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

MONte Carlo simulation for **A**strophysics and **CO**smology

Hirokazu Odaka (ISAS/JAXA)

Shin Watanabe, Yasuyuki Tanaka, Dmitry Khangulyan, Tadayuki Takahashi (ISAS/JAXA), Masao Sako (Penn), Felix Aharonian (Dublin Institute for Advanced Studies)

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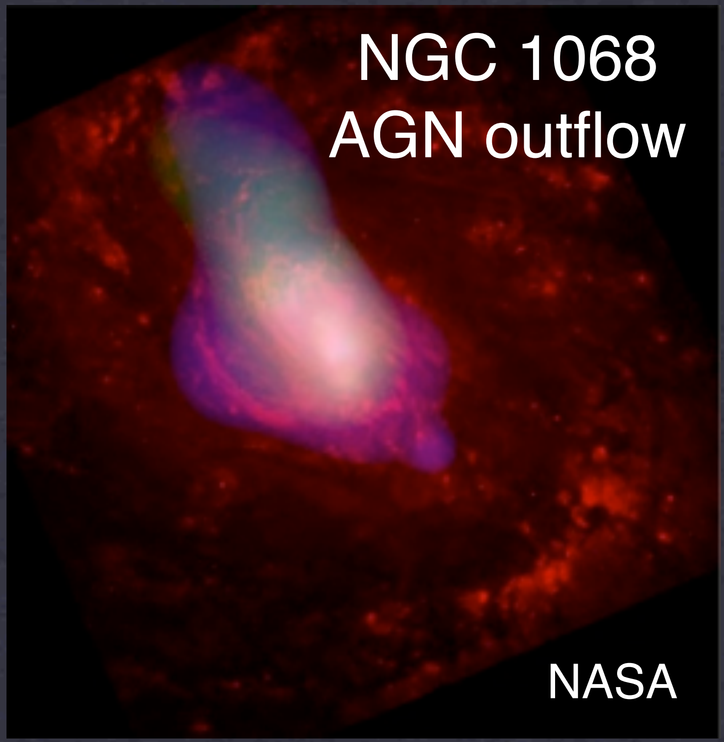
- Spectral modeling of accretion-powered pulsars
  Kazuo Makishima

- Polarization calculation
  Paolo Coppi

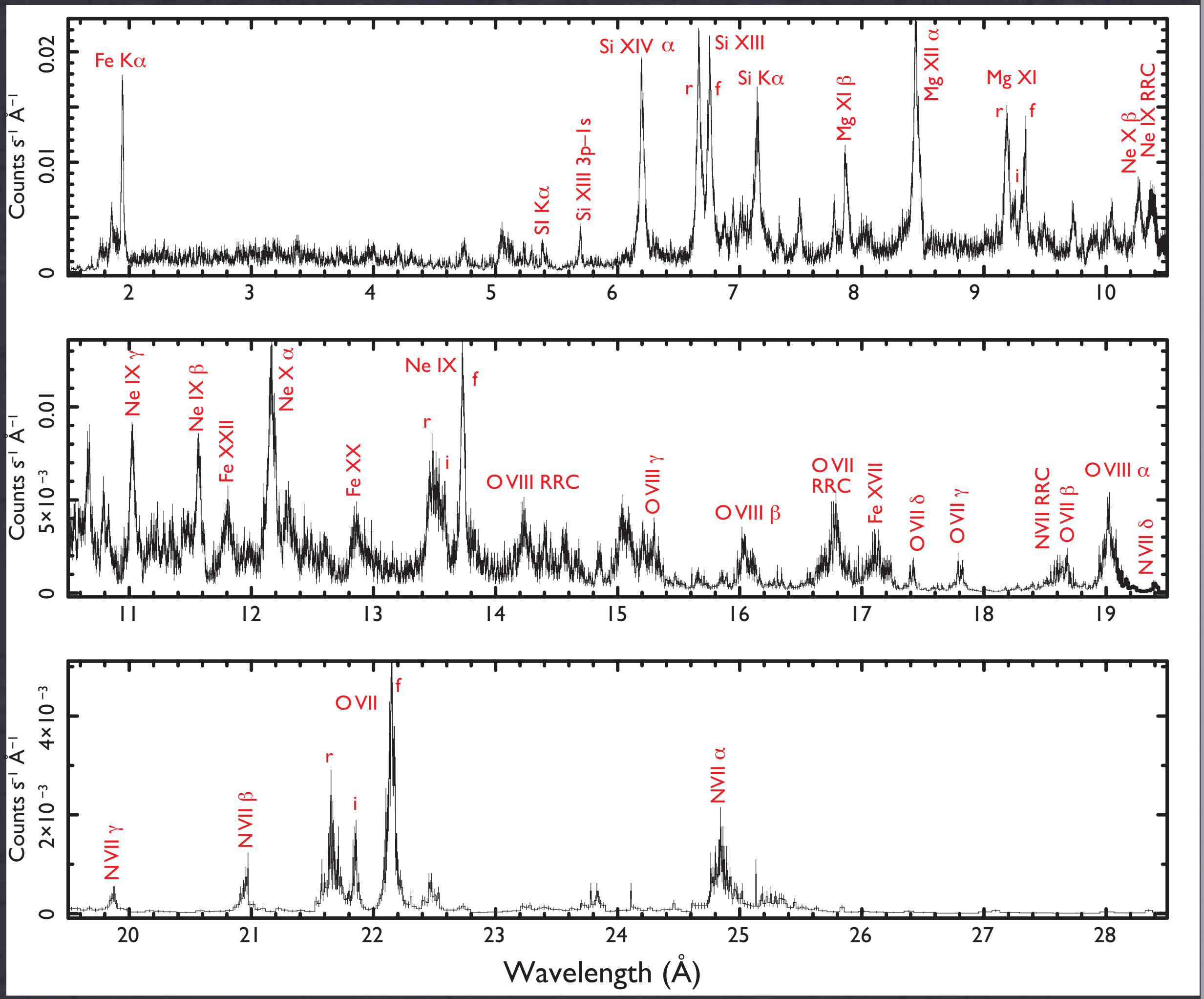
- Cross section data of scattering by helium atom
  Eugine Churazov

Modern X-ray Observations

have brought high-quality data containing detailed physical information



Chandra
←Image
Spectrum→



Evans+ (2009)

- **XMM-Newton, Chandra (1999-)**
  High-resolution grating spectrometer
  E/ΔE~100-1000 for point sources
  Line intensity, Doppler broadening/shift

- **Suzaku (2005-)**
  Wide-band, low background → Hard X-ray information with high S/N

Radiative Transfer

Interpretation of such high-quality data requires more precise astrophysical models. We have to solve a problem of radiative transfer.

$\tau \ll 1$	$\tau \sim 1$	$\tau \gg 1$
Optically thin	**<u>Reprocessing of X-ray photons</u>**	Optically thick

Optically thin

easy

Reprocessing of X-ray photons

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

  Moreover, it depends on geometry.

