Galactic Centre X-ray Time-Lapse: 3D, HD, polarised

Ildar Khabibullin (MPA&IKI)

Abstract Reflection of X-ray emission on molecular clouds in the Galactic Center has established itself as a powerful tool for joint exploration of the past Sgr A*'s activity and properties of the dense gas distribution under extreme conditions of the Central Molecular Zone. Thanks to extensive observational efforts and improvements in modelling, parameters of the recent flare(s) and characteristics of the brightest molecular complexes have been both reliably inferred. Upcoming measurements of the polarisation in reflected X-ray continuum will help to separate the signal of interest from the contaminating background and to check the underlying assumptions of the previously used techniques in an independent manner. Probing the intrinsic polarisation properties of the primary emission might become feasible, helping us to reveal its physical origin and connection to the regularly observed Sgr A*'s X-ray and infrared flares of smaller amplitude. On the other hand, high resolution imaging and spectral mapping of the reflected X-ray emission are capable of shedding the light on characteristics of the supersonic gas motions which shape the inner structure of the molecular clouds and are intricately related to the whole cycle of massive star formation. We describe the current status and highlight the future prospects of observing the unique "Galactic Center X-ray Time-Lapse" in its full power, i.e. in 3D, HD, and polarised.

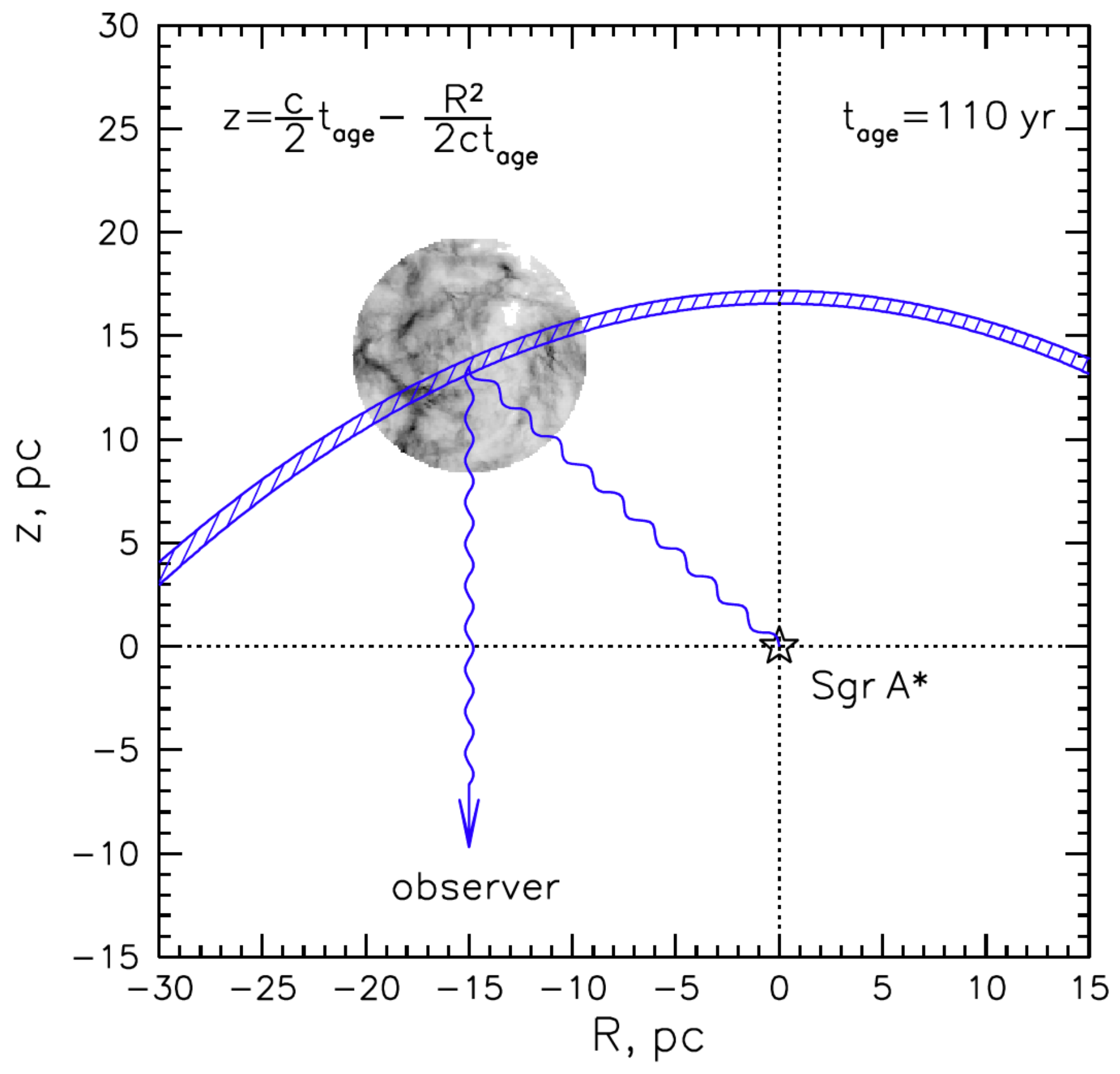
Introduction

The supermassive black hole (SMBH) in the center of our Galaxy, Sgr A*, is currently very dim but experiences regular flares of IR and X-ray emission, indicating the presence of hardly detectable accretion flow. **Was Sgr A* more active in the past?** If so, was it a high-amplitude fluctuation or a rare event of a different nature (e.g. a tidal disruption event)? Is it similar to whats happens in other low-luminosity Active Galactic Nuclei?

On the other hand, the central few hundred pc of the Galaxy contain ~5 % of its cold gas budget (concentrated in the giant molecular clouds composing the Central Molecular Zone), but it contributes 10 times less to total star formation rate. **What is the reason for inefficiency of star formation in CMZ?** Is it related to the extreme and dynamical environment in which the CMZ gas finds itself? Can it be similar to the massive star-formation in galaxies at Cosmic Noon (i.e. at redshifts ~1-2)?

Thanks to the light-travel-time delay, **reflection of X-ray emission on molecular clouds in the CMZ allows us to reconstruct the activity record of Sgr A* over the last few hundred years.** Given that the original flare(s) of the emission was short, <10 years, only a few clouds reflect X-rays at any given moment (as seen by a distant observer) and their position can be determined simply from the geometrical consideration. Thanks to high penetrative power of X-rays and weak sensitivity of X-ray albedo to the thermo- and chemo-dynamical state of the gas, **we can not only to locate the clouds, but also to investigate their inner structure in a simple and unbiased way.**

Basics of X-ray echo-tomography



The loci of points which are visible in scattered emission to the distant observer is described (in vicinity of the primary source) by the paraboloid relation

$$z=\frac{c}{2}t_{\rm age}-\frac{R^2}{2ct_{\rm age}}$$

where c is the speed of light, t_{age} - the "age" of the flare, z - relative line of sight position of the point, R - distance from it to the primary source in the picture plane (see the figure on the right).

The characteristic size of the paraboloid, R$\times t_{age}$ ~30 pc for t_{age} ~100 yrs, so it will reach the farthest regions of the CMZ (which is a few hundred pc across) in ~a few hundred years after the flare (see Churazov et al 2017b where 500-yr evolution of the reflection signal has been modelled).

