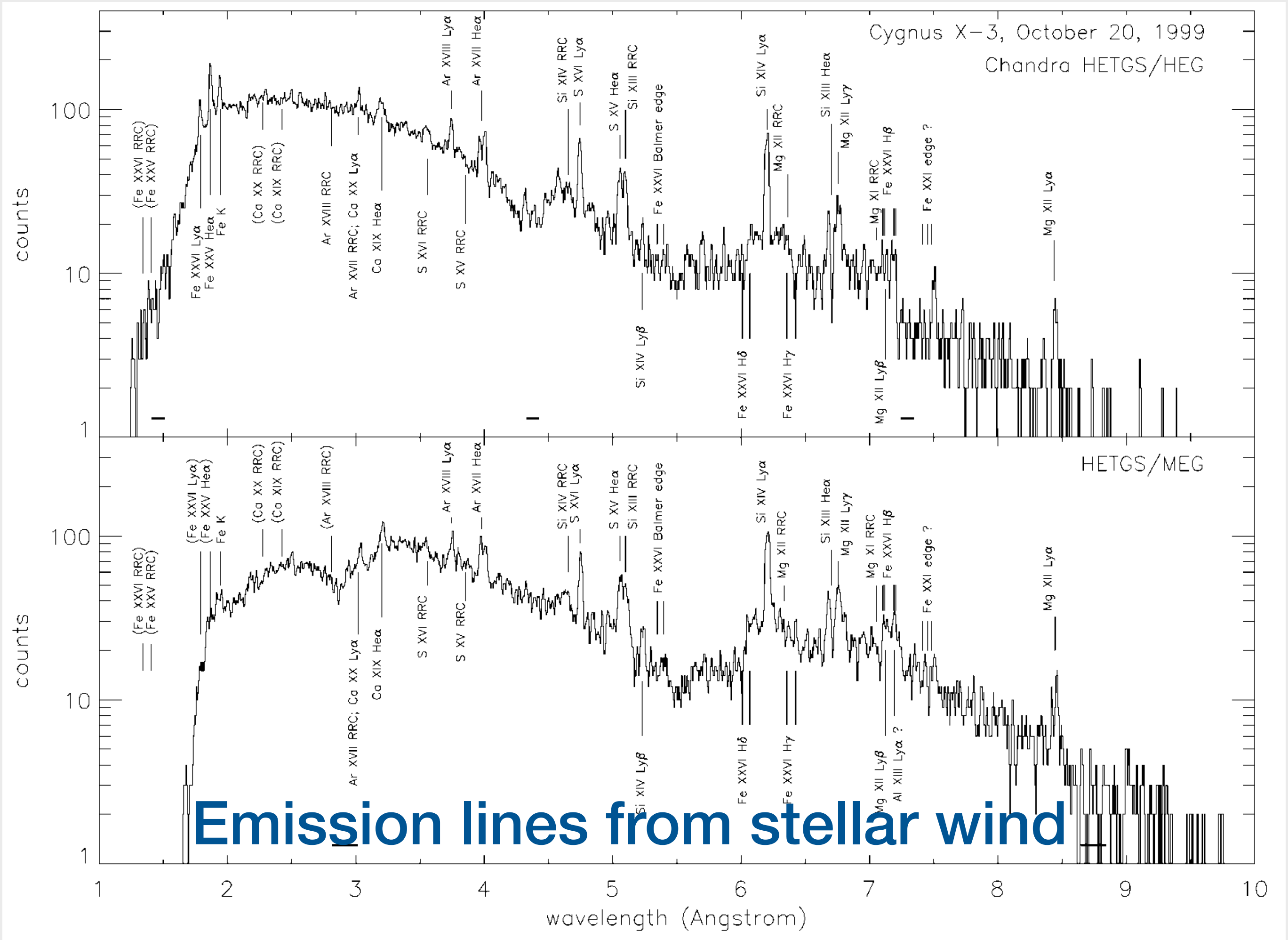


X-ray view of an accreting object

Cyg X-3 in a wide band (RXTE)

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





Hjalmarsdotter et al. 2009

Paerels et al. 2000

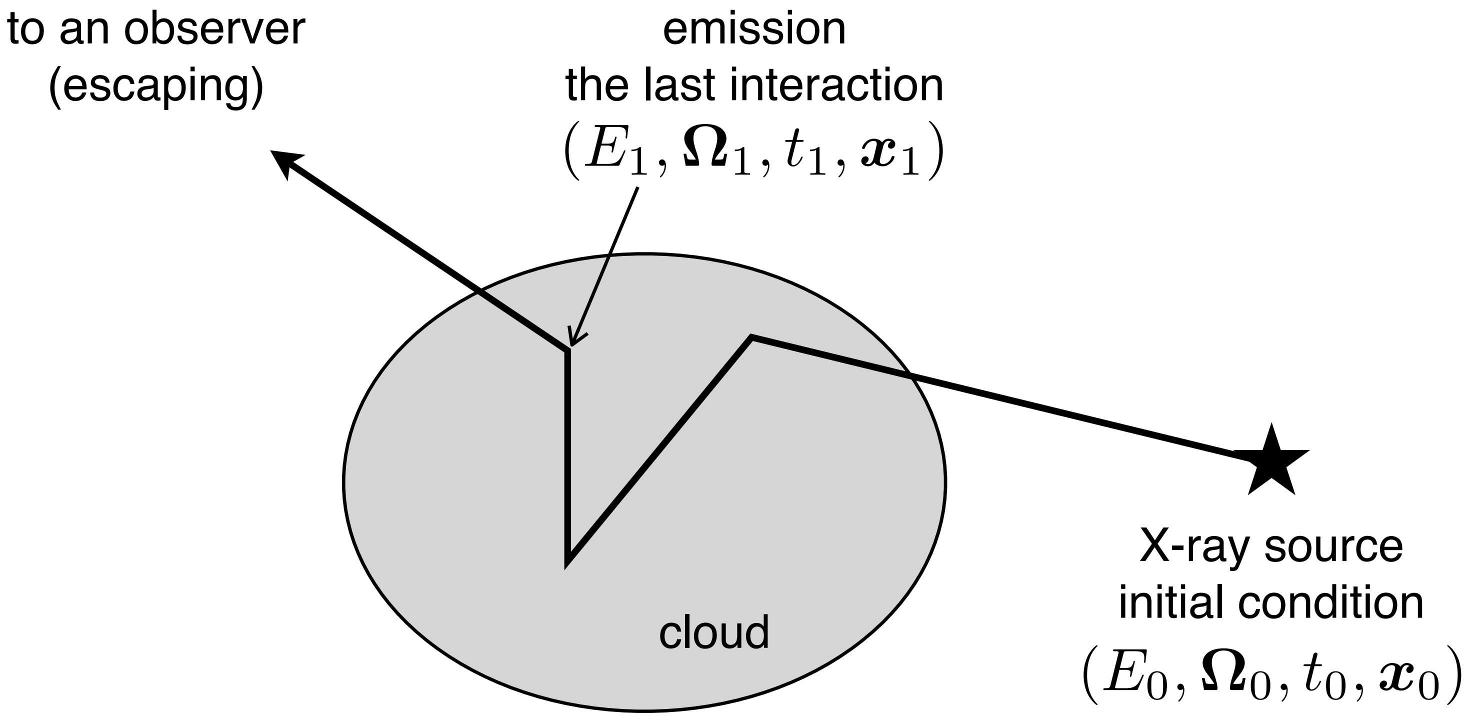
X-ray features emerging from Comptonization, disk black body, disk reflection, photoionized stellar wind, etc. tell us physical conditions of the system. We need a model to interpret this spectrum.

Monte Carlo approach to radiative transfer

Recent improvement in observational instruments allows us to obtain high-quality data. Precise comparison between the data and theoretical models requires careful treatment of X-ray generation in the accreted plasma and radiative transfer.

Monte Carlo is the simplest and the most reliable way to treat radiative transfer accurately.

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



Odaka et al. 2011

MONACO—Monte Carlo approach

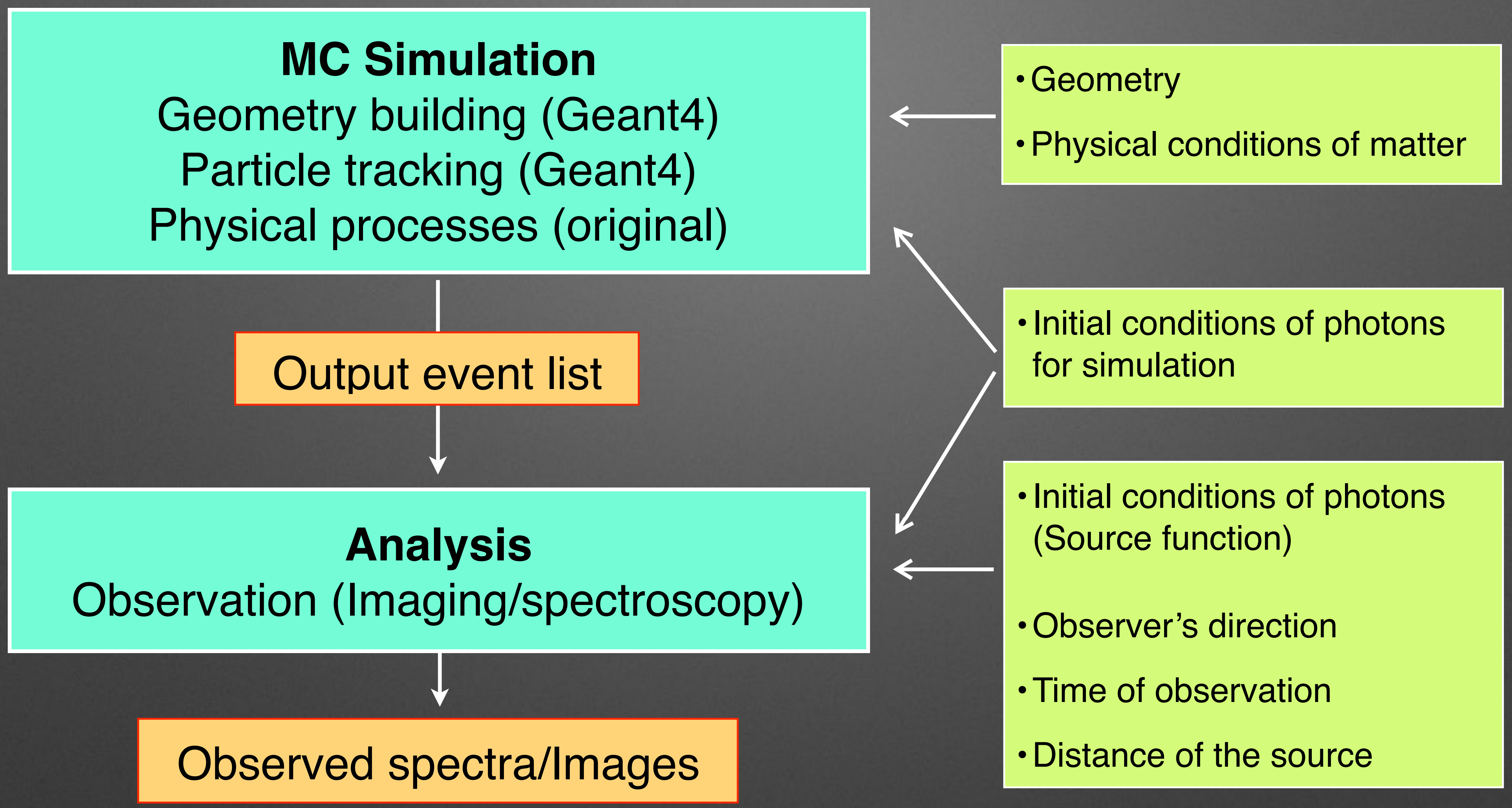
We have developed a new multi-purpose calculation framework of X-ray radiation based on Monte Carlo Simulations for observational study.