Optically thick

Statistical approach
continuous approximation
diffusion approximation
→differential equation

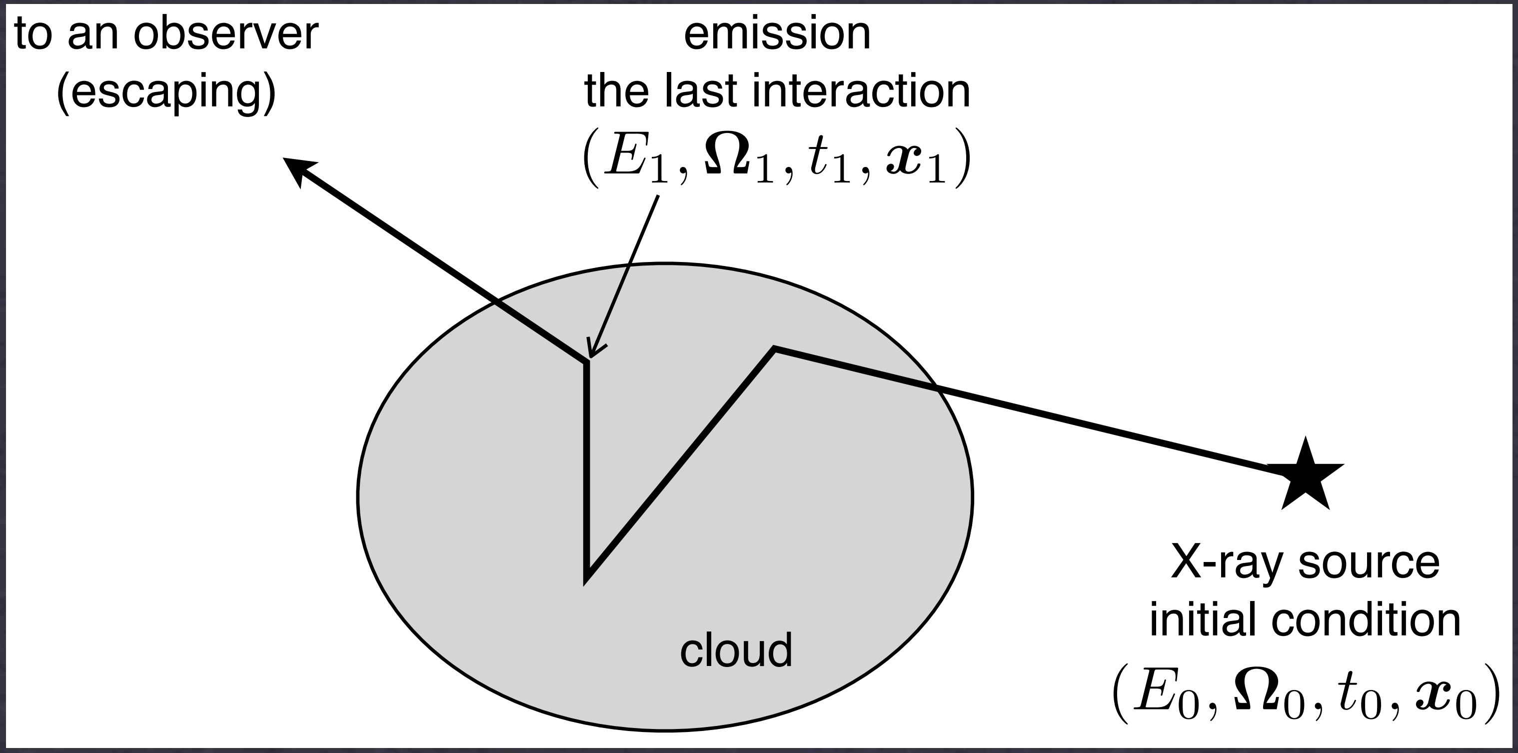
Black body if very thick
e.g. standard accretion disk

optical thickness

Monte Carlo approach

Monte Carlo Simulation

Tracking photons by calculating their propagation and interactions based on Monte Carlo method

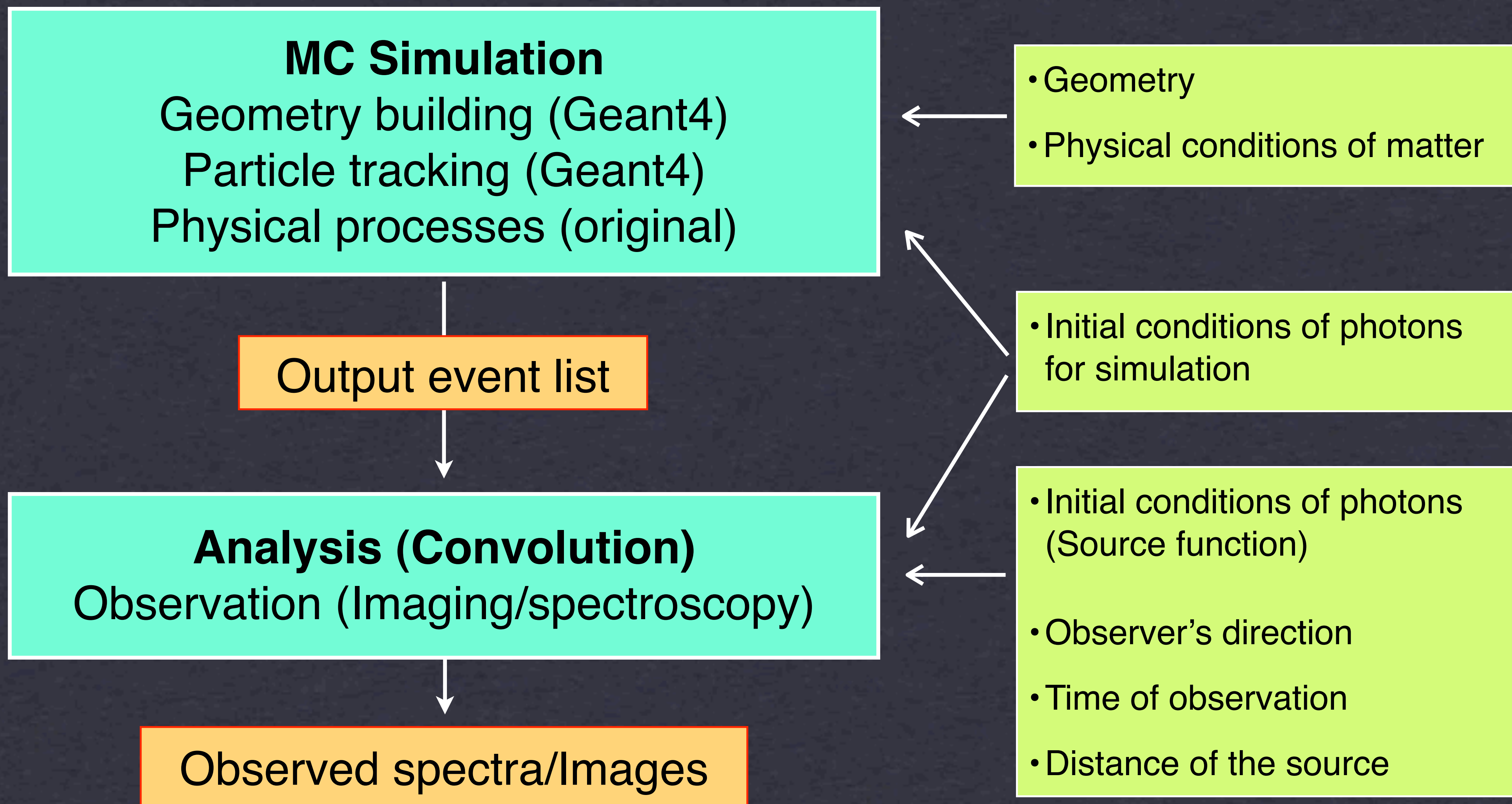


Process of one event:
1) generate a photon, record initial conditions
2) calculate the next interaction point
3) invoke the interaction, reprocess photons
4) repeat 2-3
5) record the last interaction information if a photon escapes from the system.

A MC simulation generates a list of events containing a response of the system.
Convolution of this event list with the initial conditions produces the final spectrum/image.
(similar to methods of Green's function)

Odaka+ (2011)

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.