For the flare duration of dt, the line-of-sight thickness of this region is dz~cxdt~3 pc if dt~10 years. The actual v_z=dz/dt

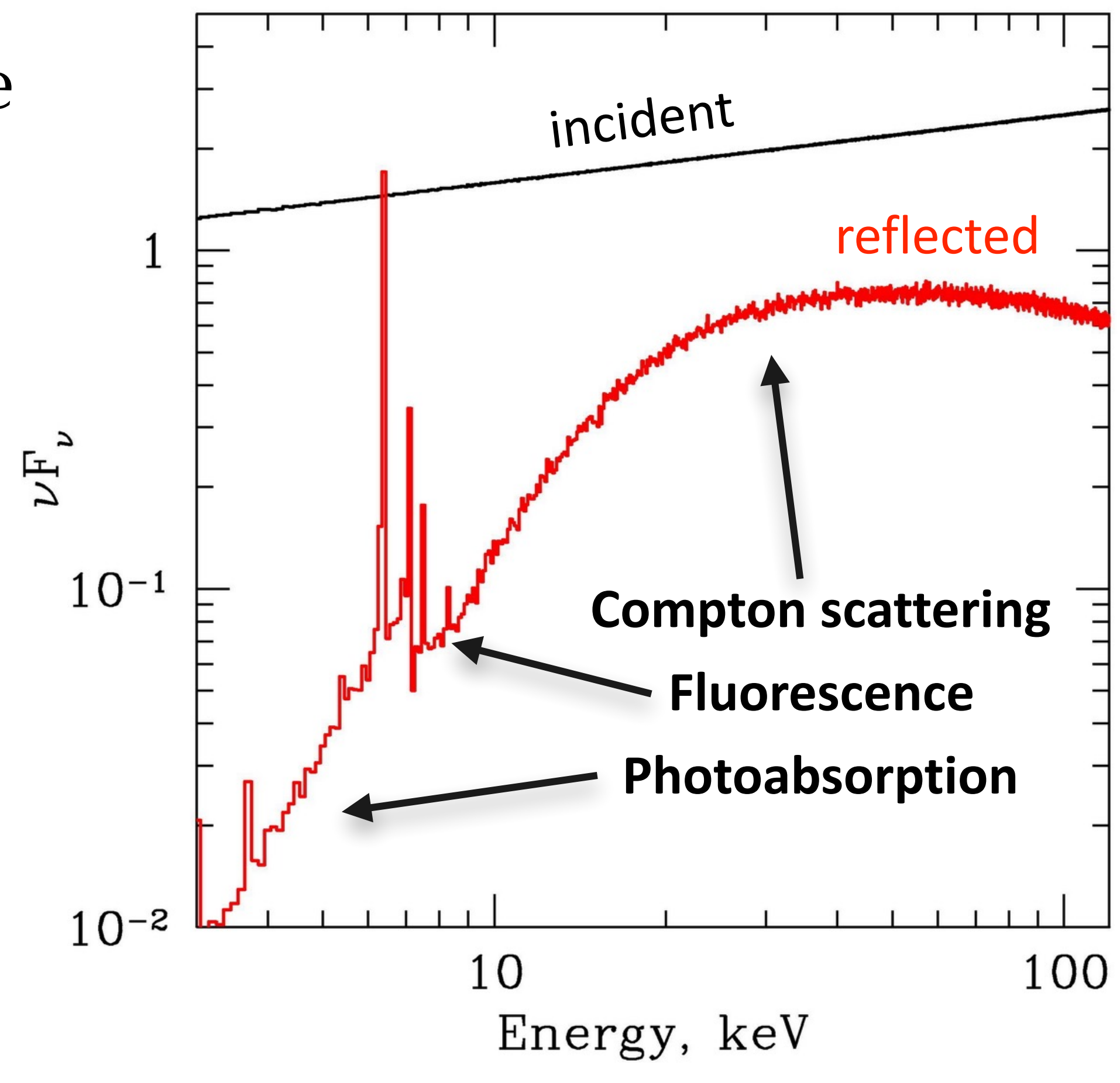
$$v_z=\frac{c}{2}\left[1+\left(\frac{R}{c\,t_{\rm age}}\right)^2\right]$$

depends solely on the relative disposition of the cloud, so that it can be used as a proxy for determining z (or t_{age}).

Basics of X-ray reflection on cold gas

Interaction of X-ray emission with the cold atomic and molecular gas is well explored and can be readily modelled (e.g. Sunyaev & Churazov 1998). The key processes are:

1) Compton scattering on the electrons of H, H_2 and He
2) Photoelectric absorption by inner-shell electrons of neutral atoms of the "metals" (e.g. oxygen, neon, silicon and iron)
3) Fluorescent line emission following inner-shell photo-absorption (e.g. 6.4 keV line of neutral iron)



Observational signatures of X-ray reflection

1) Hard X-ray spectrum
2) Fluorescent emission lines with large equivalent width (e.g. ~1 keV for iron 6.4 keV line)
3) Intensity correlates with the number density of the gas

$$I_{\rm X}=\frac{L_{\rm X}}{4\pi D_{\rm sc}^2}\,\frac{\sigma_{4-8}}{4\pi}\,\delta z\,\bar{\rho}_{\rm H}$$

as far as optically thin limit holds:

$$N_H\lesssim 3\times10^{23}\ {\rm cm}^{-2}$$

4) Variability on the time-scales comparable with ~max(duration of the flare, light-crossing-time of a cloud)

5) The Compton scattered continuum is polarised with the polarisation degree determined primarily by the scattering geometry, i.e. relative disposition of the reflecting cloud

Galactic Centre X-ray Time-Lapse: 3D, HD, polarised

Ildar Khabibullin (MPA&IKI)

Observational status

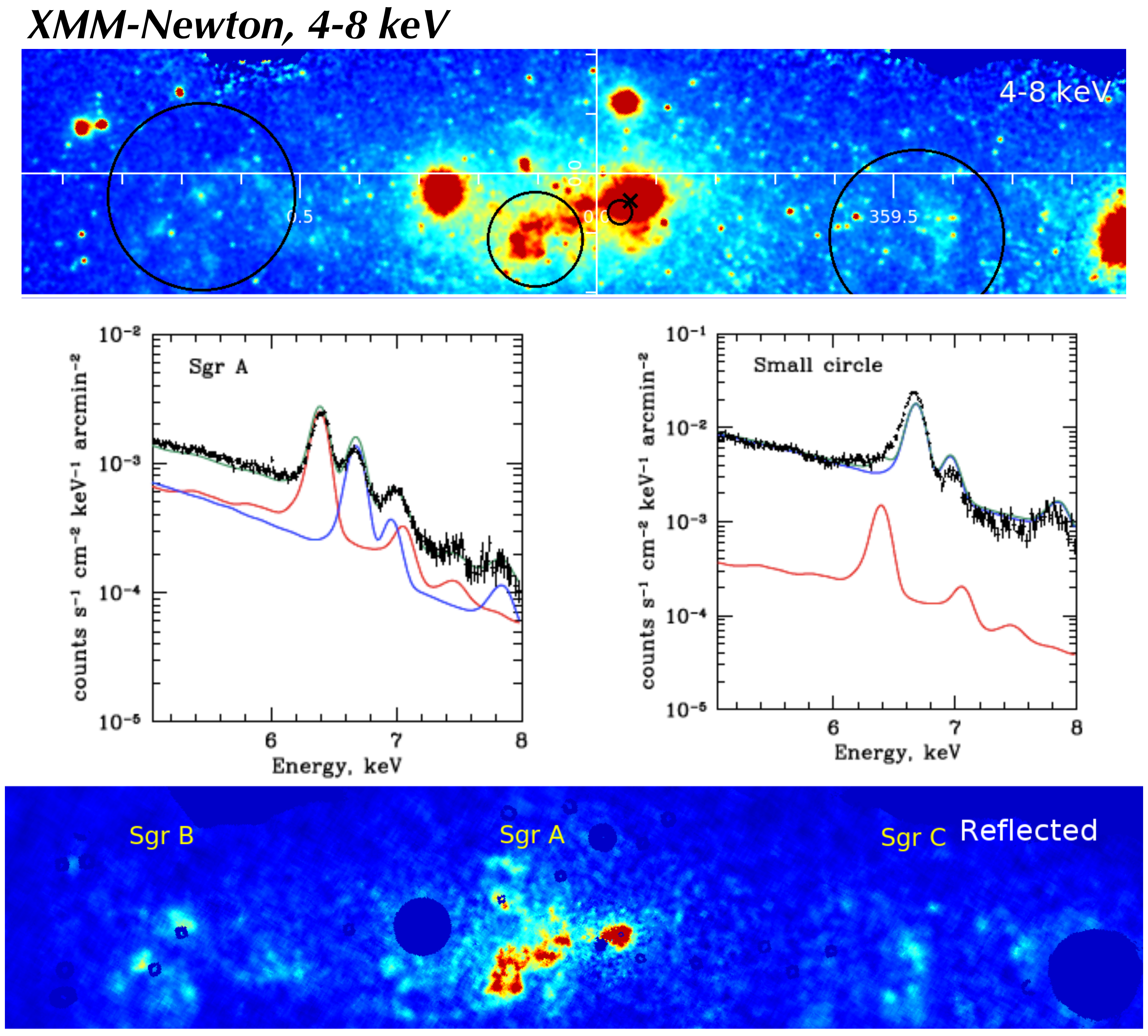
Hard X-ray emission consistent with the position of the CMZ molecular clouds was first detected by GRANAT/ART-P (Sunyaev, Markevitch and Pavlinsky 1993), followed by the detection of fluorescent emission of iron by ASCA (Koyama et al 1996).