MONACO:

Monte Carlo simulation for **A**strophysics and **Co**smology

Alphonse Mucha (1897)

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 (thanks to the universal design of G4VProcess)
  ←need to treat plasma, detailed atomic processes of atoms, molecules and ions
  ←need to treat gas motion that makes Doppler effects (shifts and broadening)

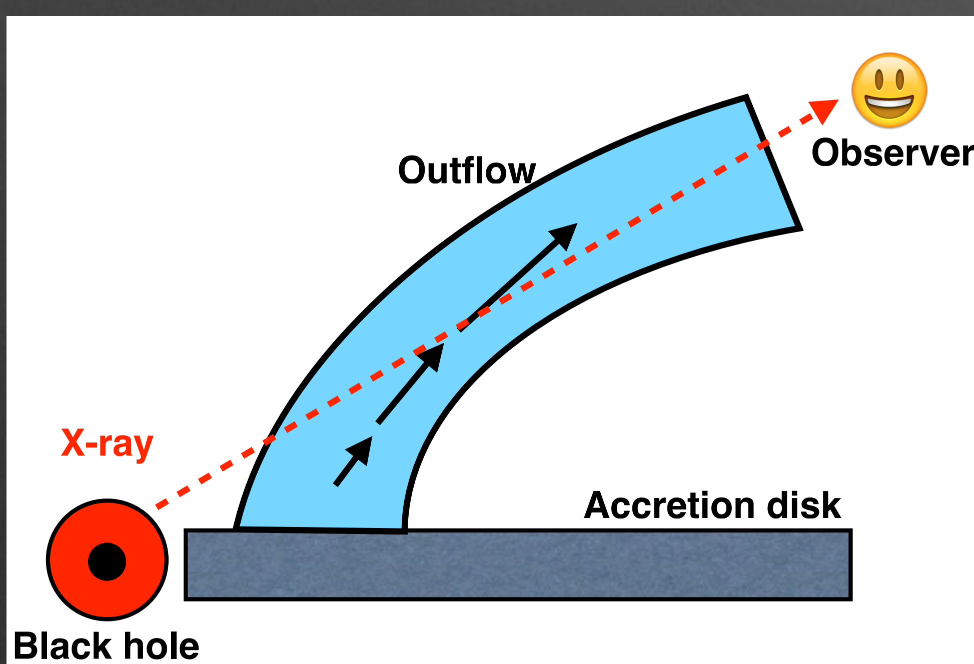
Physics lists

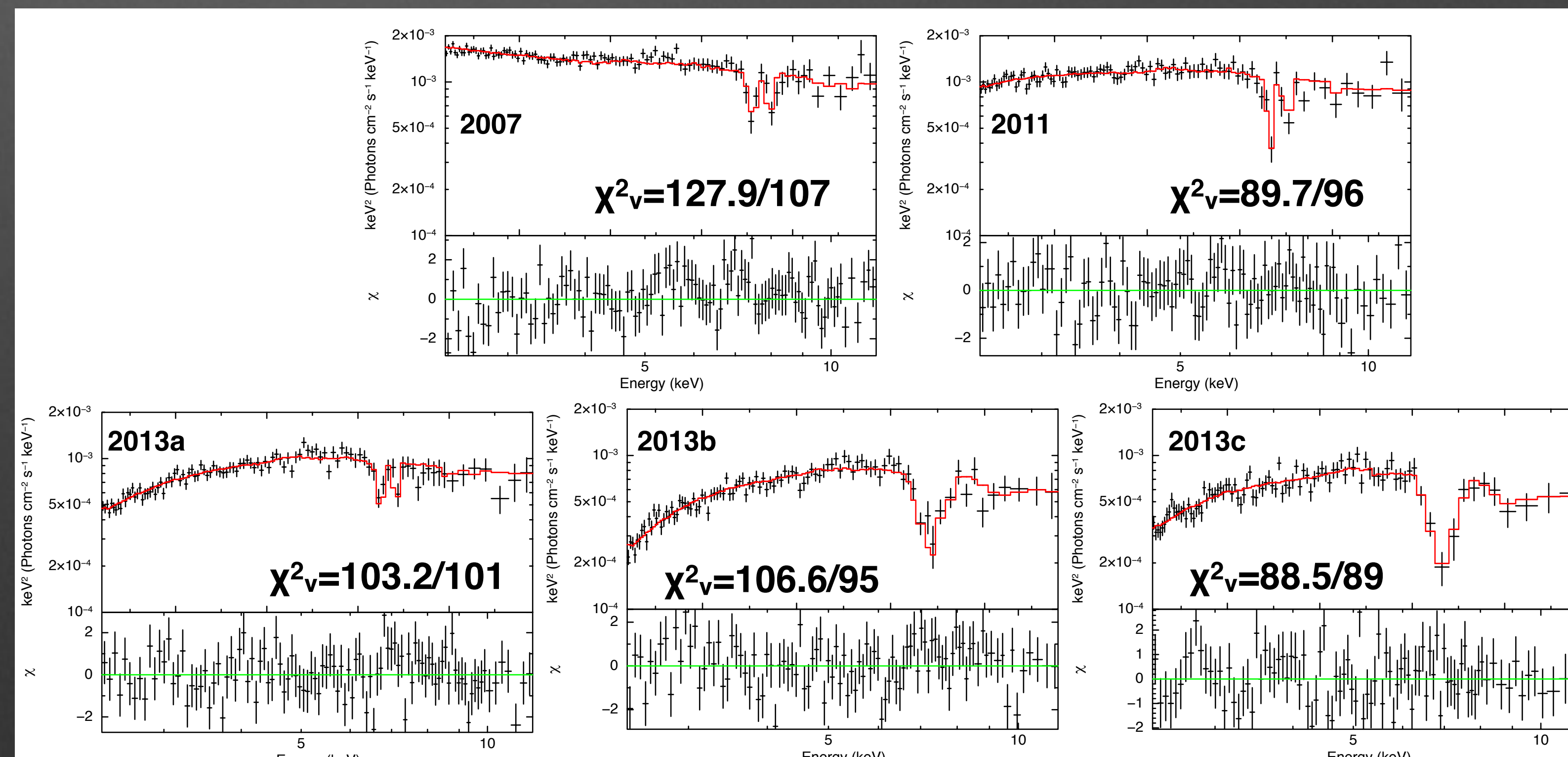
Several physical processes important in accretion-powered sources are implemented.

Cold matter	Photoelectric absorption followed by fluorescence and scattering by electrons bound to neutral atoms or molecules are responsible for generating spectral features of X-ray reflection - X-ray reflection nebulae (Odaka et al. 2011) - AGN molecular tori (Furui et al. in prep.)
Photoionized plasma	Gas is ionized by strong X-ray radiations in the vicinity of accreting objects. Photoionization and photoexcitation of various ion species result in emission lines and absorption lines - Stellar winds in X-ray binaries (Watanabe et al. 2006) - AGN outflows (Hagino et al. 2015) - Super soft X-ray sources (bright WDs) (Wada et al. in prep.)
Comptonization	This process plays an important role in cooling a hot accretion flow through X-ray radiation - Accretion flows onto NS (Odaka et al. 2014) - Accretion flows onto BH (Odaka et al. in prep.)

AGN ultra fast outflow

- Some luminous quasars display deep blue-shifted absorption lines of hydrogen/helium-like ions of iron.
- Mildly relativistic (0.3c) wind arising from an accretion disk of AGN.
- The outflow is highly ionized by the luminous X-rays from the AGN central engine.