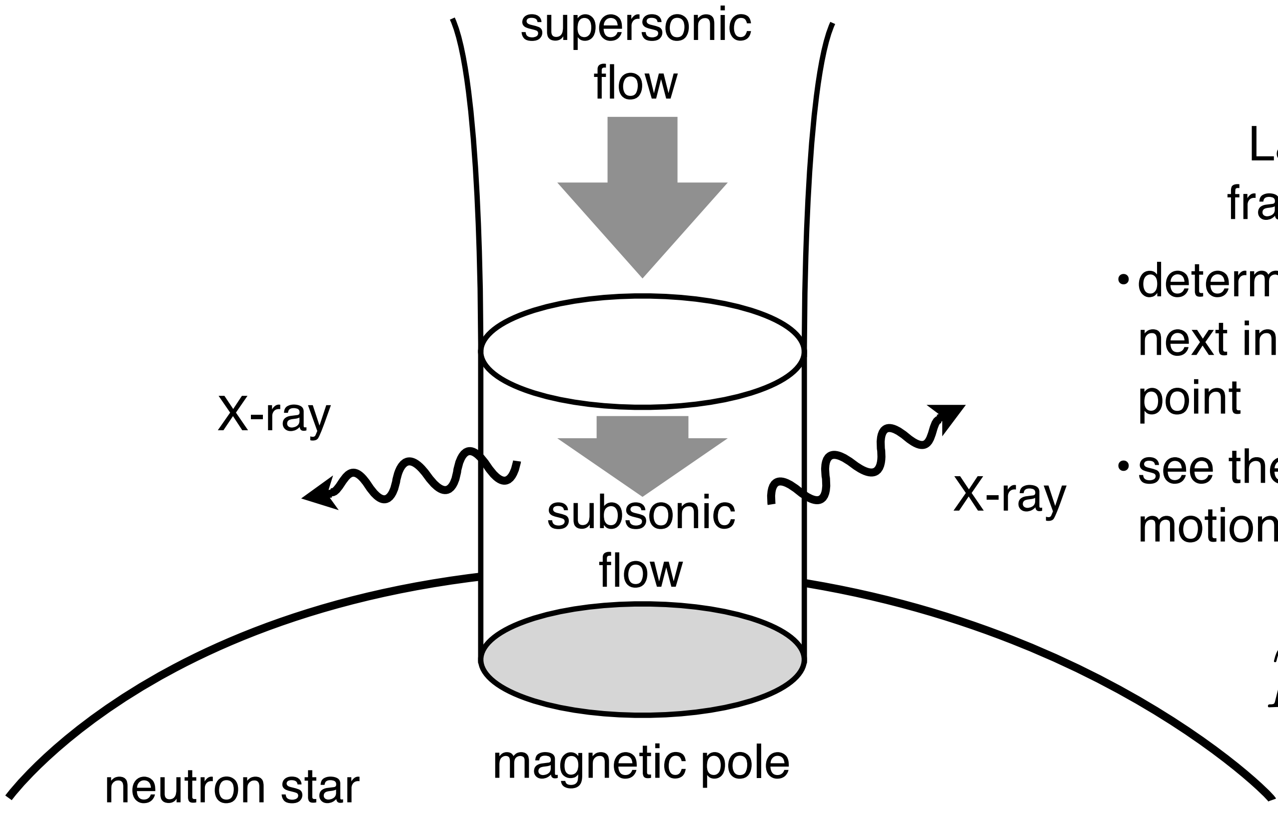
Physical Processes

MONACO has extensible structure;
you can (easily) add new physical processes.
We have implemented:

State of matter	Processes	Applications
Hot plasma	(Inverse) Compton scattering	Accretion flows Hot coronae around compact objects
Photoionized plasma	Photoionization Photoexciation	Stellar winds in X-ray binaries AGN outflows
Neutral matter	Photoabsorption Scattering by bound electrons	X-ray reflection nebulae (molecular clouds) AGN tori

Comptonization in Accretion Flow

optically thick	Analytical/numerical methods are effective.
not optically thick complicated geometry high energy band	The process is essentially discrete. →Monte Carlo approach is suitable.



Thermal & bulk Comptonization
Becker & Wolff (2007)

Using Lorentz transformation

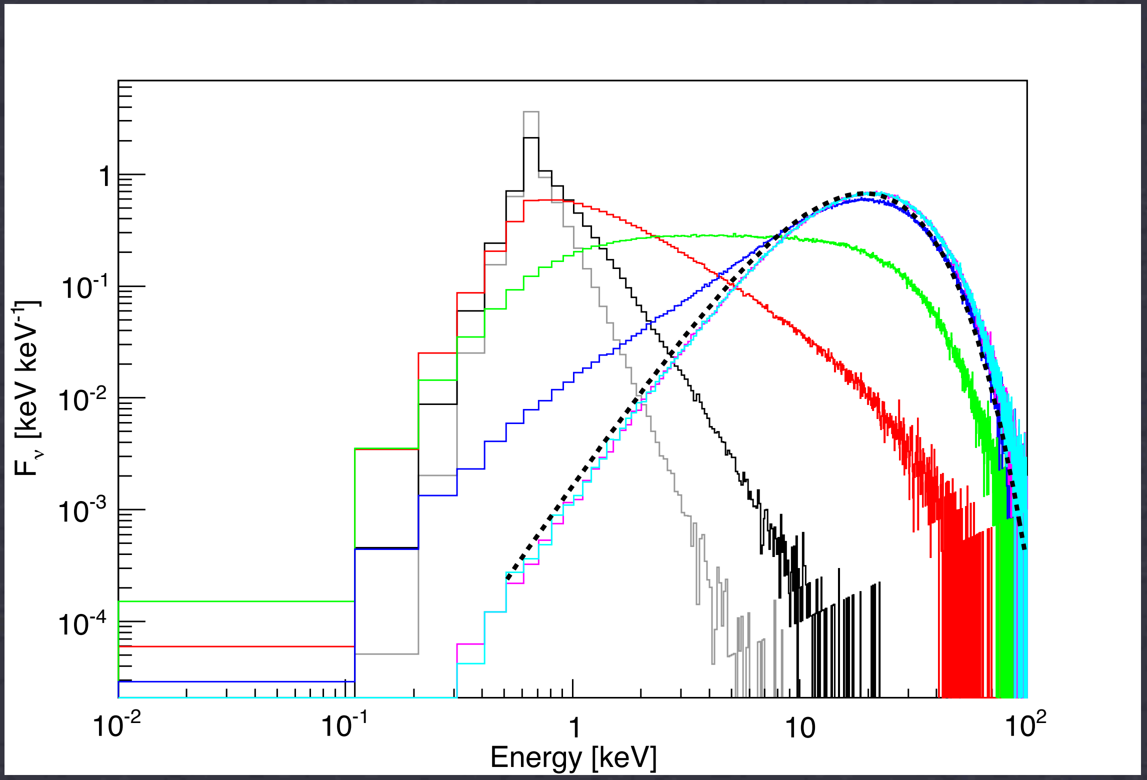
Lab frame	Bulk motion's frame	Target electron's frame
• determine the next interaction point • see the bulk motion	• select the target electron • see the thermal motion	• calculate scattering by a rest electron

$$p^{\mu} \xrightarrow{\text{Lorentz transformation}} p'^{\mu} \xrightarrow{\text{Lorentz transformation}} p''^{\mu}$$