The morphology and spectral shape of this emission have been confirmed and explored in great detail by all major X-ray observatories, including Chandra, XMM-Newton, INTEGRAL, Suzaku, NuSTAR. The historical decay of the emission from the once brightest molecular complex has been discovered followed by discovery of the rapid (apparently superluminal) variations of the diffuse emission.

All the observed features are consistent with the expectations for the scenario invoking reflection of a flare of X-ray emission on molecular gas. Other models (e.g. emission due to the elevated level of cosmic ray background in the Galactic Centre region) have difficulties in explaining either the special or temporal properties of the emission.

In the framework of this scenario, one can fully exploit the theoretical predictions to further improve its characterisation and physical description. This includes predictions of the spectral shape, spatial and temporal variations, and polarisation of the reflected continuum.

Spectral decomposition of the diffuse emission

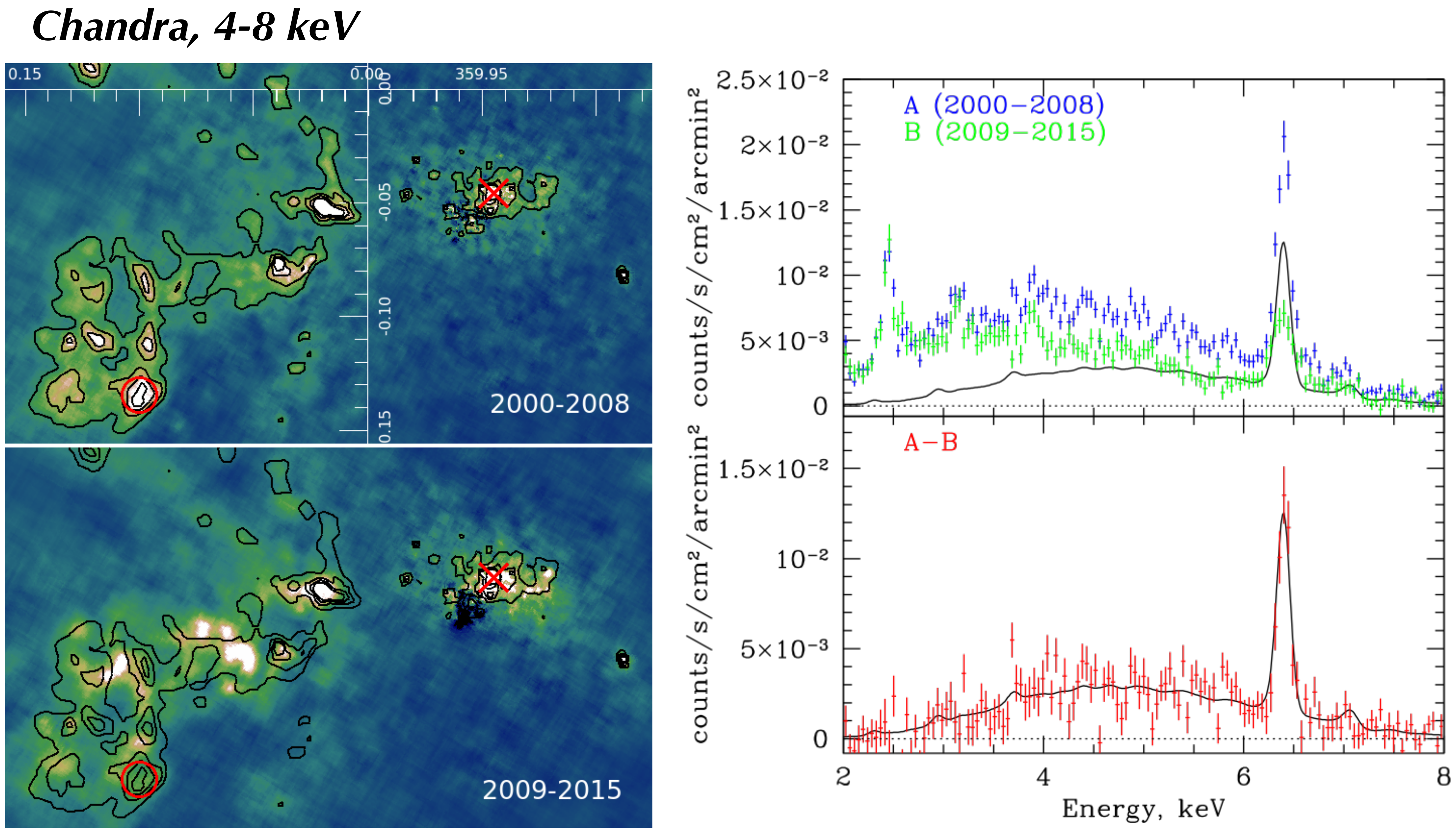


Linear spectral decomposition technique (Churazov et al 2017b) allows us to separate the reflection signal from the diffuse emission of different nature abundant in the Galactic Centre.

Fine structure and variability

The reflected X-ray emission is indeed well structured on ~pc scales, similar to the distribution of the molecular gas density (see the map on the right).

The diffuse emission is variable at the timescales as short a few years, and the difference spectrum is fully consistent with the prediction for the X-ray reflection (see the spectra on the right).