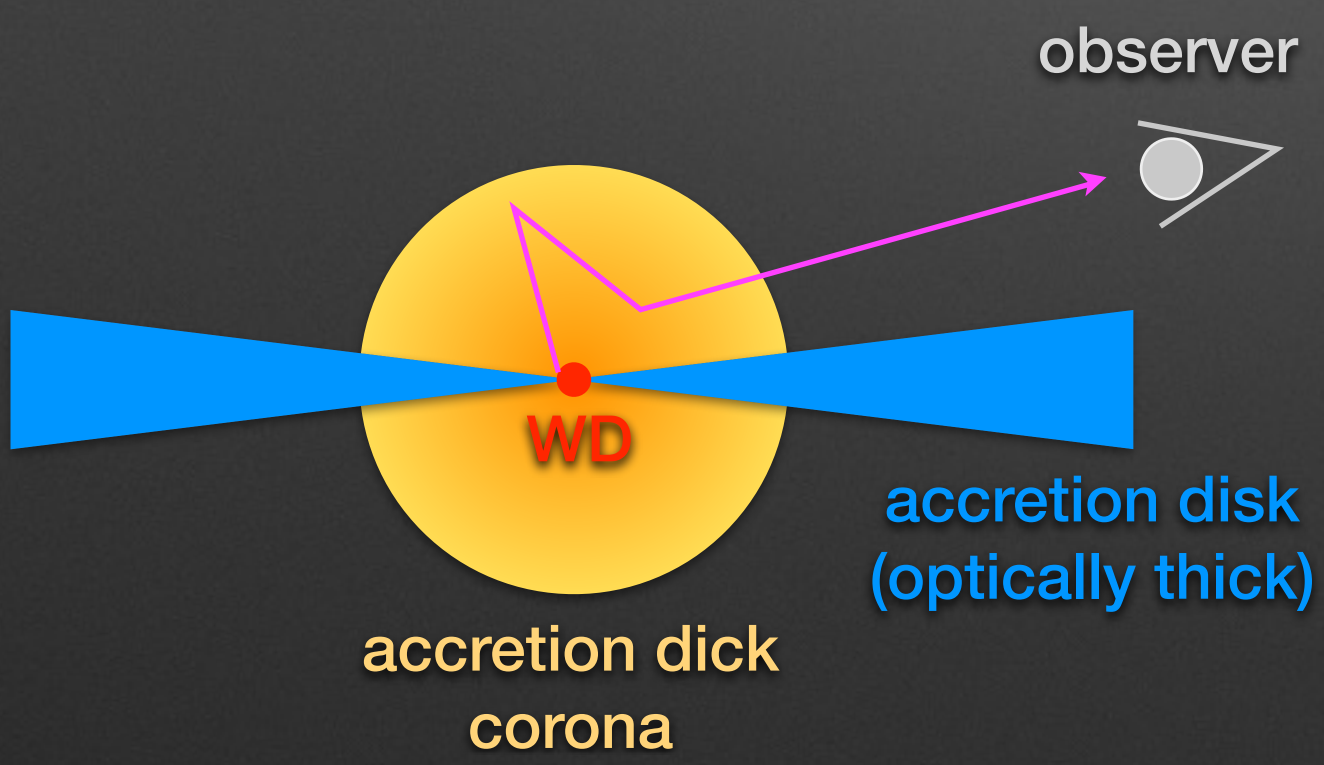


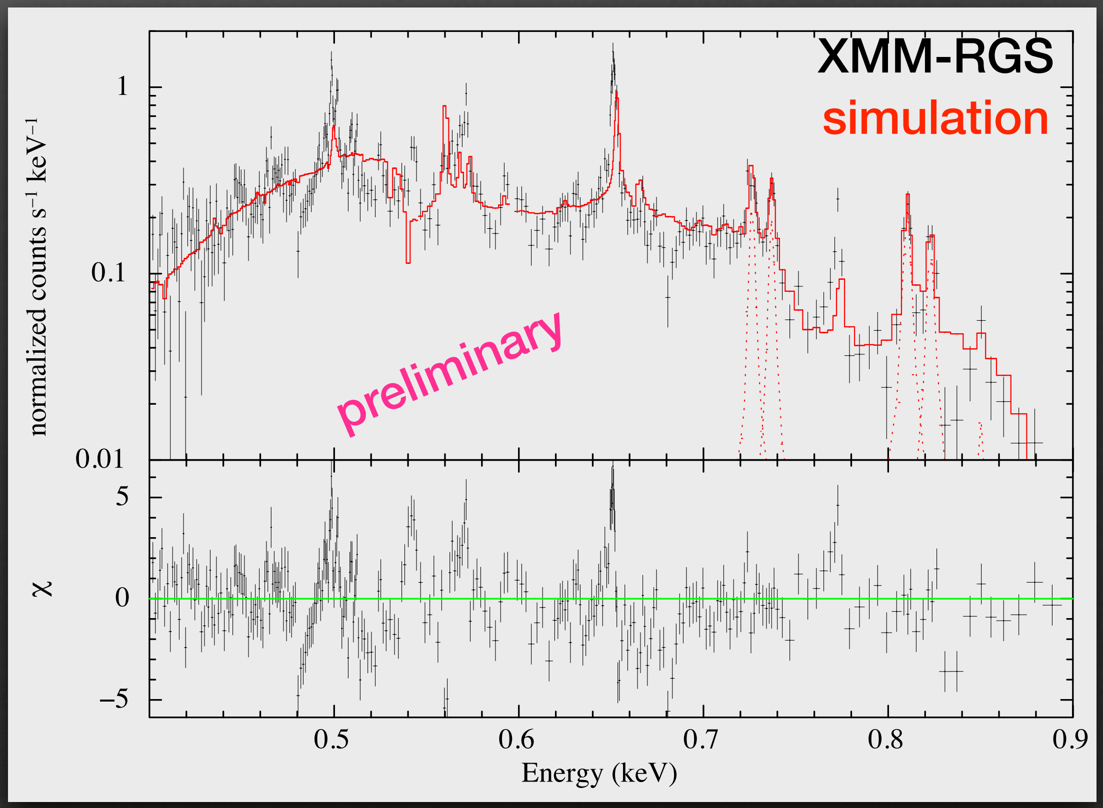
➡ **We successfully reproduced all the spectra of PDS 456 by changing only the terminal velocity and the outflowing angle**

Hagino et al. 2015

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}.
- There exists an accretion disk corona (ADC) which displays plenty of emission lines via photoionization—very difficult to build a physical model.
- This is the first attempt to reproduce the high-resolution X-ray spectrum of CAL 87 (SSS in LMC) in the context of accurate photoionization modeling.

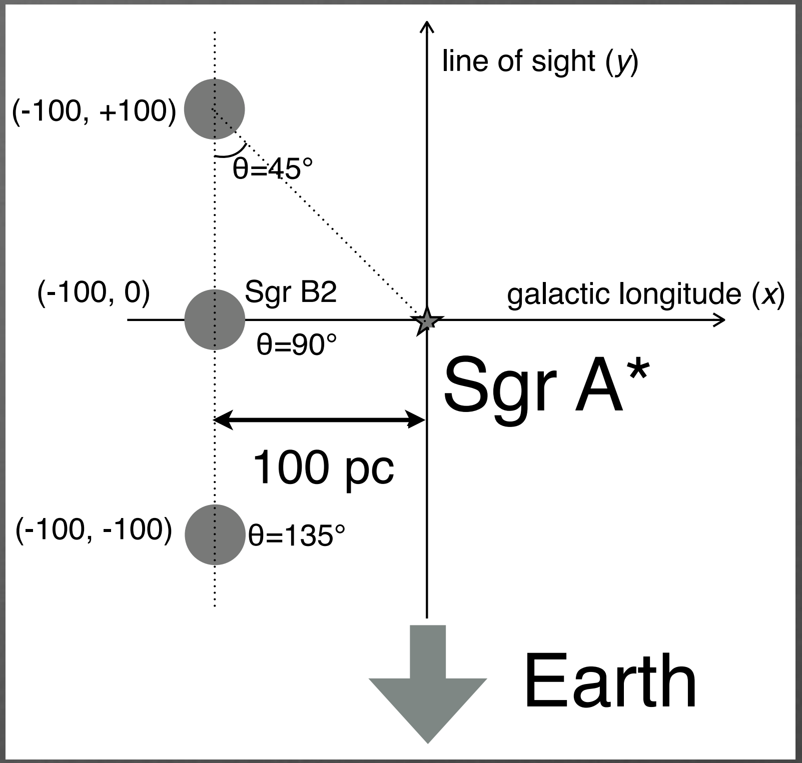


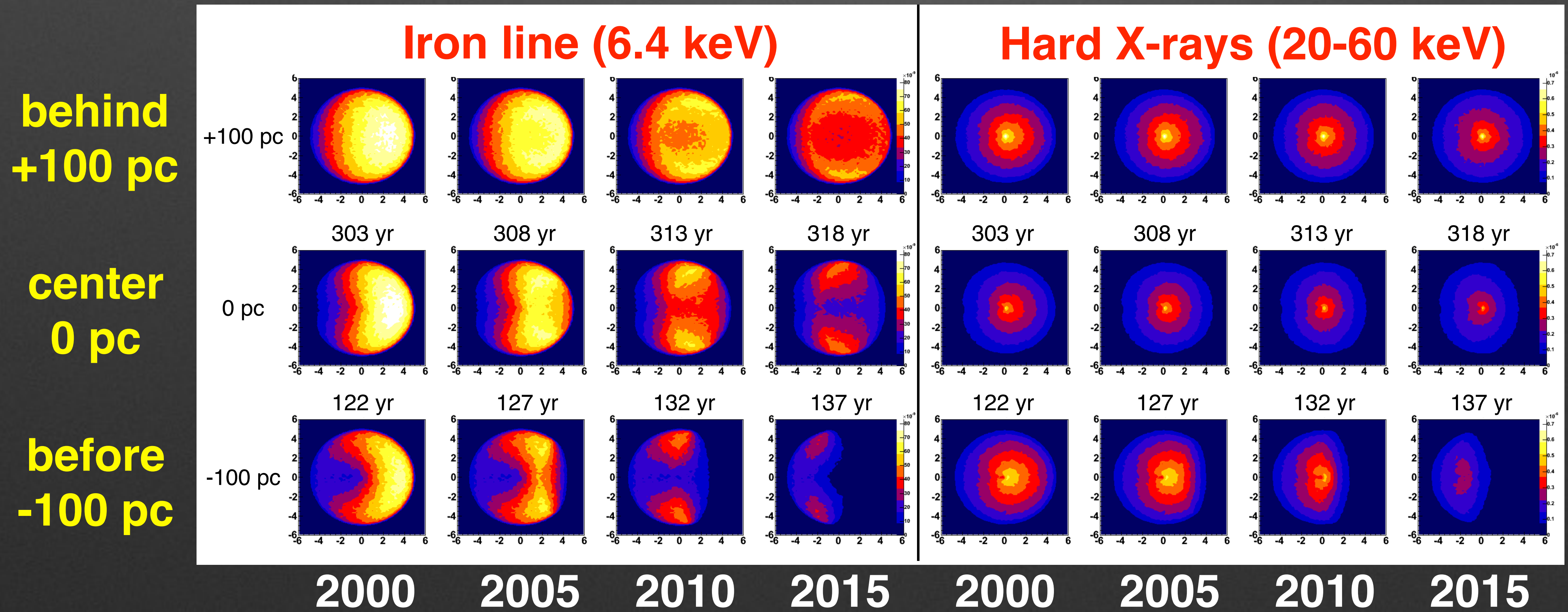


Wada et al. in prep.