$$p_1^{\mu} \longleftarrow p_1'^{\mu} \longleftarrow p_1''^{\mu}$$

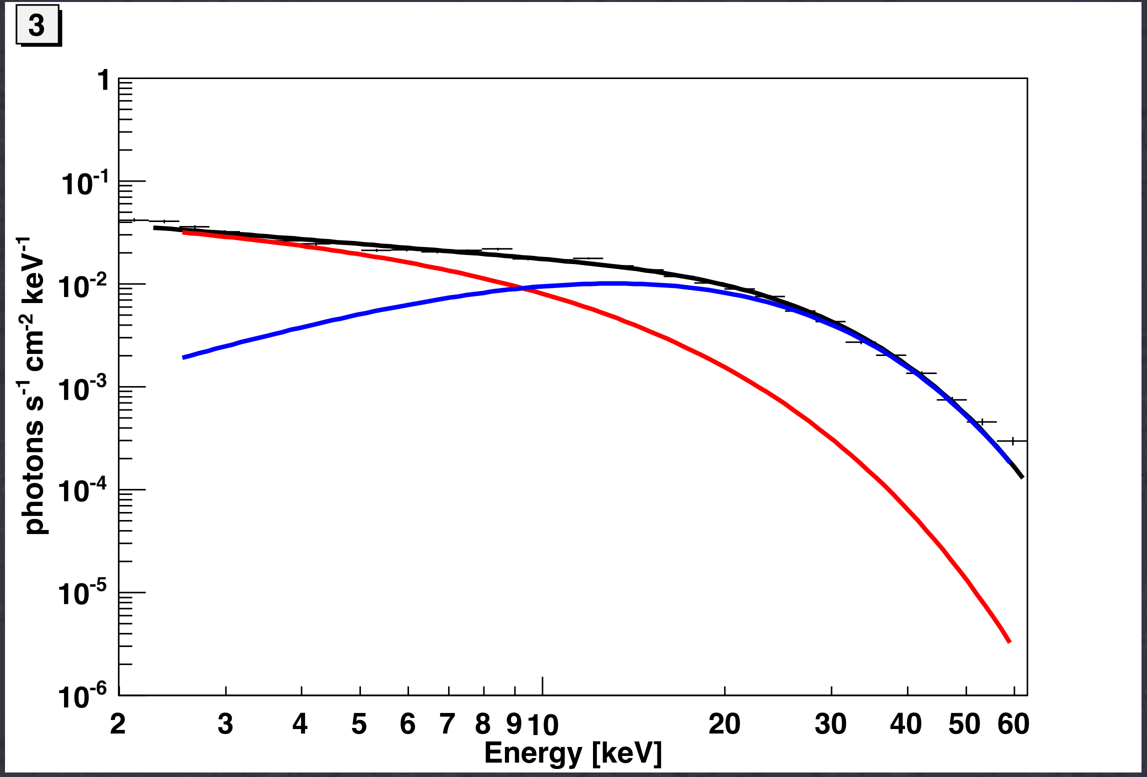
Magnetic field effects can be included.

Comptonized Spectrum



Pure thermal Comptonization

- ✓ Spherical cloud of different Thomson depths
- ✓ Temperature: 6.4 keV
- ✓ Seed: monochromatic 0.64 keV
- ✓ For large τ, the spectrum agrees with the theoretical spectrum of saturated Comptonization.



Accretion Column Model

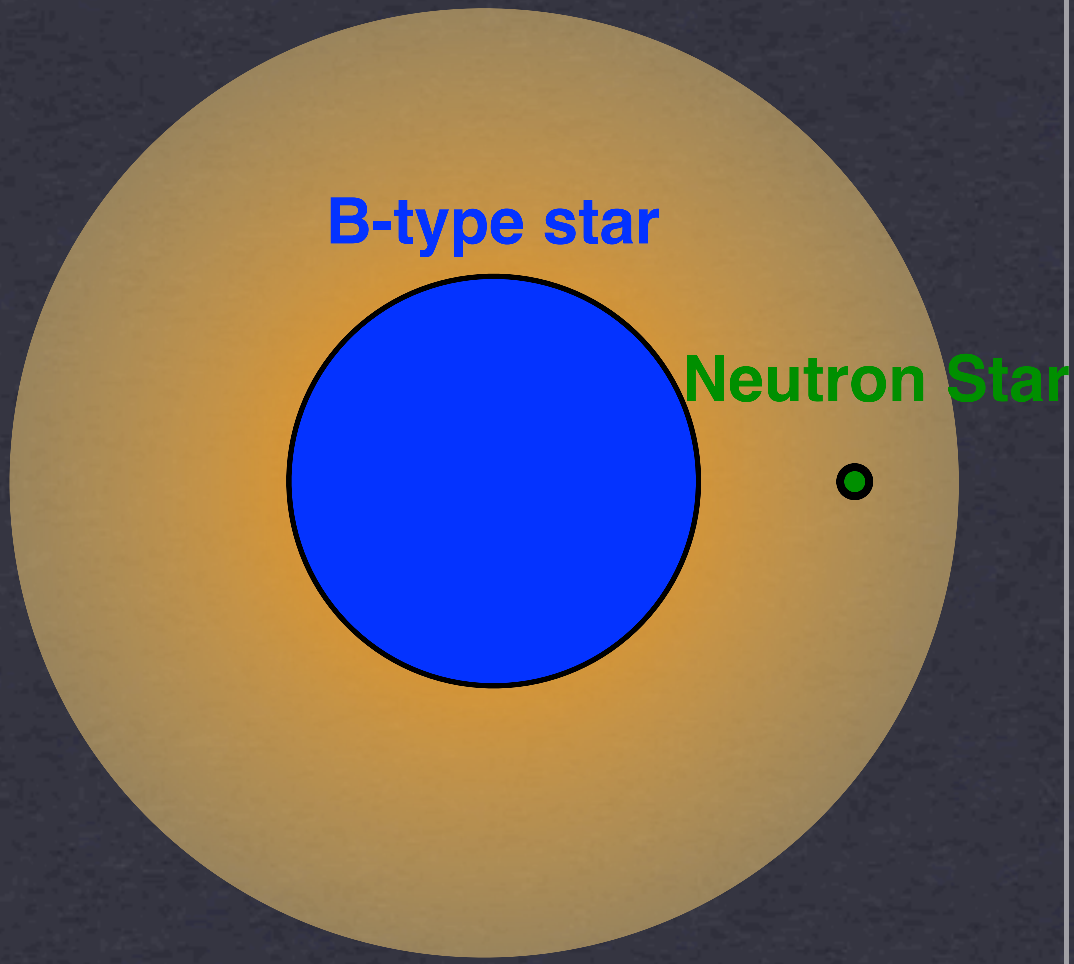
- ✓ Assuming Vela X-1's column
- ✓ Temperature: 6 keV
- ✓ Seed: thermal bremsstrahlung
- ✓ Column radius: 200 m
- ✓ Magnetic field effect included approximately
- ✓ Successfully generated a power law with a quasi-exponential cutoff.

Odaka et al. in prep. & Suzaku conference poster in July at Stanford.

Photoionized Plasma

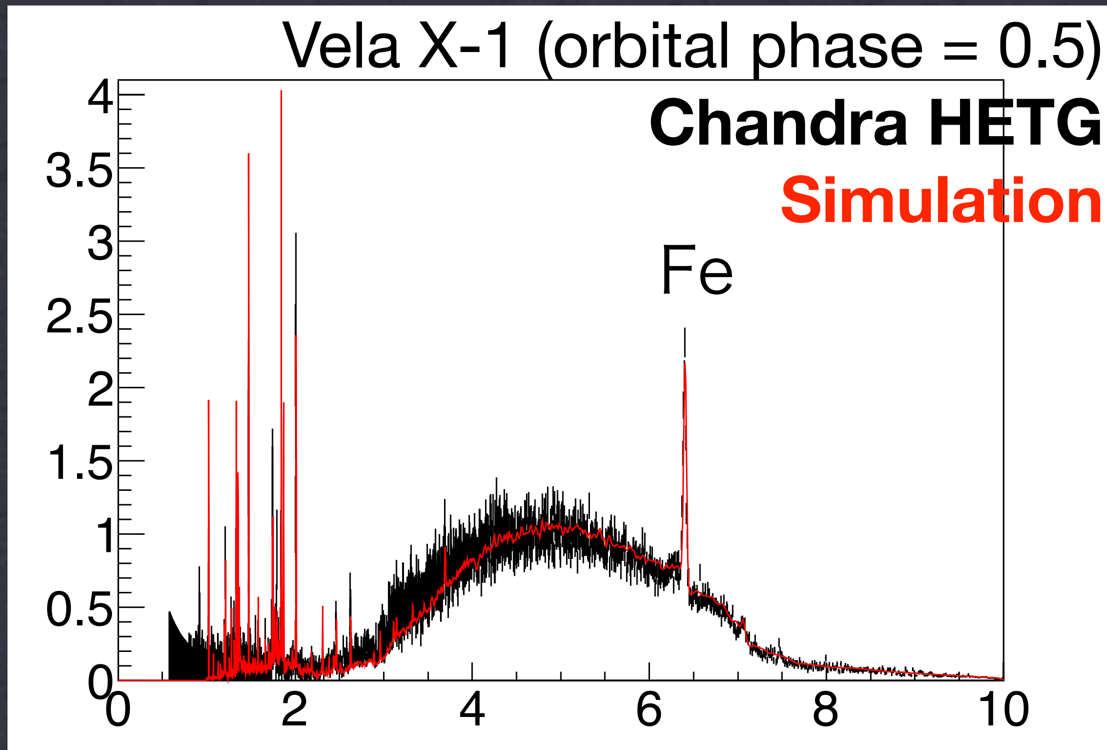
- Stellar wind in an HMXB is the best laboratory to study photoionized plasmas.