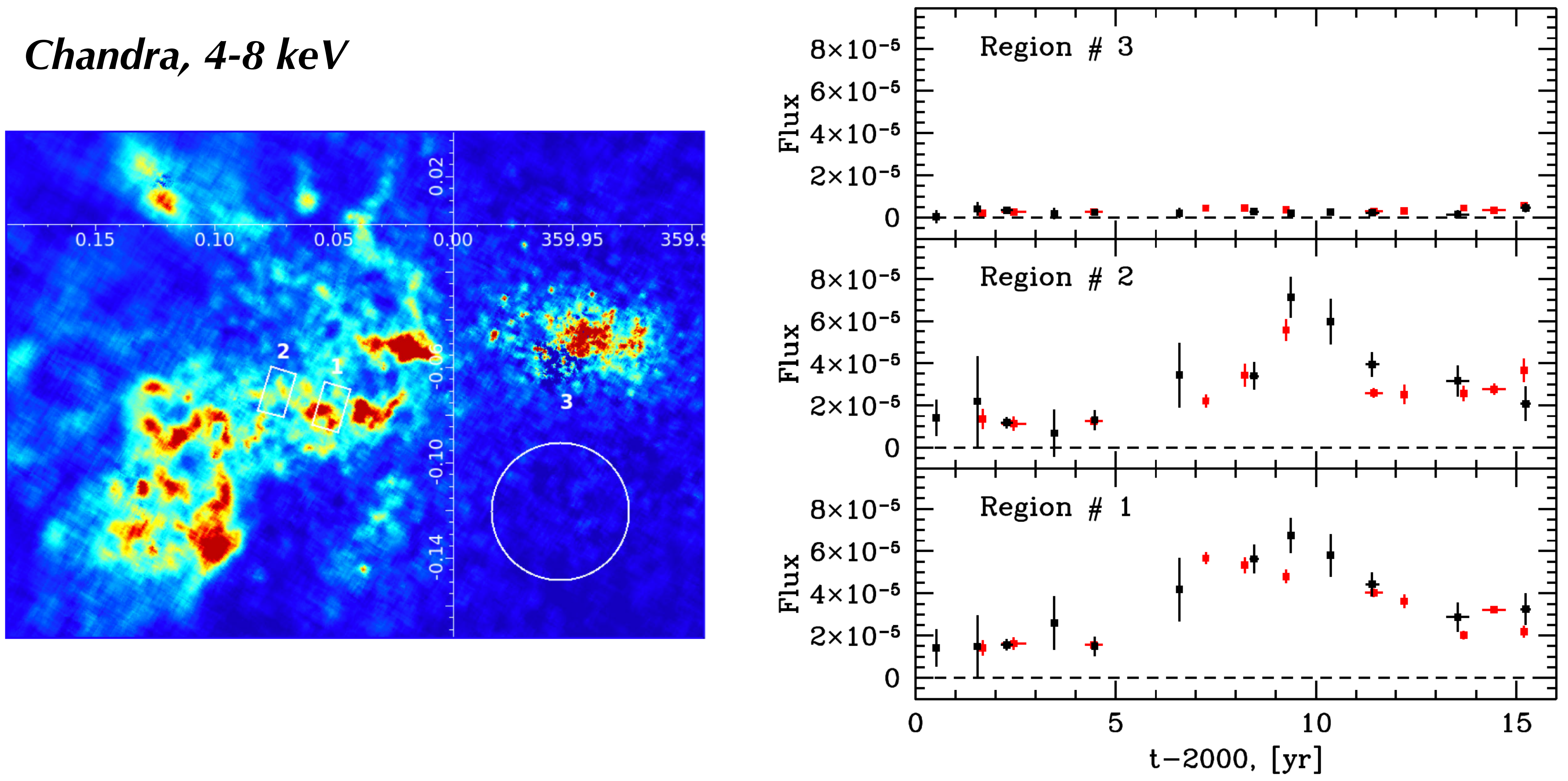


Churazov et al 2017a

Short flare paradigm

The light-curves of the reflected emission from bright individual clumps (shown on the right) indicates that the duration of the flare was shorter than the corresponding light-crossing-times, namely it should be shorter that ~1.6 years based on the data for the smallest clumps.

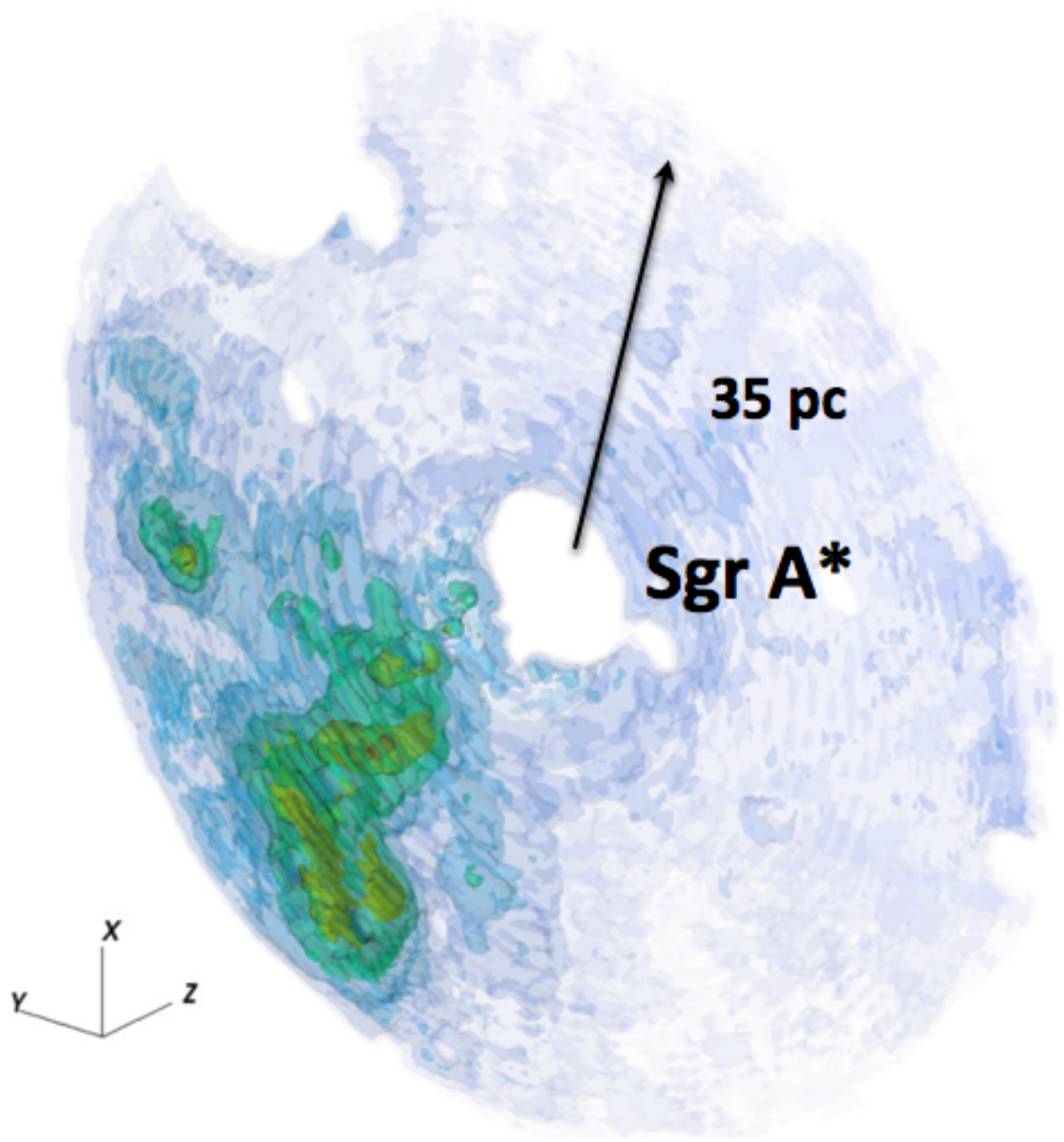
This implies that at any given moment only a very thin (<1 pc) slice of molecular gas contributes to the observed emission. The statistical properties of the emission should closely flow those of the molecular gas distribution.