Giant molecular cloud in the Galactic center

- Giant molecular cloud Sgr B2 has been reflecting a past outburst of SMBH Sgr A*, displaying Fe fluorescence line at 6.4 keV.
- It shows strong time variability over a few year scale.
- Such objects are good probes of molecular clouds themselves and the black hole activity.

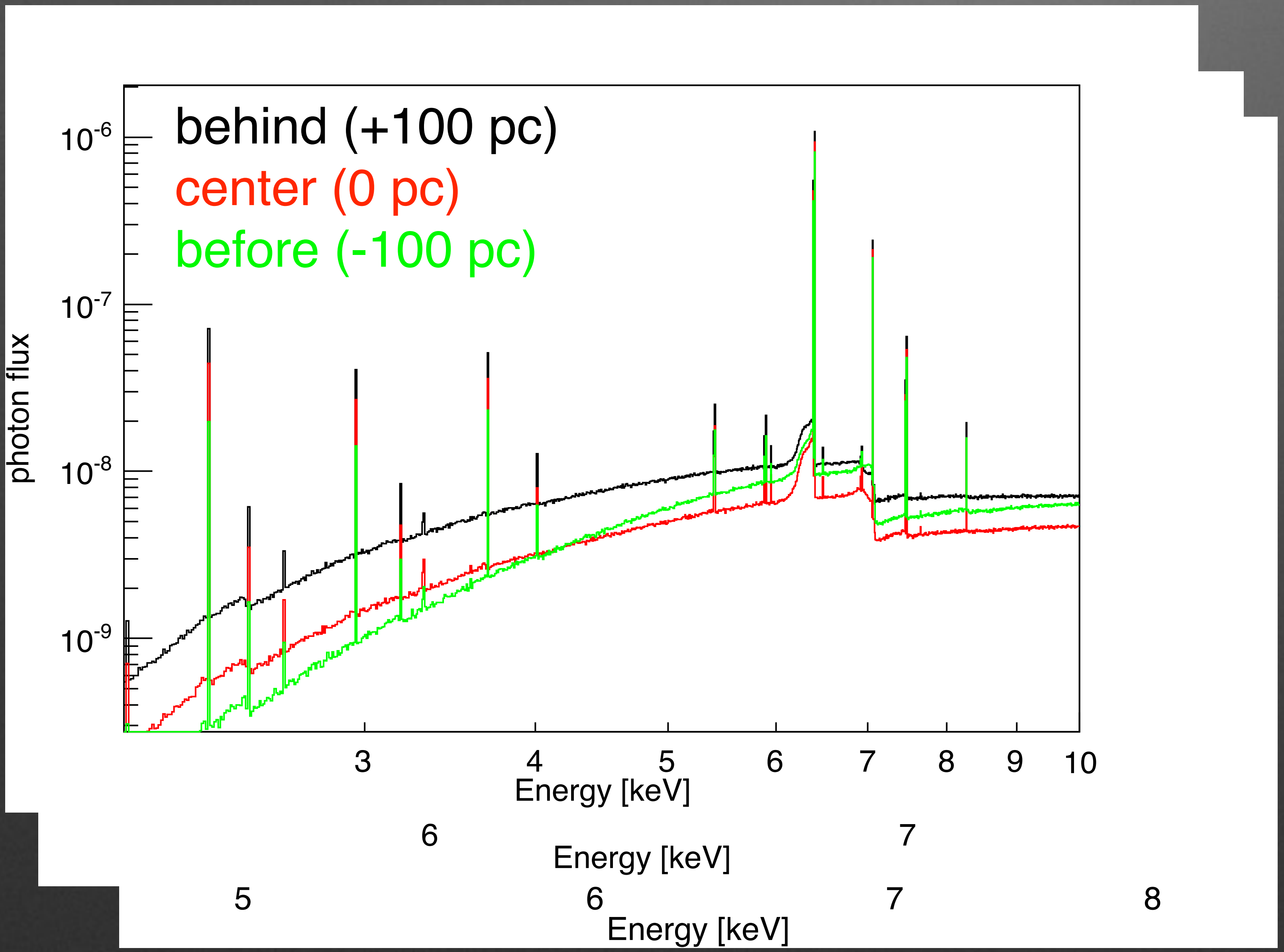




Odaka et al. 2011

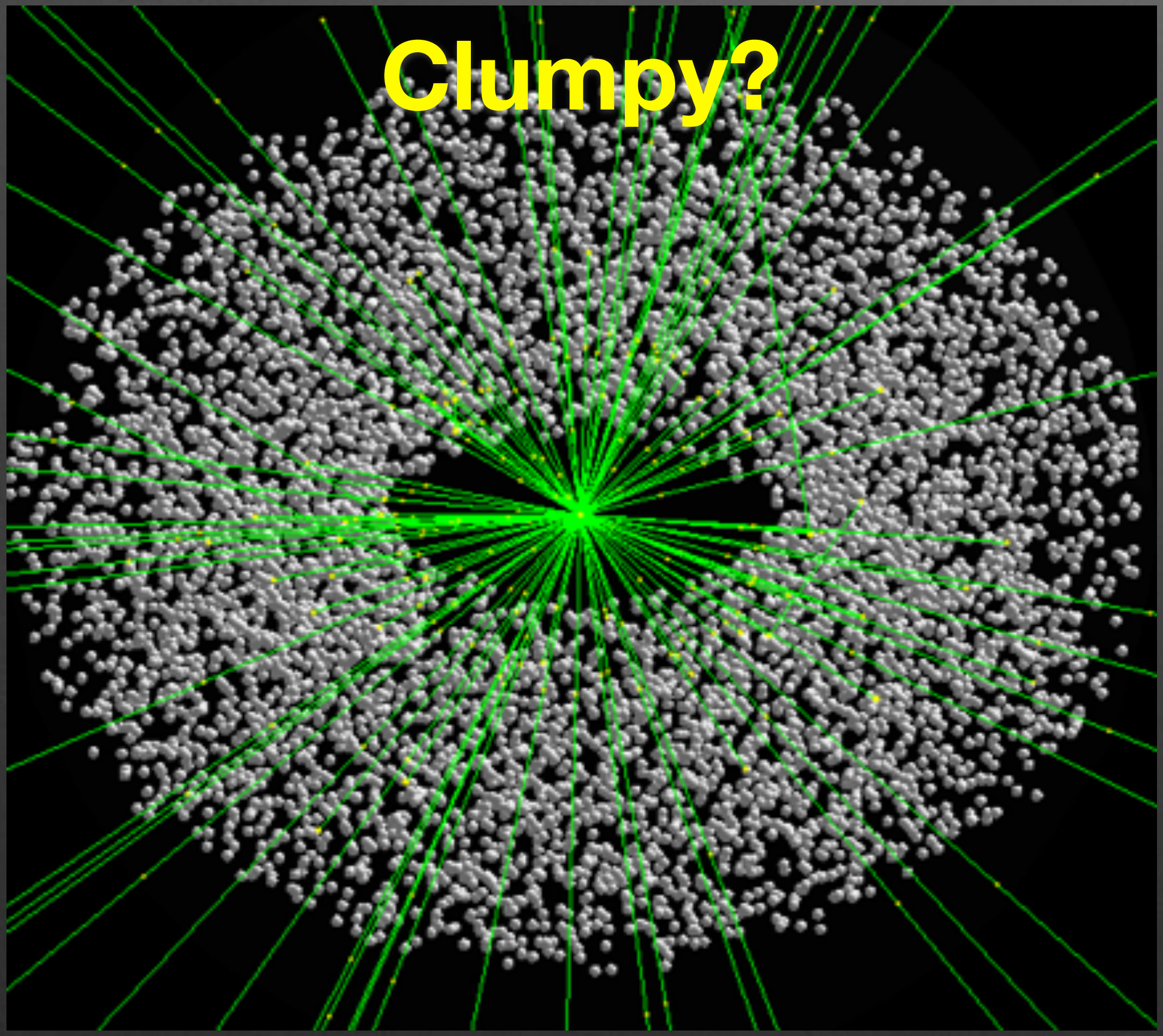
Giant molecular cloud in the Galactic center

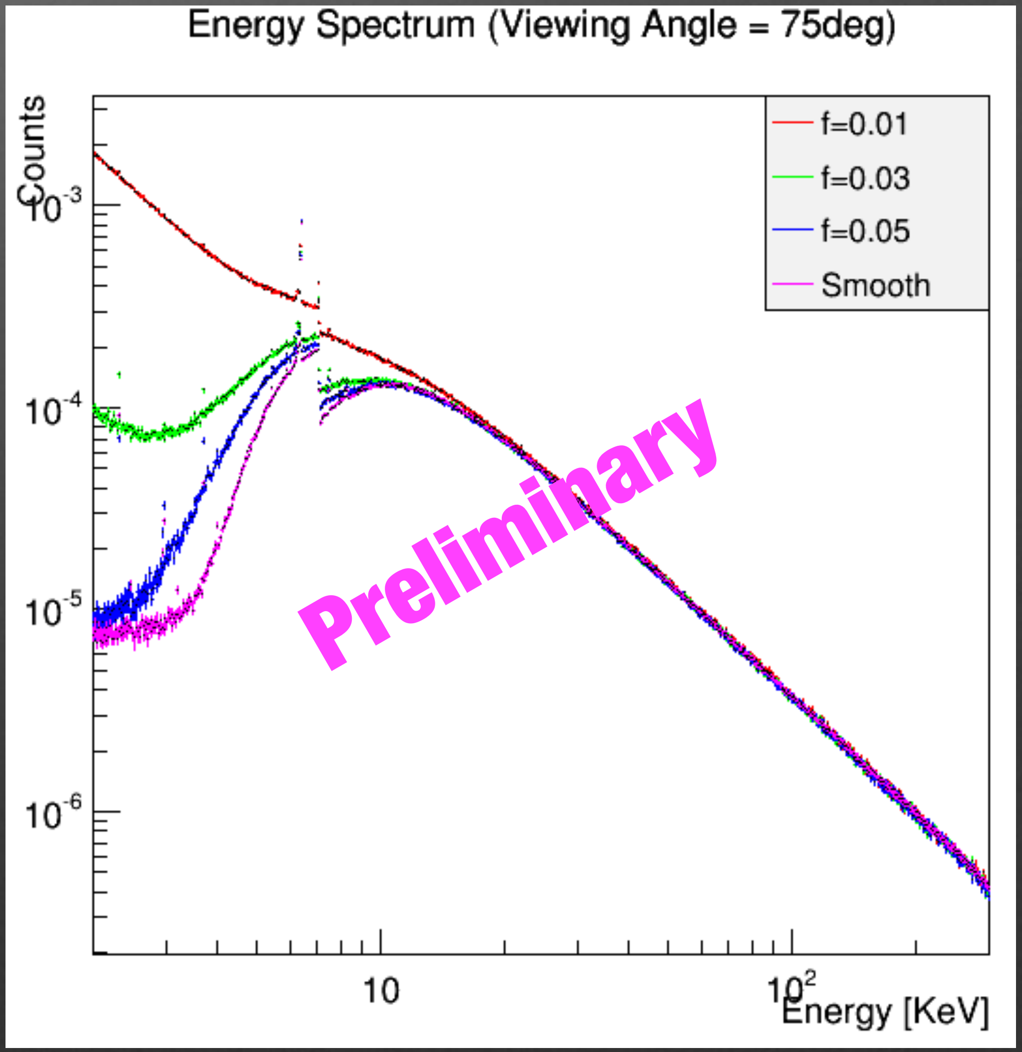
Compton shoulder, which is produced by Compton down-scattering of strong fluorescence lines (e.g. Fe Kα), has a potential diagnostic power.