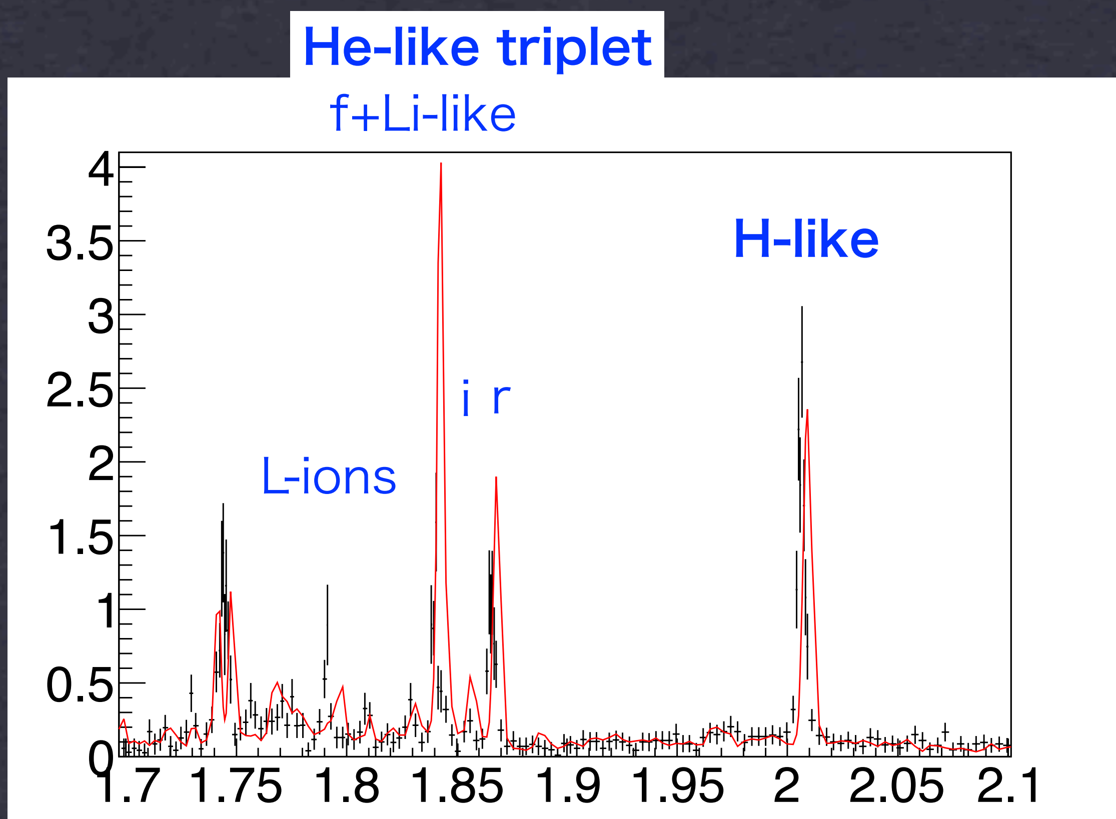
- Radiation from a photoionized plasma can be regarded as reprocessed emissions from illuminated matter.
  →MC simulation is suitable.



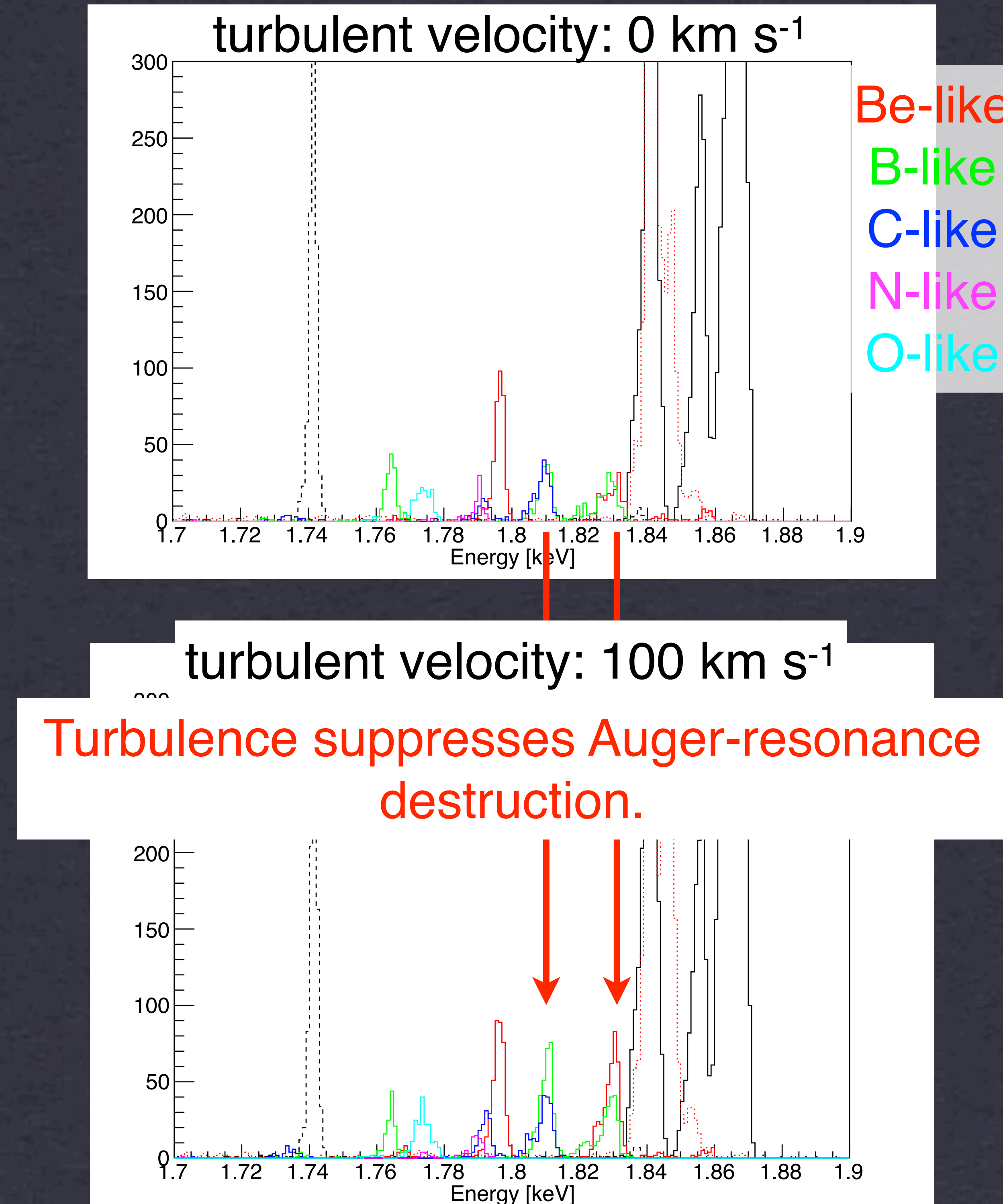
- Our MC simulation successfully reproduced Vela X-1 spectrum for lines of H, He-like ions (Watanabe+ 2006).