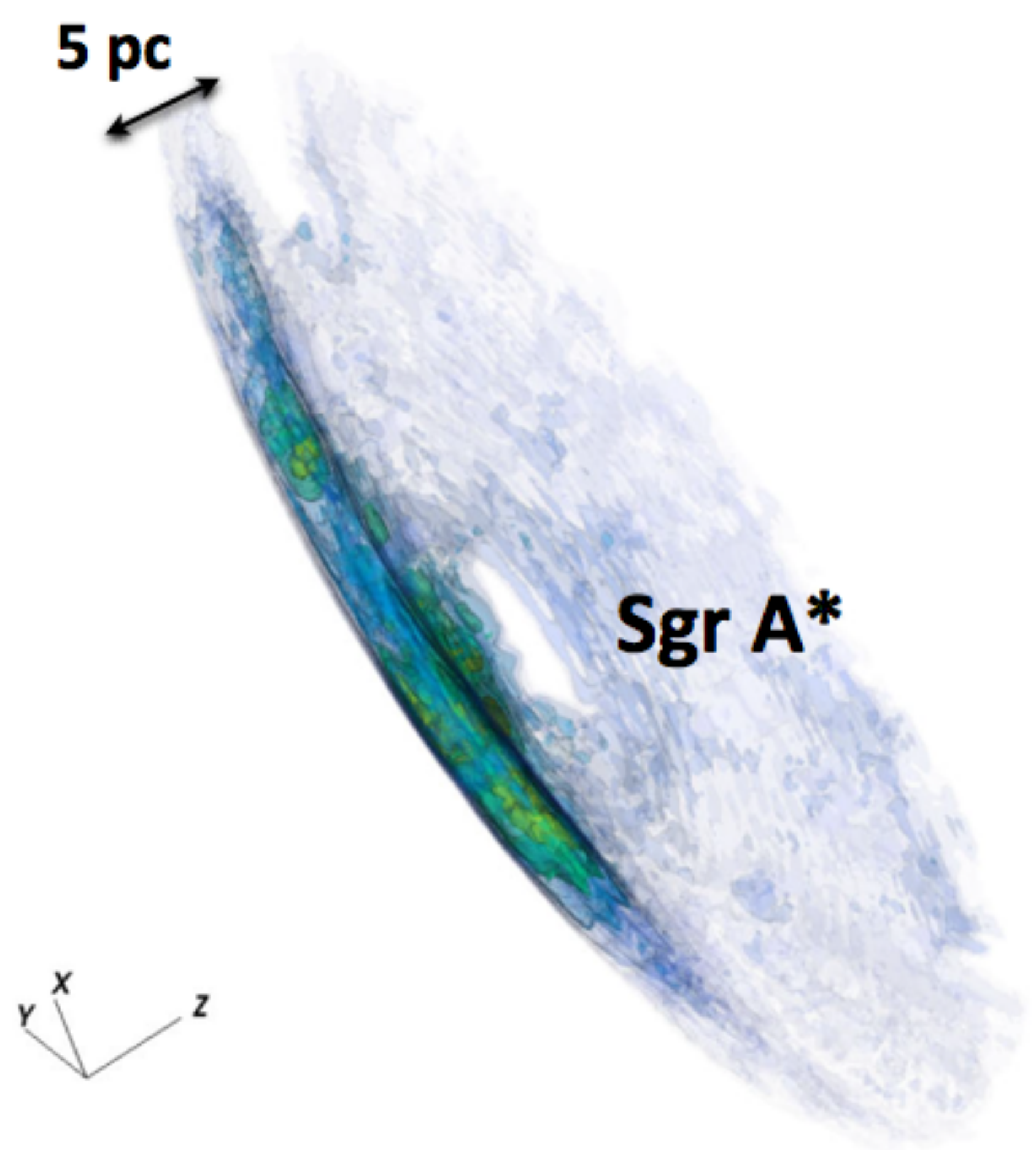


Galactic Centre X-ray Time-Lapse:
3D, HD, polarised

Ildar Khabibullin (MPA&IKI)