AGN dusty torus

- An obscuring dusty molecular torus is believed to exist around an AGN.
- While most X-ray studies have assumed smooth torus models, infrared observations suggest that the torus has a clumpy structure.
- We build a new spectral model to extract torus parameters from X-ray observations.

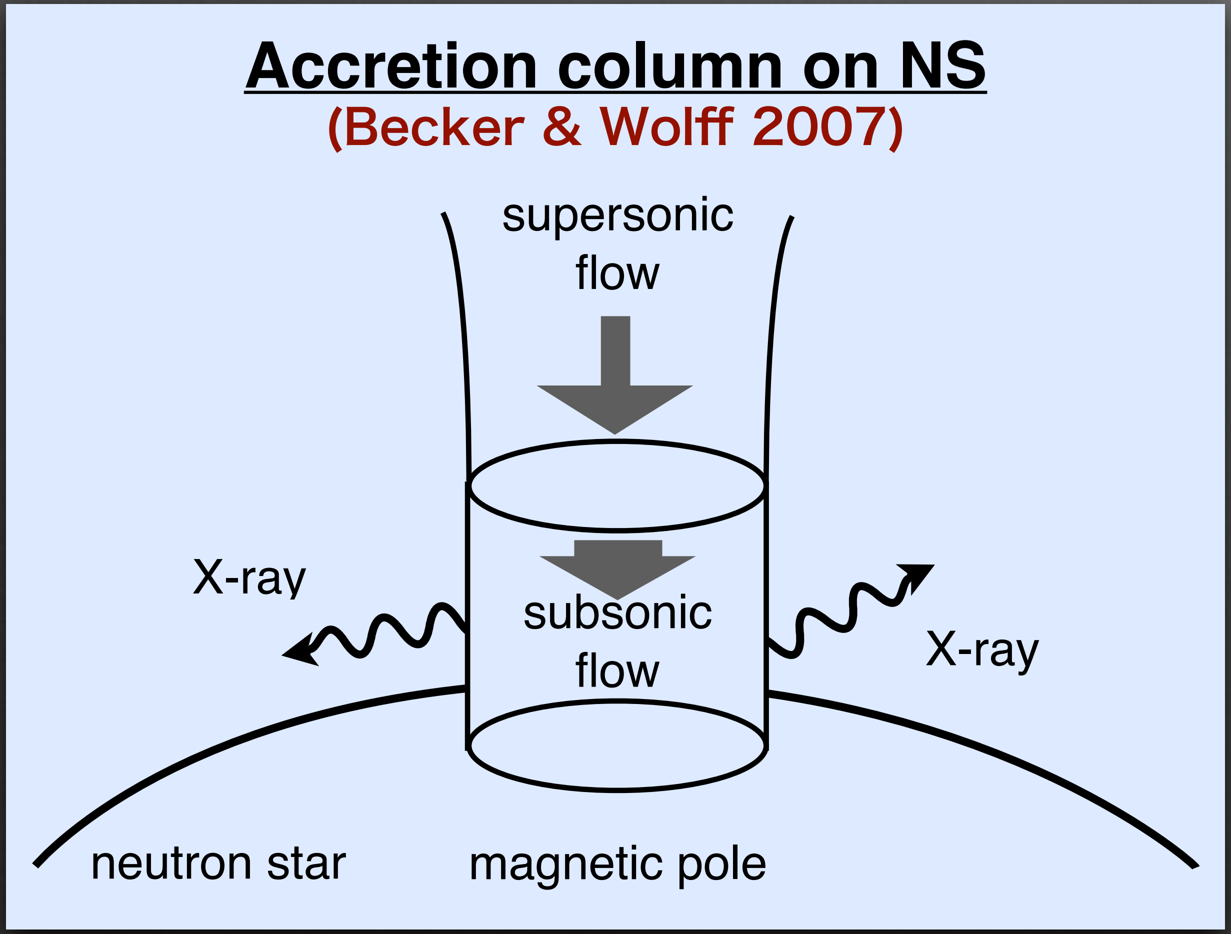


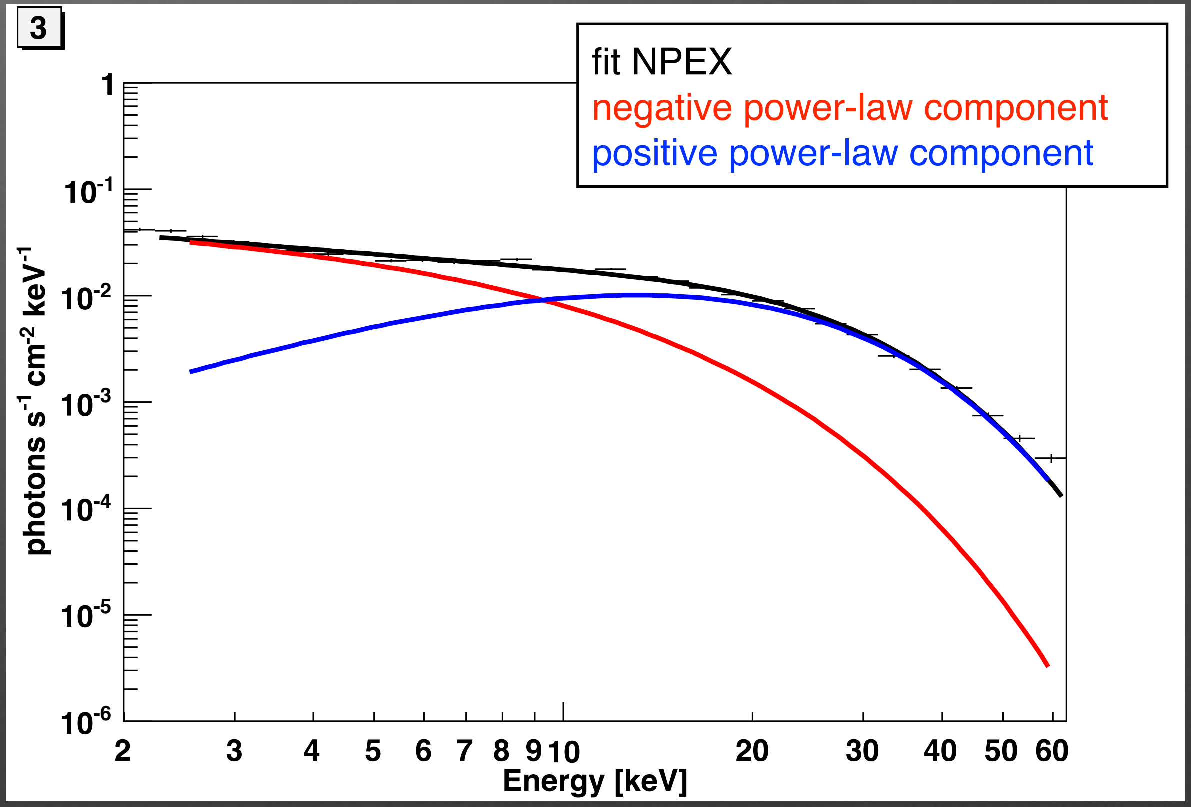


Furui et al. in prep.

Accretion flow onto neutron stars

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.