- We recently extended this code to L-shell ions (Li-, Be-...like).





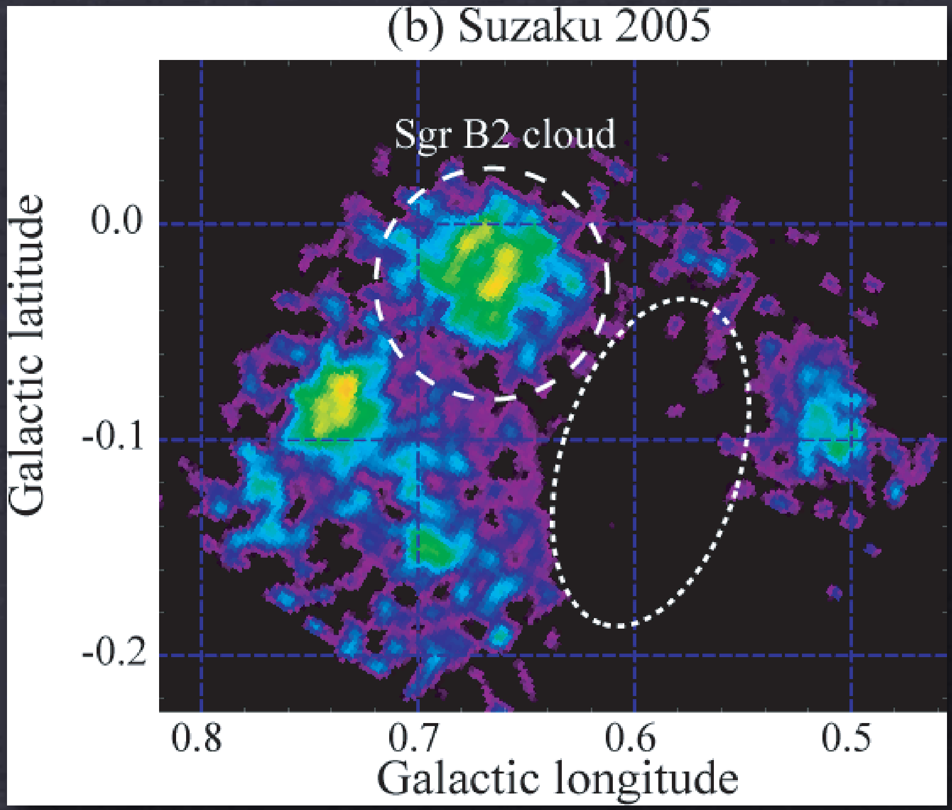
First attempt to reproduce Si-K complex of Vela X-1 spectrum obtained by Chandra. Model parameters are not optimized yet.



Monte Carlo simulation is a powerful tool to simulate effects of turbulence on a line spectrum.

X-ray Reflection Nebula

- Giant molecular cloud Sgr B2 has been reflecting a past outburst of SMBH Sgr A*, displaying strong Fe fluorescence at 6.4 keV.
It shows strong time variability over a few year scale.

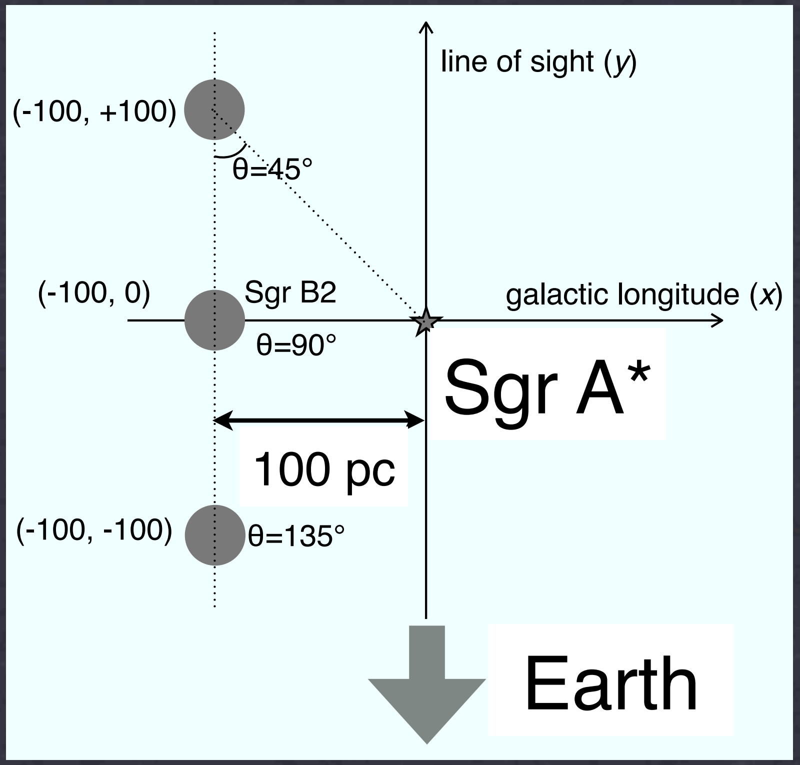


Koyama+ (2008)

- Such objects are good probes of molecular clouds themselves and the black hole activity.

- We have to consider multiple scatterings and structure of the cloud. → Monte Carlo simulation

Diagnostics of Molecular Clouds

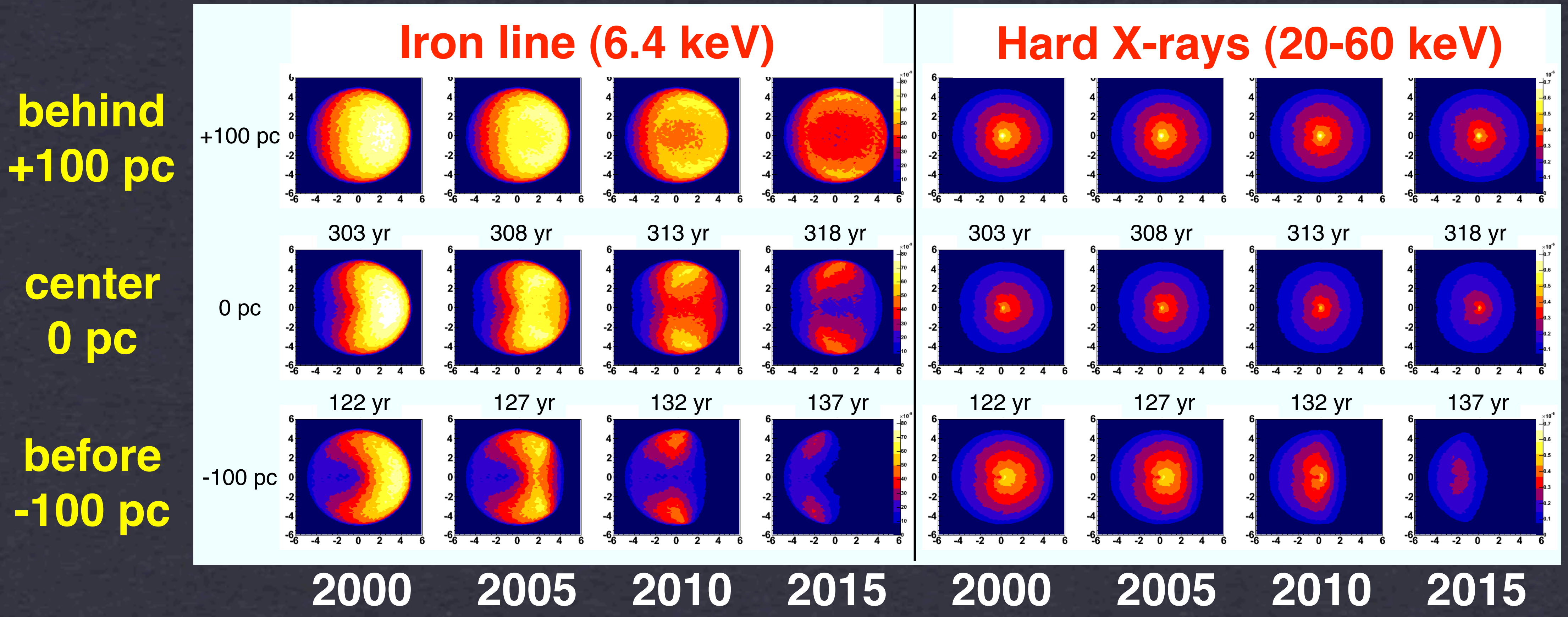


Odaka+ (2011)