3D distribution of the illuminated molecular gas

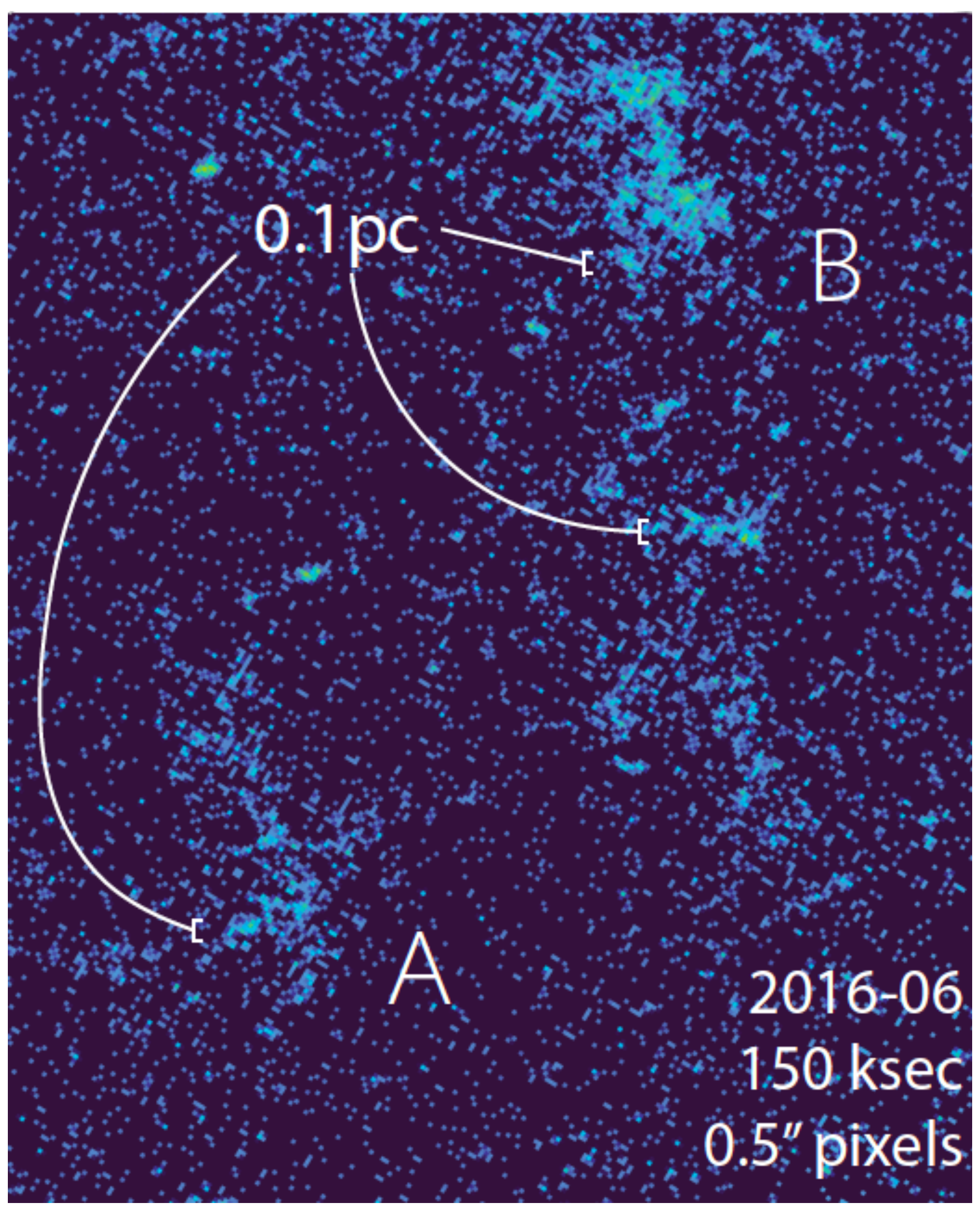


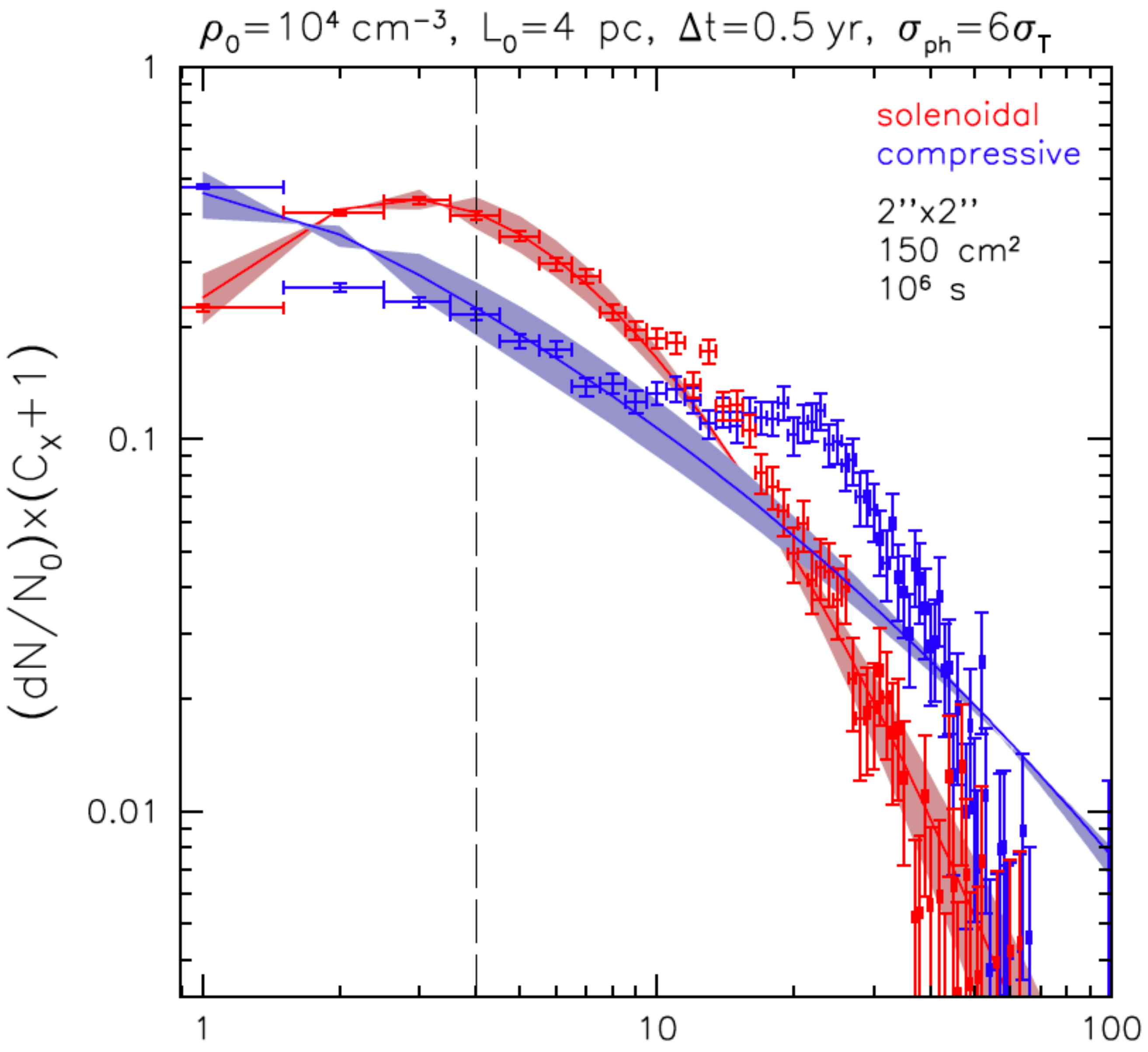


Knowing parameters of the flare we can reconstruct 3D distribution of the illuminated molecular gas on the scale of few tens of pc (Churazov et al 2017a).

High resolution imaging of the molecular gas

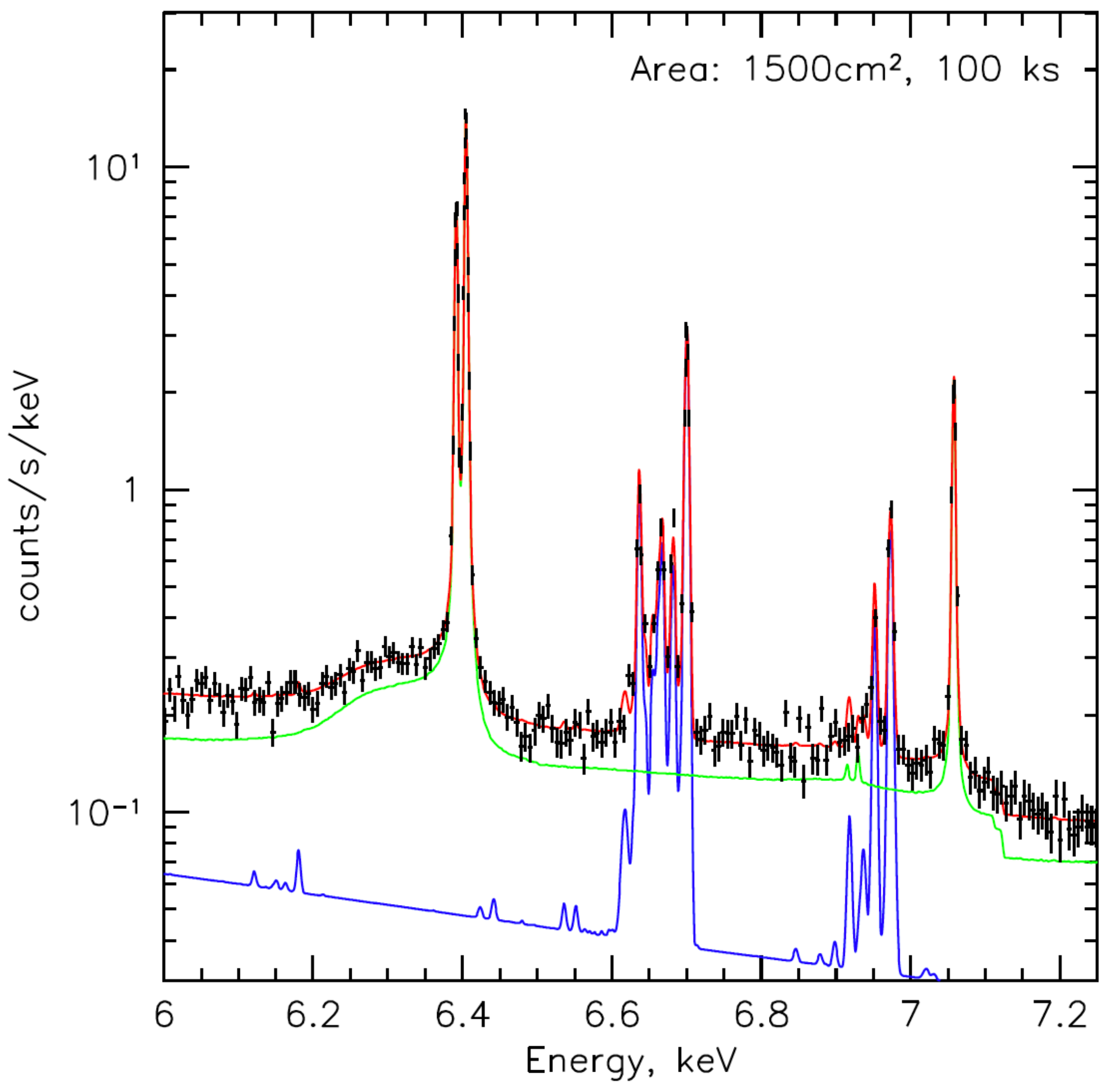
Sensitive high resolution imaging characterises statistics of the gas density field and turbulence properties **from 10 pc down to sub-pc scales**, potentially probing atomic-to-molecular transition and seeding of the star formation. The dominant mode of the supersonic turbulence can be explored in this way (Kahbibullin et al 2020).