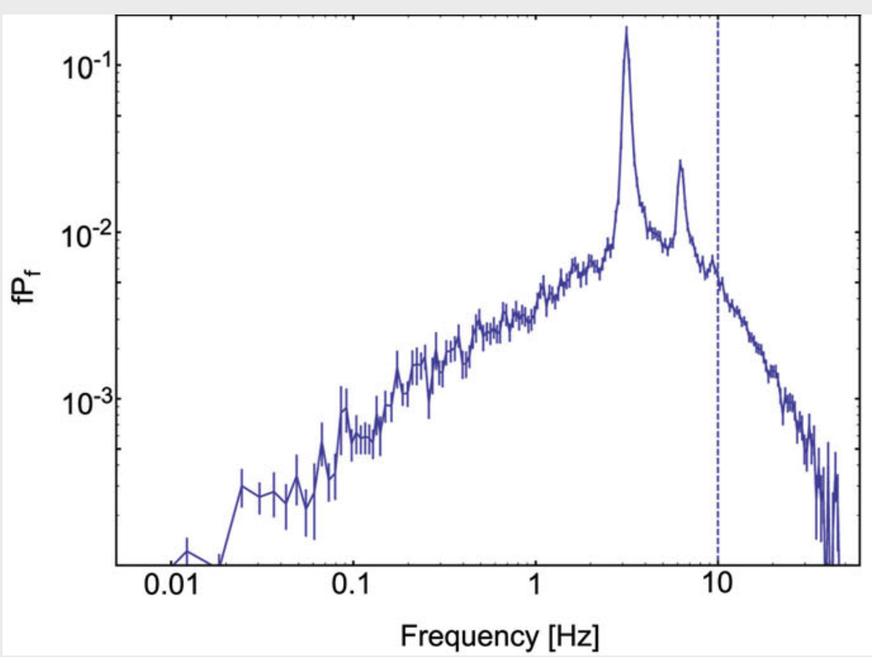
Odaka et al. 2013, 2014

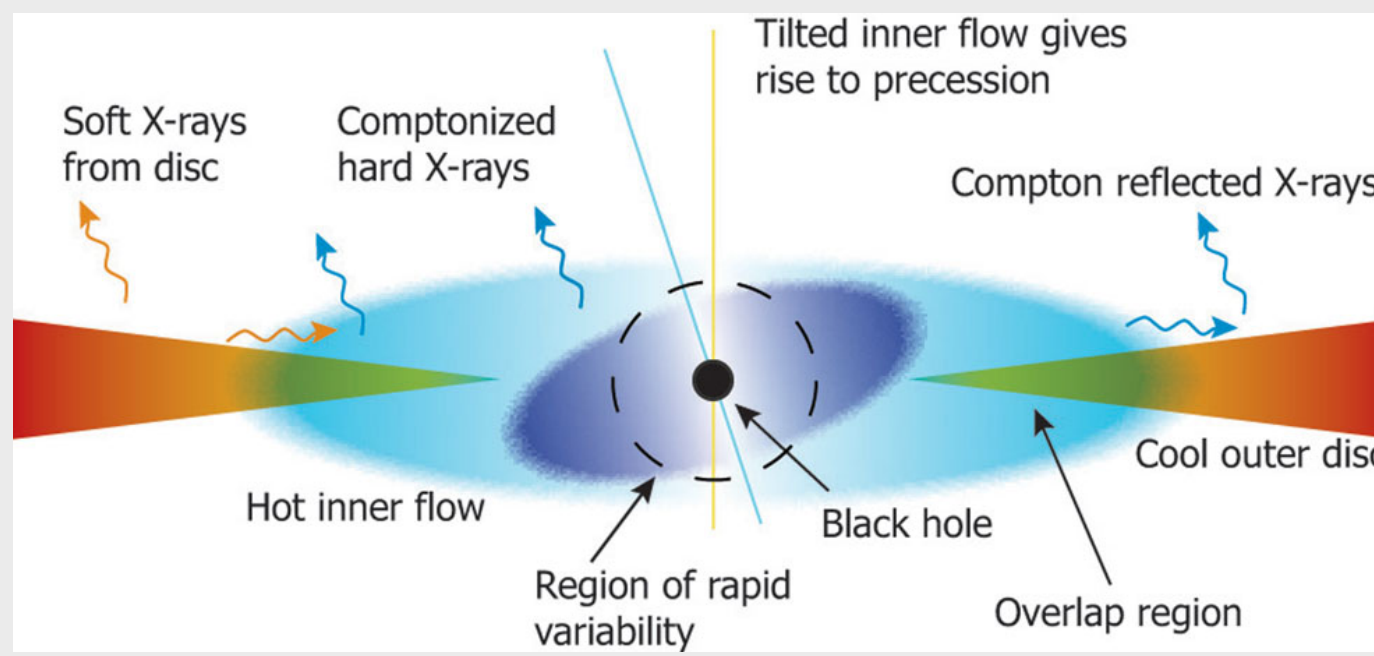
We found a set of self-consistent solutions that agree with the observations of accreting NS Vela X-1 and have reasonable model parameters.
column radius = 200 m, kTe = 6 keV, B field=2×10^{12} G

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.