Parameters:

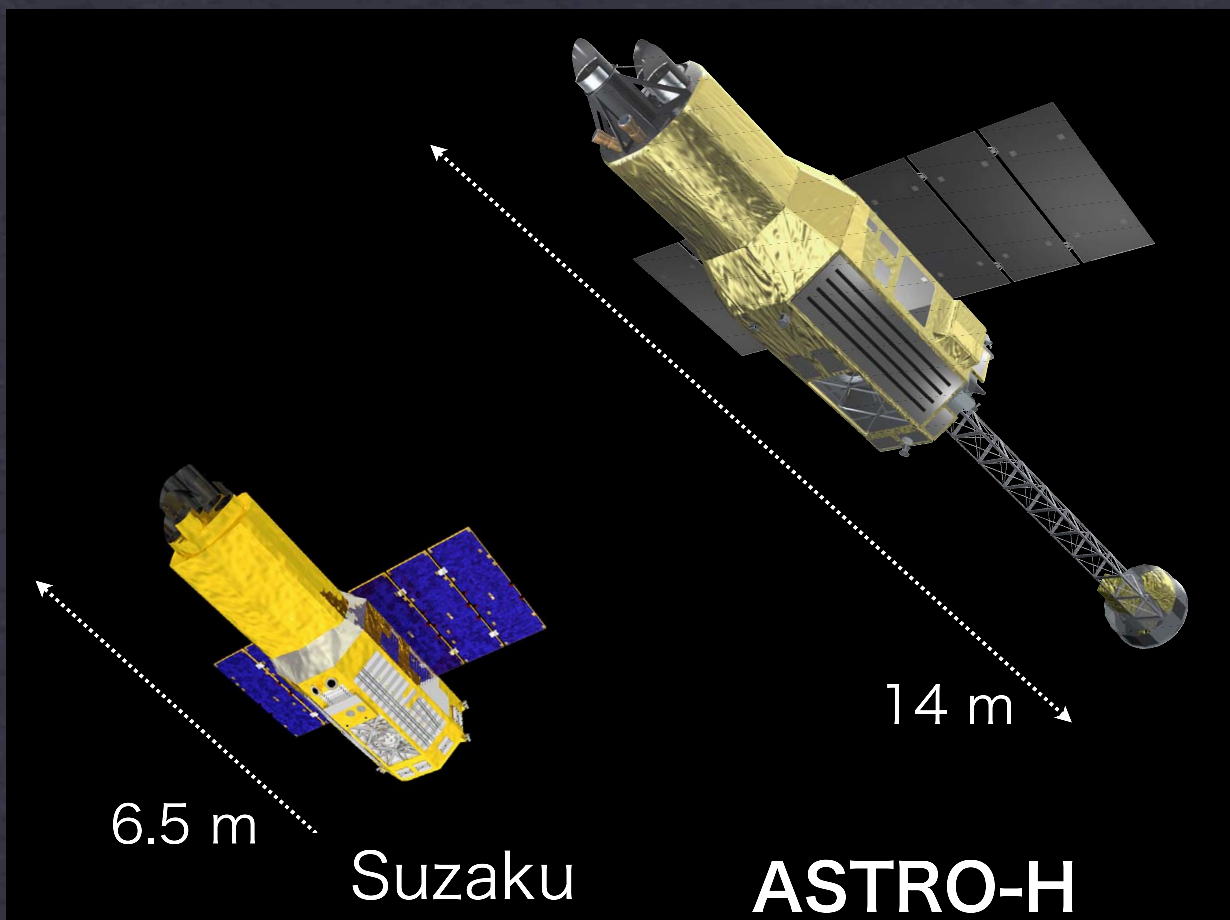
- line-of-sight position of the cloud
- mass
- density profile
- chemical composition