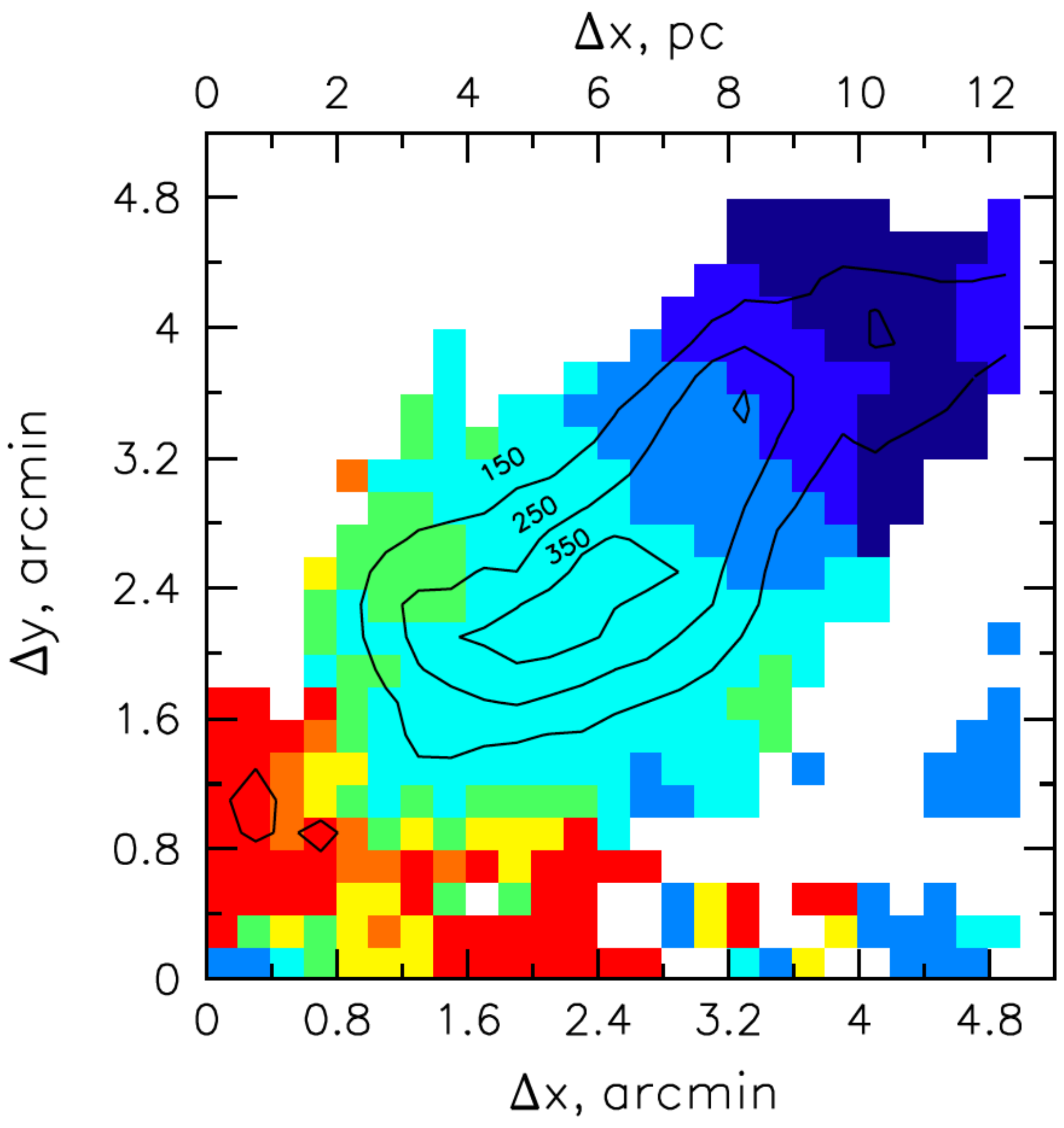




Measuring gas velocities

Future missions equipped with X-ray micro- calorimeters will be capable of measuring global velocity fields via spectral mapping in the iron 6.4 keV line. Combining these data with molecular line emission and masers will allow to reconstruct 3D velocity field (Churazov et al 2019, Khabibullin et al 2020).

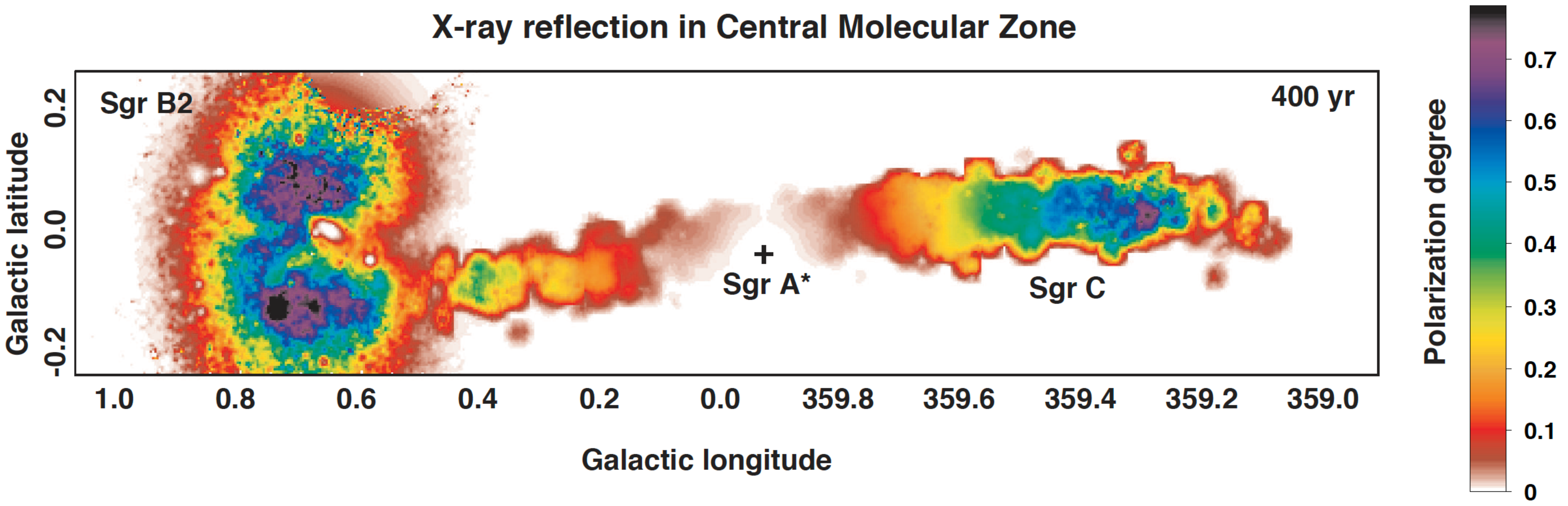




Galactic Centre X-ray Time-Lapse:
3D, HD, polarised

Ildar Khabibullin (MPA&IKI)