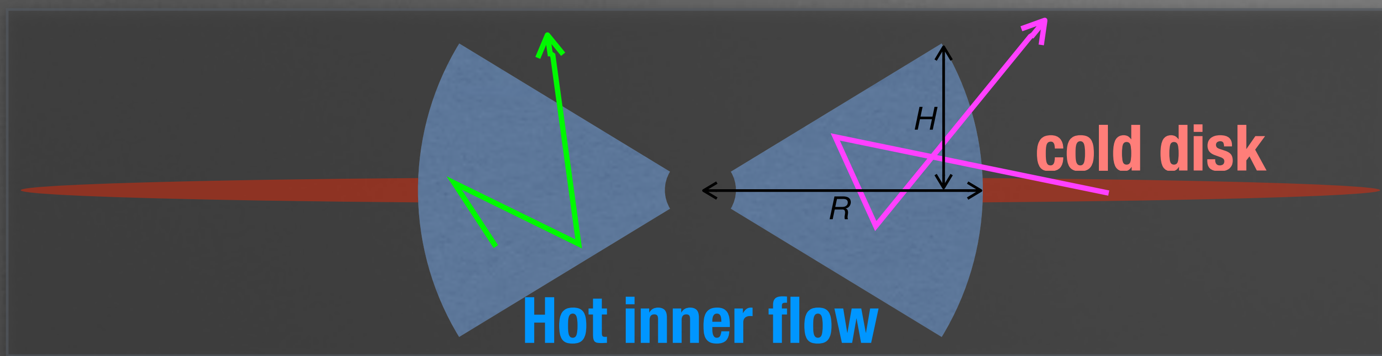
QPOs in power spectral density

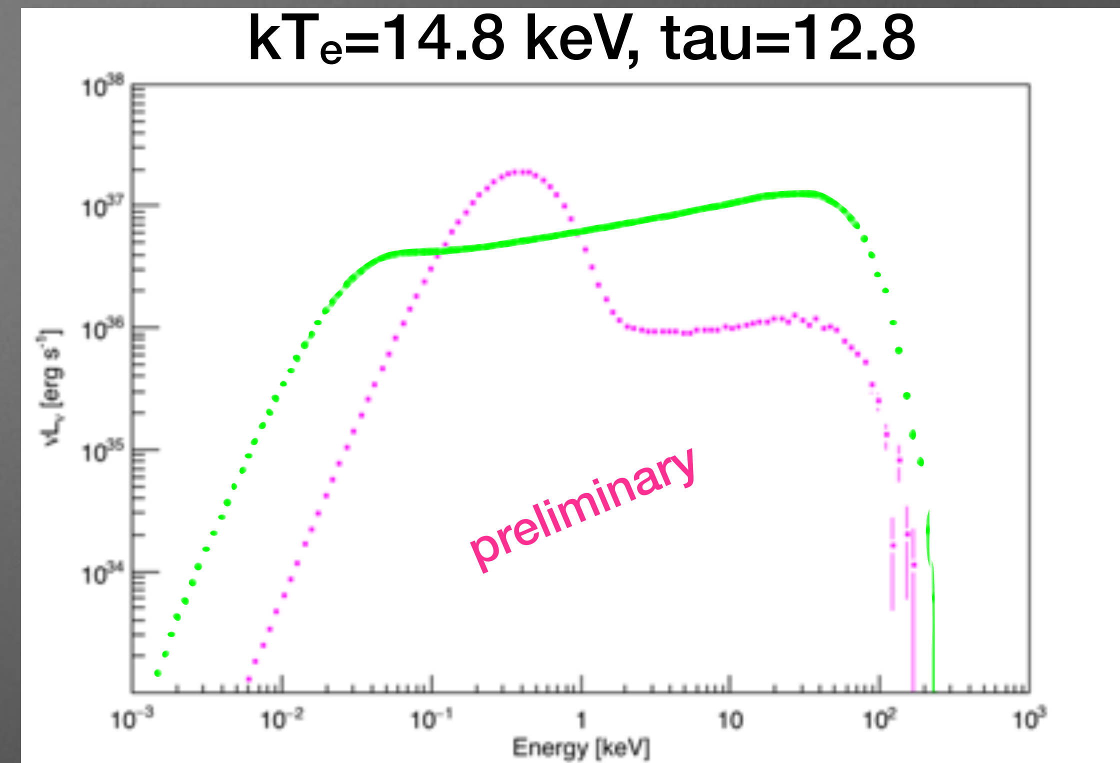




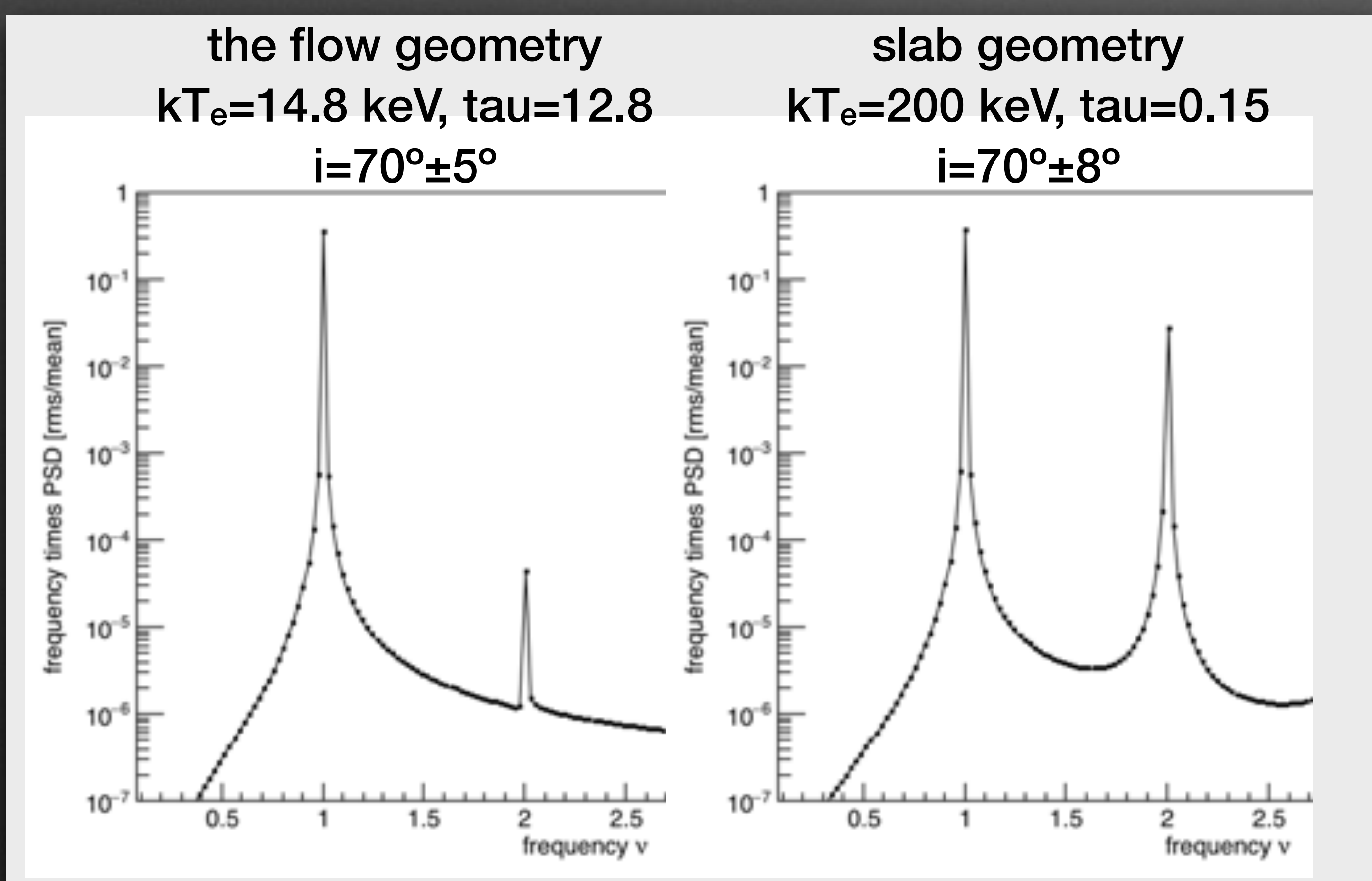
Axelsson et al. 2013

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.

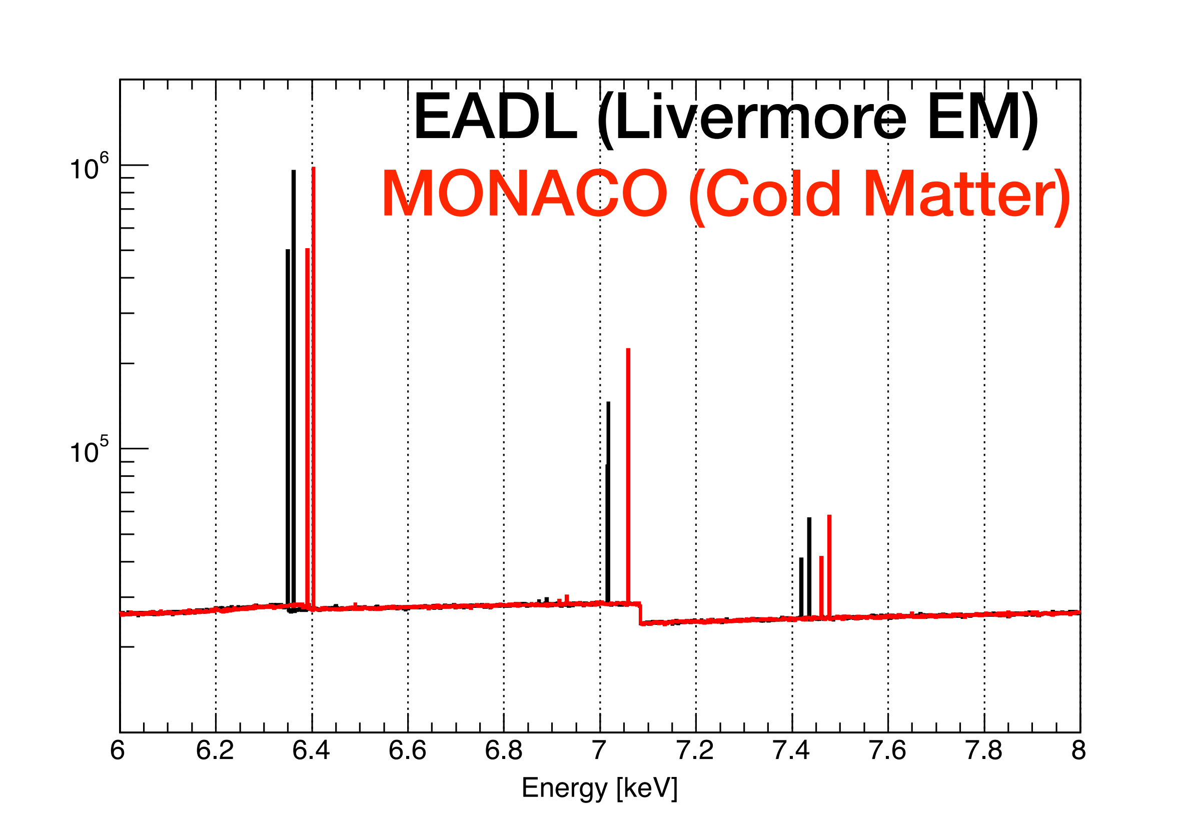
Odaka et al. in prep.

Issues arising when Geant4 applied to astrophysical problems

Database of EM physics

- G4EMLOW6.41 (data files for low energy electromagnetic processes) uses EPDL97, EEDL, and EADL.
- We astrophysicists are very sensitive to absolute values of the line/edge energies since we need to measure dynamics through the Doppler shift/broadening.
- ASTRO-H micro-calorimeter will achieve an energy resolution of 5 eV for the iron K line (6.4 keV).

Line (keV)	G4EMLOW version 6.41	X-ray Data Booklet	NIST
Fe Kα1	6.363	6.404	6.404
Fe Kα2	6.350	6.391	6.391
Fe Kβ1	7.017	7.058	7.058
Fe K-edge	7.083	7.112	7.110