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

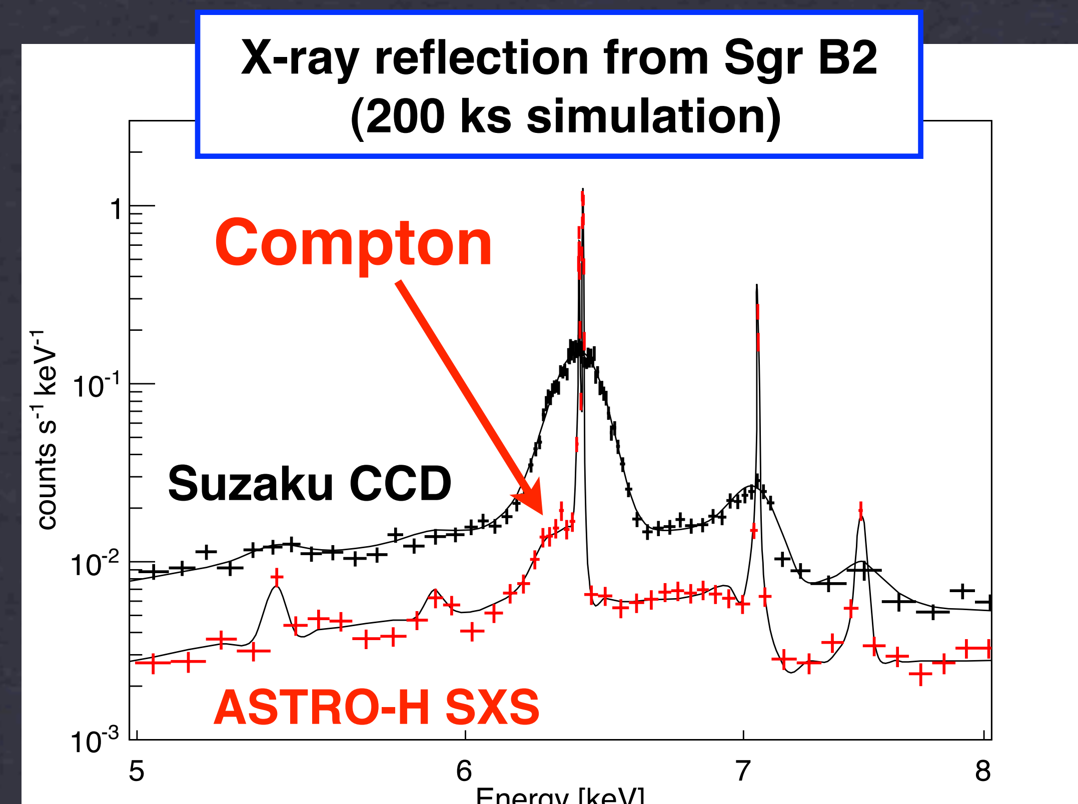


ASTRO-H Observatory

Scheduled for launch in 2014



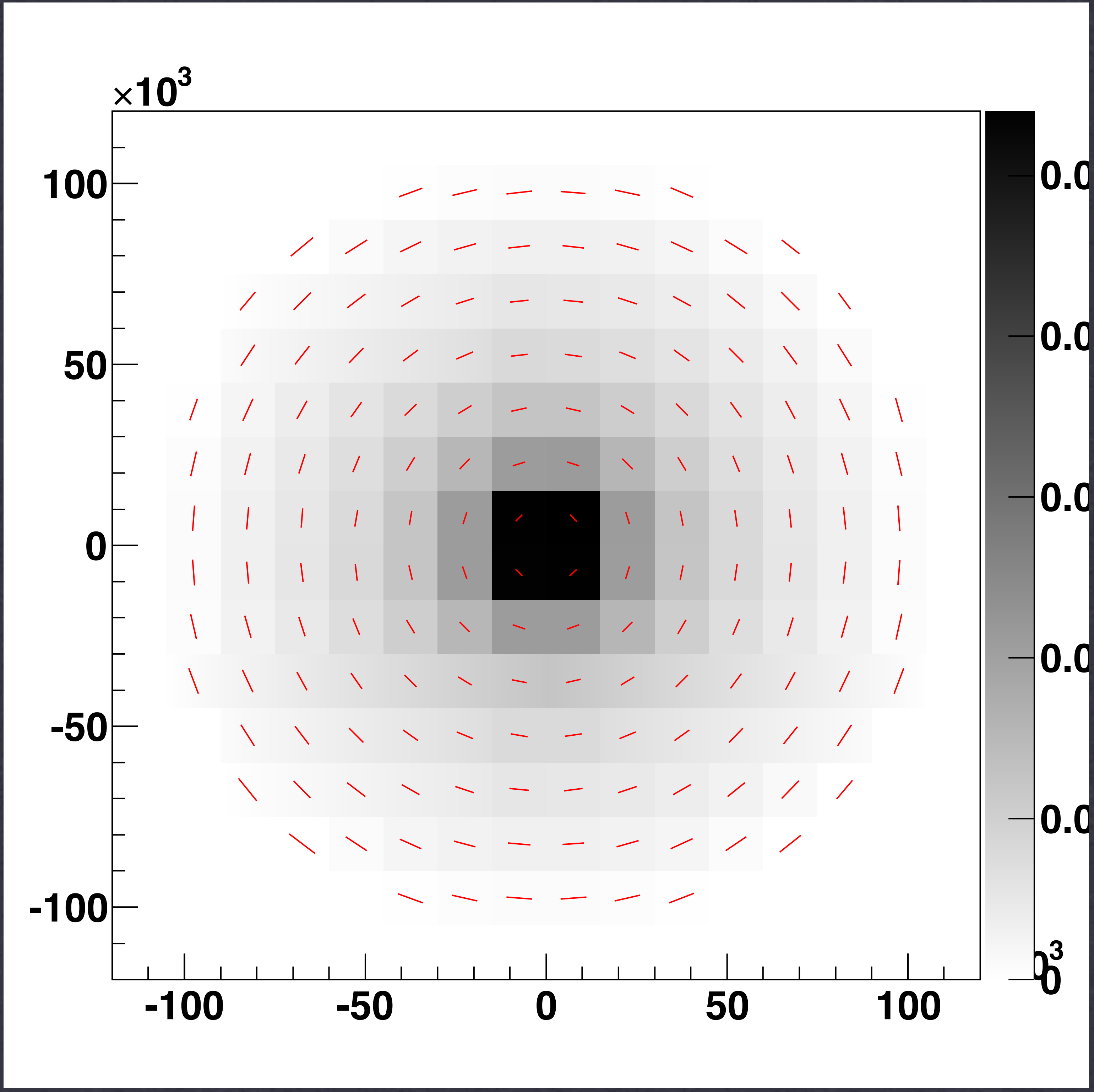
Micro-calorimeter
Energy res. ΔE = 5 eV at 6 keV
Hard X-ray mirror + imager
Imaging spectroscopy up to 80 keV



Large effective area = Good statistics

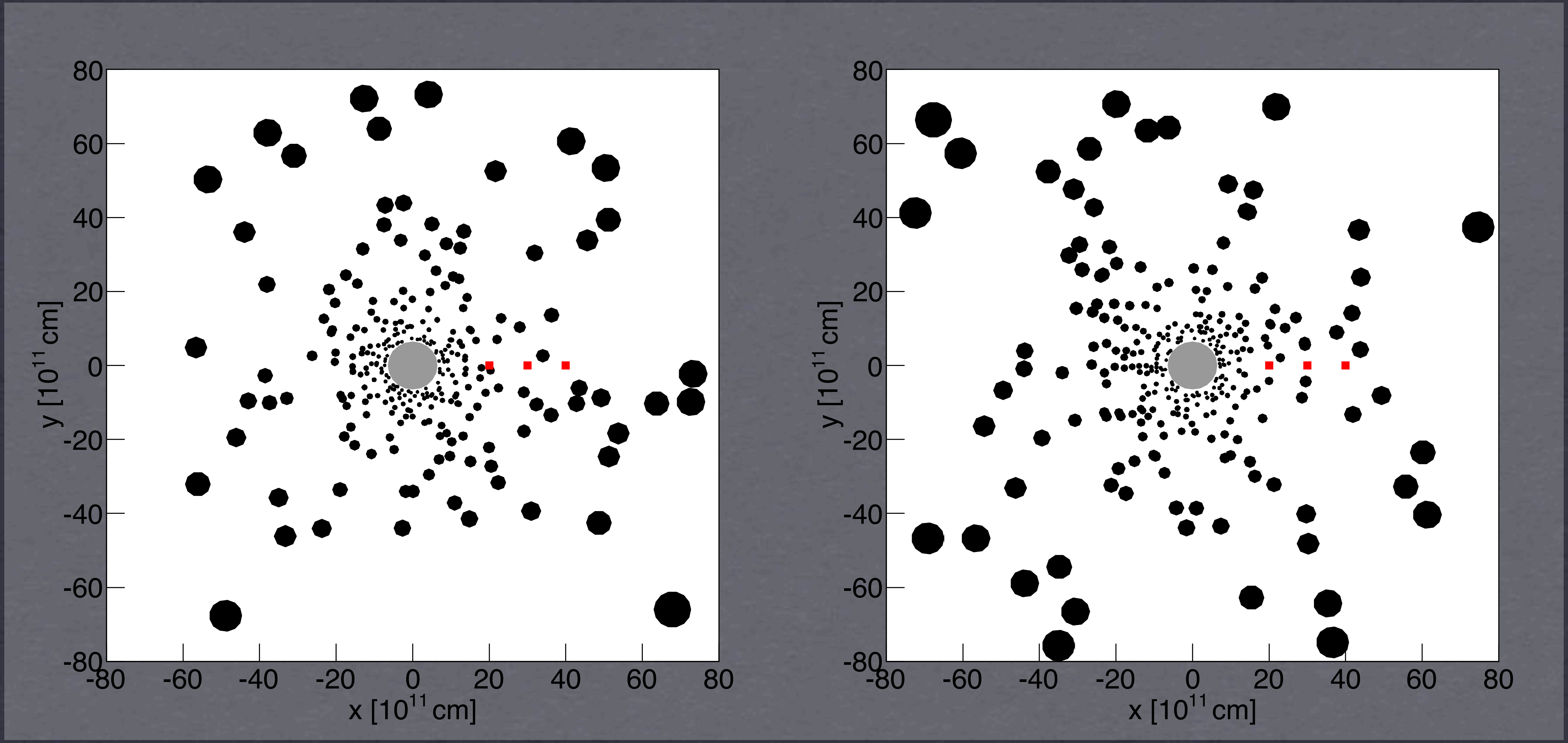
High S/N data obtained by ASTRO-H will open high-precision physics experiments at cosmic laboratories.
Our MC framework based on accurate treatment of X-ray radiative transfer enables evaluation of systematic errors due to astrophysical objects.

Imaging Polarimetry



Complicated Geometry

Simple model of clumpy stellar wind



Summary of MONACO

- We have been developing a new calculation framework of X-ray radiation based on Monte Carlo method.
- It is multi-purpose, easy to use, and extensible.
- This MC framework will enable us to interpret high S/N data obtained by modern/future X-ray observatories.
- We are going to prepare to open it to the public.