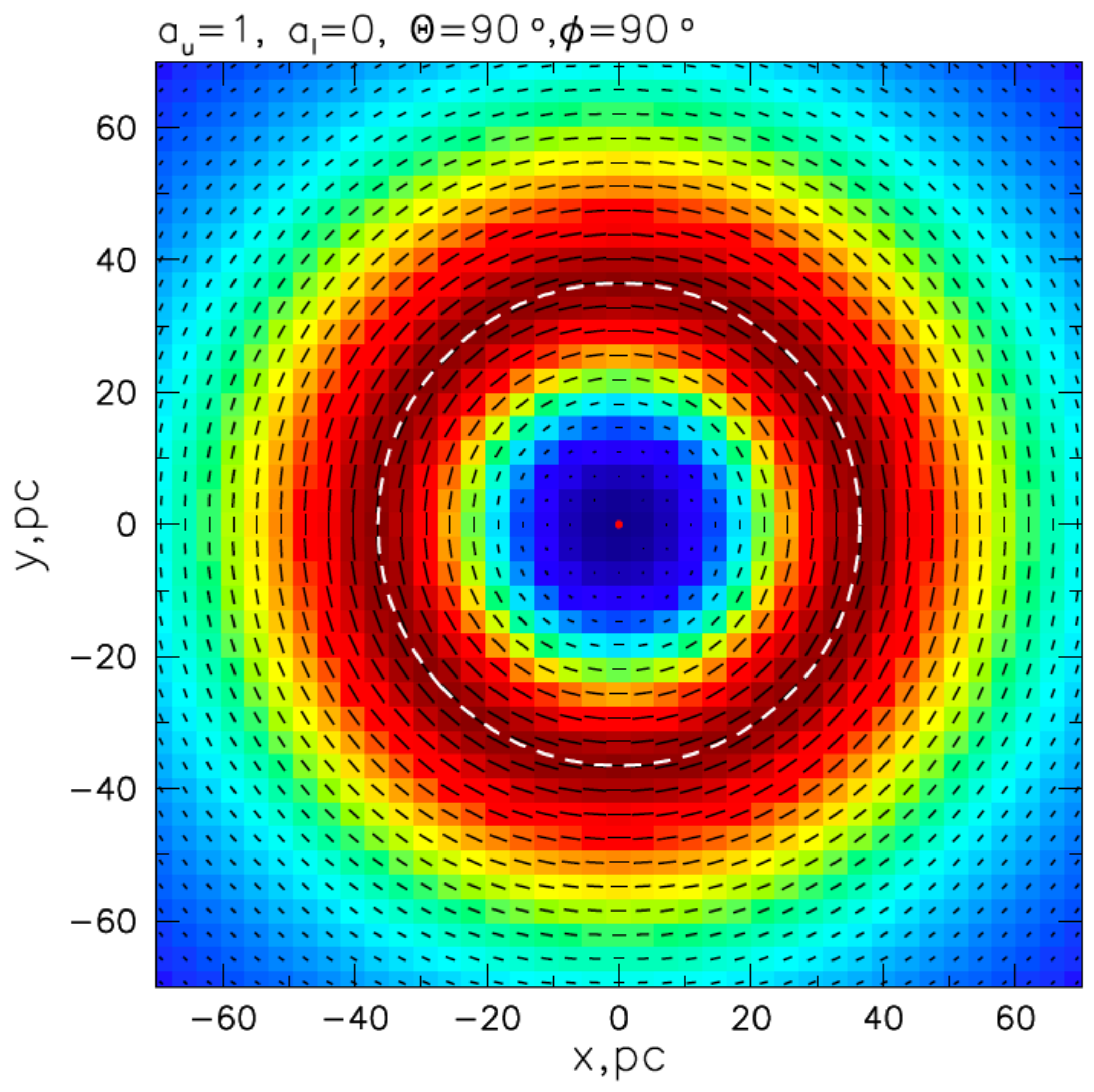
Global Polarisation Signal



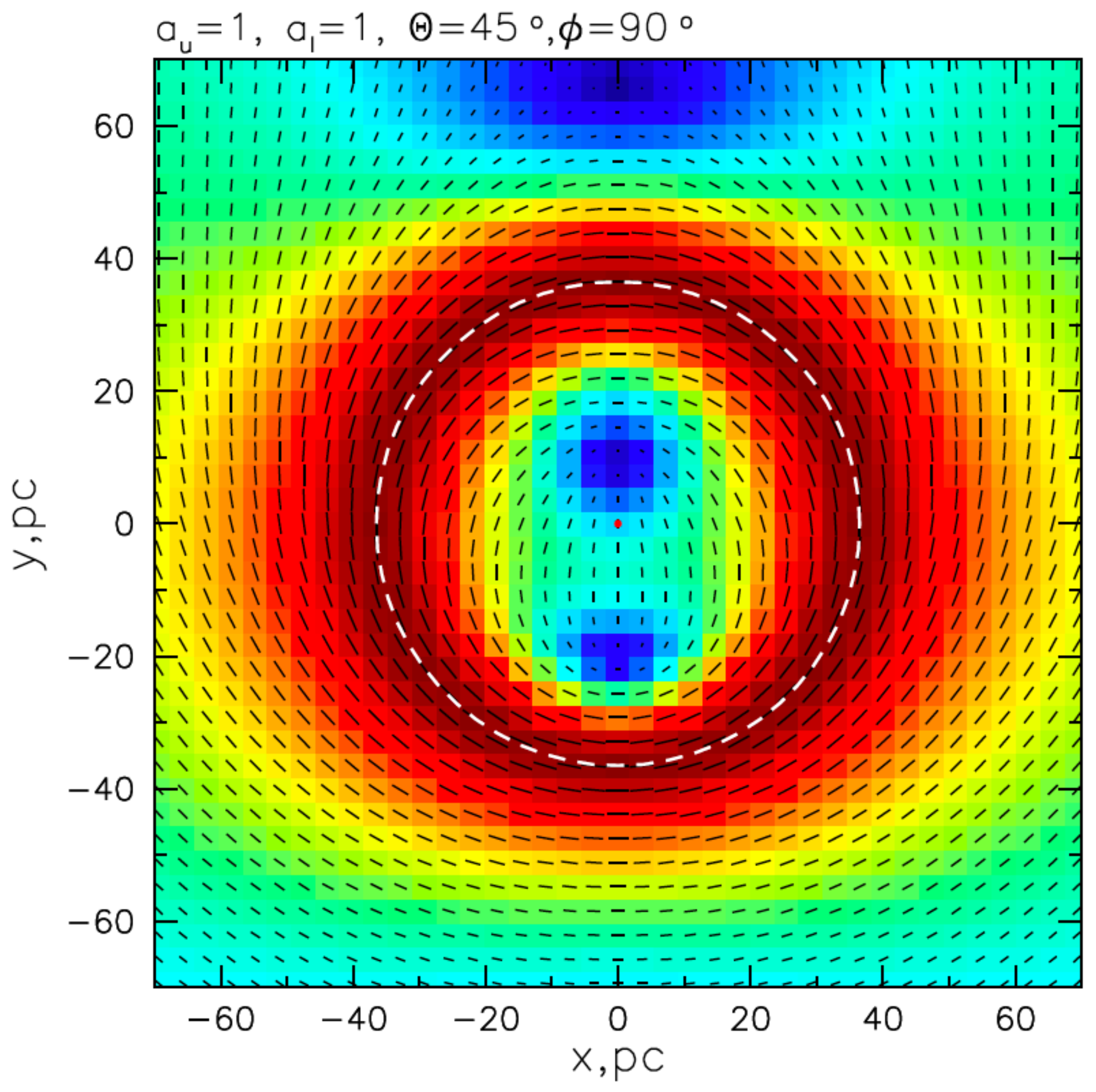
Knowing parameters of the flare and assuming some distribution of the molecular clouds across the CMZ, we can predict the global polarisation pattern of the reflected emission, given that the primary emission was unpolarised (Churazov et al 2017b).

Impact of the intrinsic polarisation

If the primary emission contain a certain fraction of linearly-polarised emission, the expected pattern of the reflected emission changes, including total normalisation, polarisation degree and polarisation plane orientation. The consistency of the observed pattern with the prediction for the unpolarised primary source can be checked already on the data of the upcoming imaging X-ray polarimeter IXPE (Khabibullin, Churazov, Sunyaev 2020).



Unpolarised primary source



50% polarised primary source

Conclusions

The X-ray reflection paradigm has already established itself as a powerful to determine the past activity record of Sgr A* and to reconstruct 3D distribution of the molecular clouds in the Central Molecular Zone.
The next step will be to characterise both the flare of X-ray emission and the inner properties of the clouds in more detail, helping to answer the key physical questions related to them.

Future advances in data and modelling are capable of bringing us many possibilities:

1) Sensitive high resolution imaging characterises statistics of the gas density field and turbulence properties from 10 pc down to sub-pc scales, potentially probing atomic-to-molecular transition and seeding of the star formation.
2) Future missions equipped with X-ray micro- calorimeters will be capable of measuring global velocity fields via spectral mapping in the iron 6.4 keV line. Combining these data with molecular line emission and masers will allow to reconstruct 3D velocity field.
3) Intrinsic polarisation of the primary source might have noticeable impact on the global and local properties of the polarisation signal (total intensity, polarisation degree and direction). This will be tested already with *IXPE*.