Astronomical scale

- We are interested in a wide scale of astrophysical objects from galactic compact objects (~10 km) to active galactic nuclei (10^{16} m) and even to clusters of galaxies (10^{23} m), while most Geant4 applications focus on systems smaller than ~10 m.
- A simulation of a large system appears to result in errors in tracking. One solution is obviously to scale the simulation setup since the optical depth is only essential (absolute size is not).
- However, the absolute value of the density can be sometimes important, so a real scale simulation would be convenient.
- Limits of floating point numbers are probably OK (should be careful for very large systems)
- Tolerance of the geometry tracking should affect the simulation. We set the tolerance values by calling G4GeometryManager::SetWorldMaximumExtent(). This is an example for a world size of 10^{11} cm:

```
Surface tolerance: 1 cm (OK)
Angular tolerance: 1e-09 (OK)
Radial tolerance: 1e-10 cm (???)
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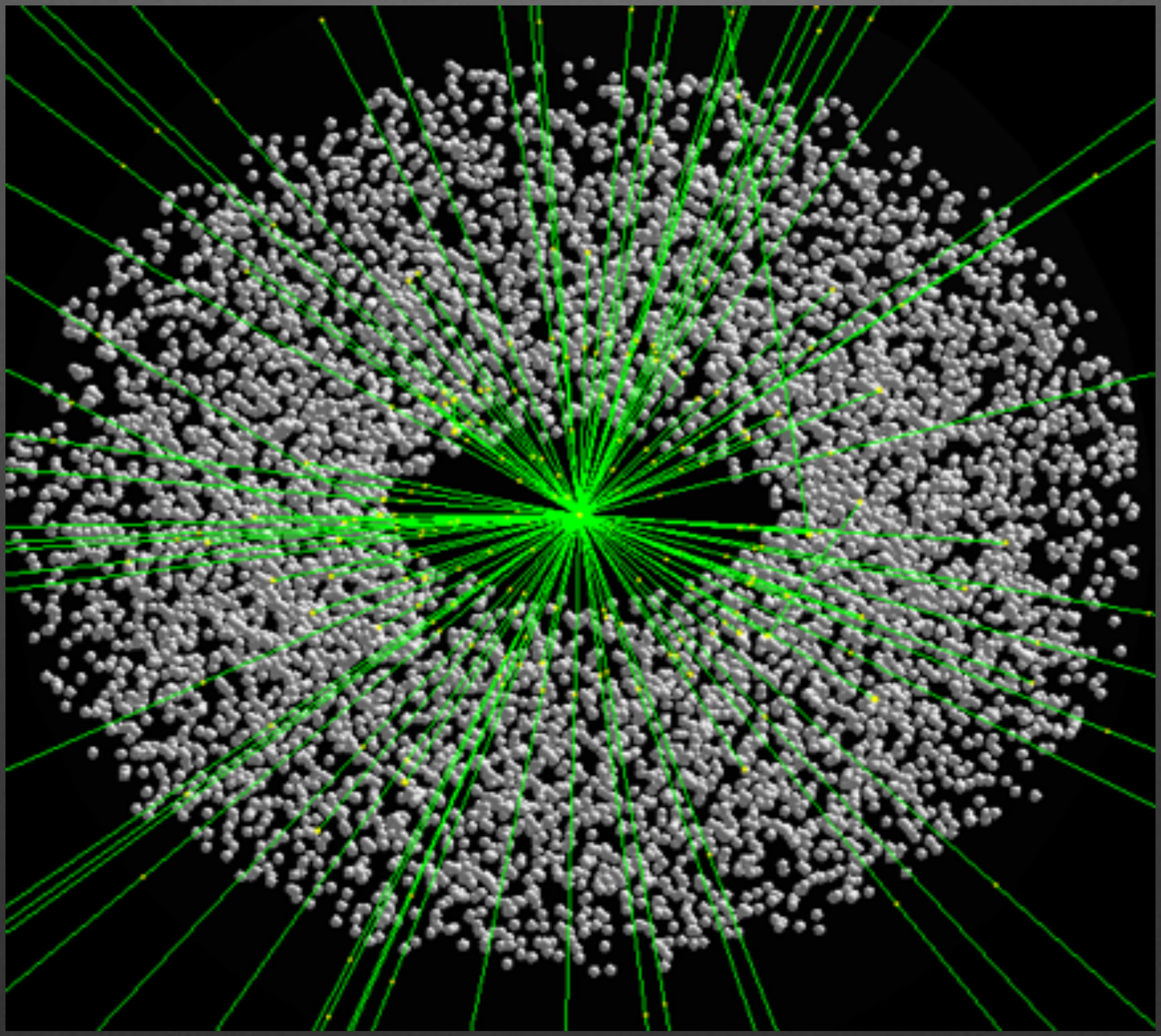
Volume placement (1)

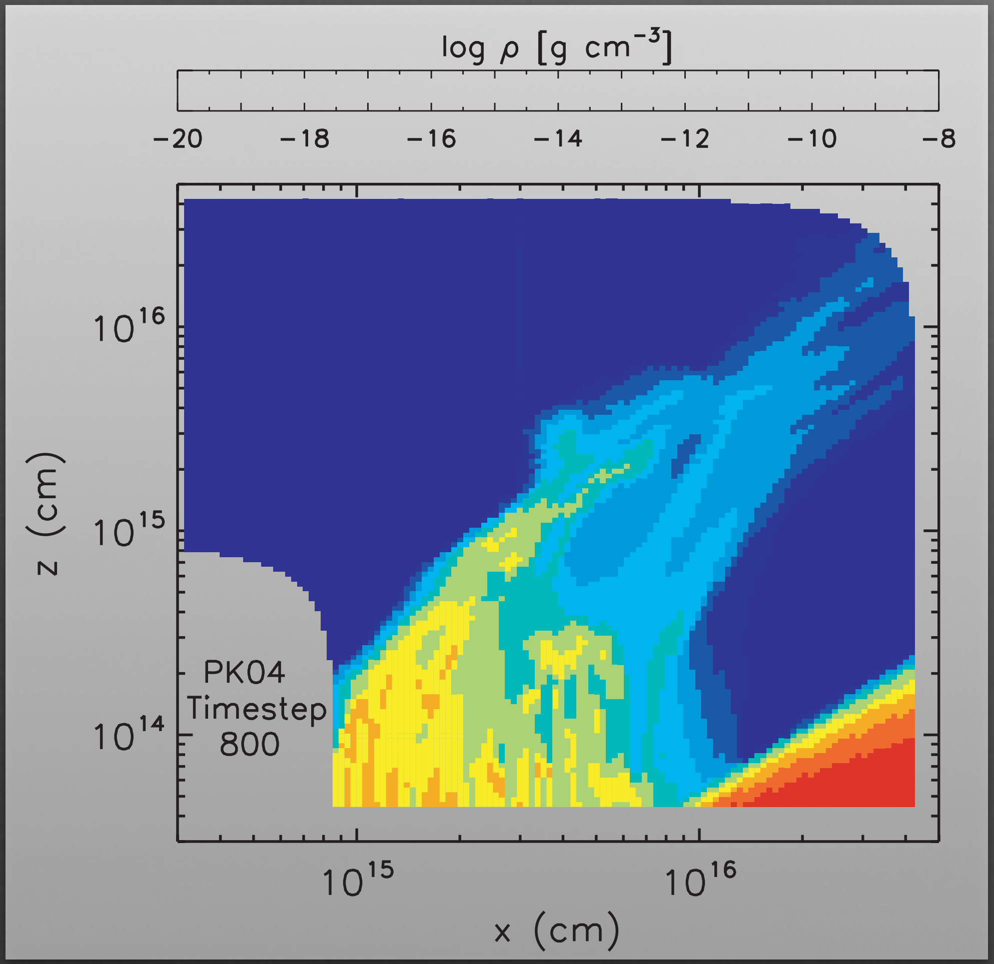
- Is it wise to put a number (e.g. 1 million) of clumps in a flat volume hierarchy (in a single mother volume)???

AGN clumpy torus



Volume placement (2)

AGN outflow



Sim et al. 2010

- The mass model would be an output of a serious hydrodynamical simulation.
- The simulation gives density and velocity at each point (voxel).
- How can Geant4 treat this type of mass model? Many boxes?

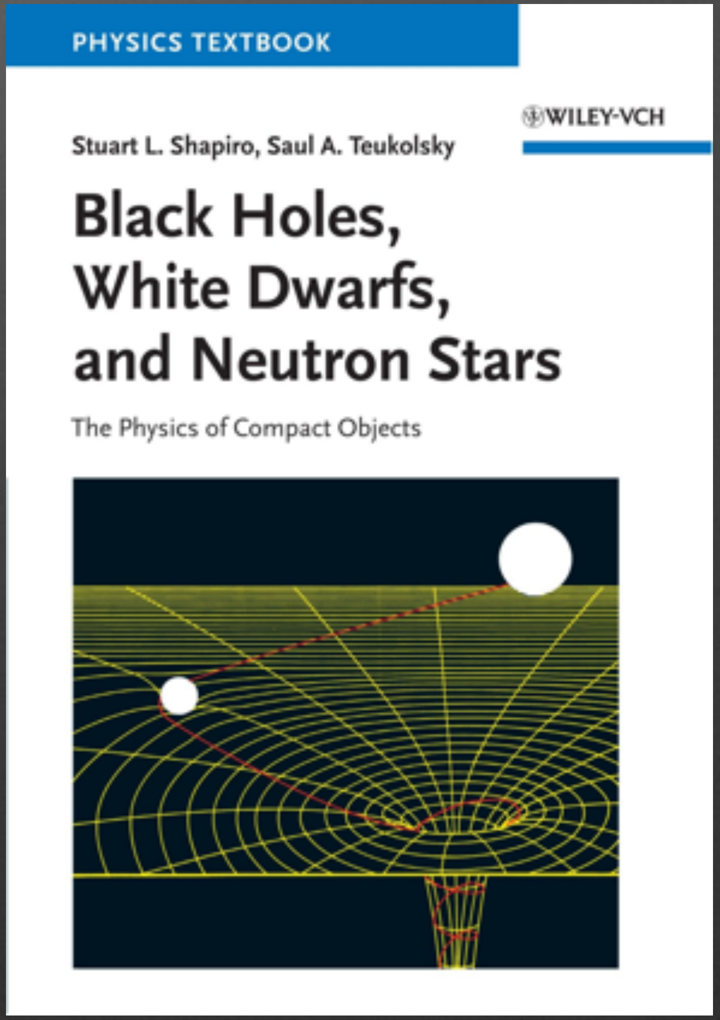
General relativity

- In the presence of a strong gravitational field, general relativity should taken into account for calculating photon transportation.
- A photon “straightly” runs along the curved spacetime.
- Does geant4 have any functions suitable to treat such behavior of the particle?

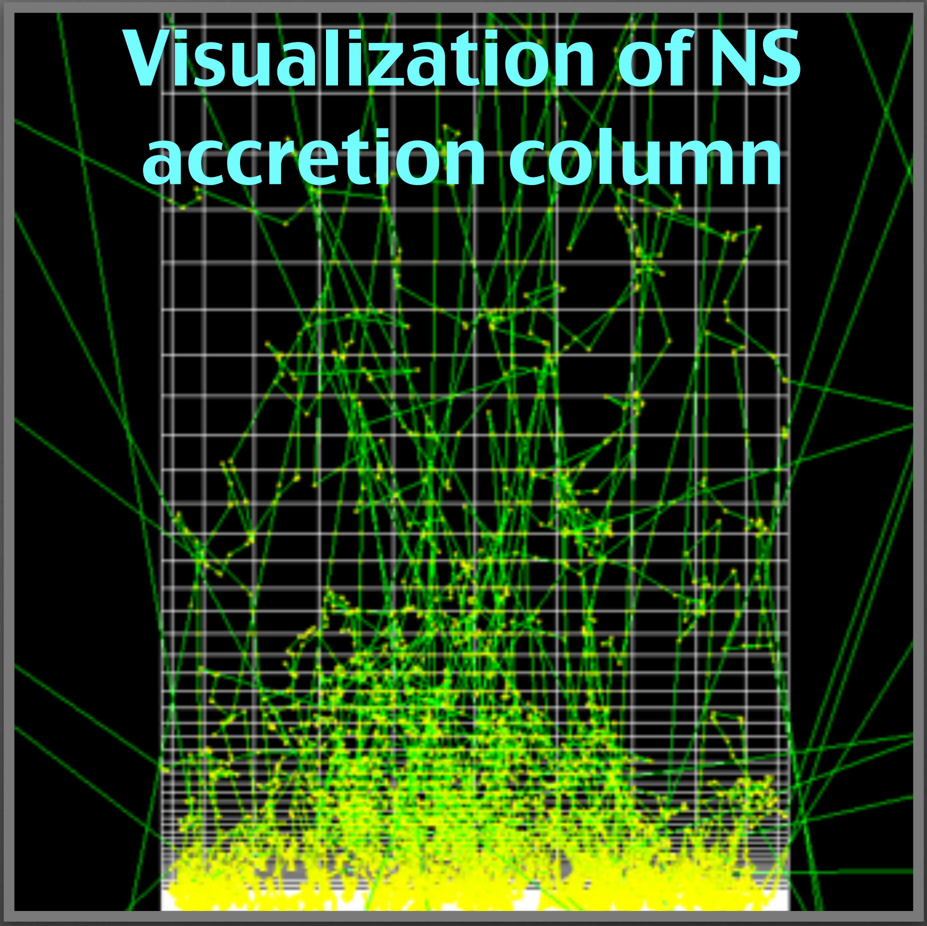
$$
\begin{aligned}
ds^2 = &-\left(1-\frac{2GMr}{\rho^2}\right)dt^2 - \frac{2GMar\sin^2\theta}{\rho^2}(dt\,d\phi + d\phi\,dt) \\
&+\frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 + \frac{\sin^2\theta}{\rho^2}\left[(r^2+a^2)^2 - a^2\Delta\sin^2\theta\right]d\phi^2,
\end{aligned}
$$

$$\Delta(r) = r^2 - 2GMr + a^2,$$

$$\rho^2(r,\ \theta) = r^2 + a^2\cos^2\theta.$$



Conclusions



We have developed a general-purpose X-ray spectrum synthesizer called MONACO using the Geant4 toolkit library.

Geant4 nicely works with a wide variety of astrophysical problems and is producing exciting results.

Collaborators of the MONACO project
Framework: Shin Watanabe, Tadayuki Takahashi
Reflection from molecular clouds: Felix Aharonian, Dmitry Khangulyan
Compton shoulders: Hiroki Yoneda, Andrew Fabian
AGN torus: Shunya Furui, Yasushi Fukazawa, Toshihiro Kawaguchi, Masanori Ohno, Atsushi Tanimoto, Yoshihiro Ueda
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