Data formats for Kerr hole transfer functions

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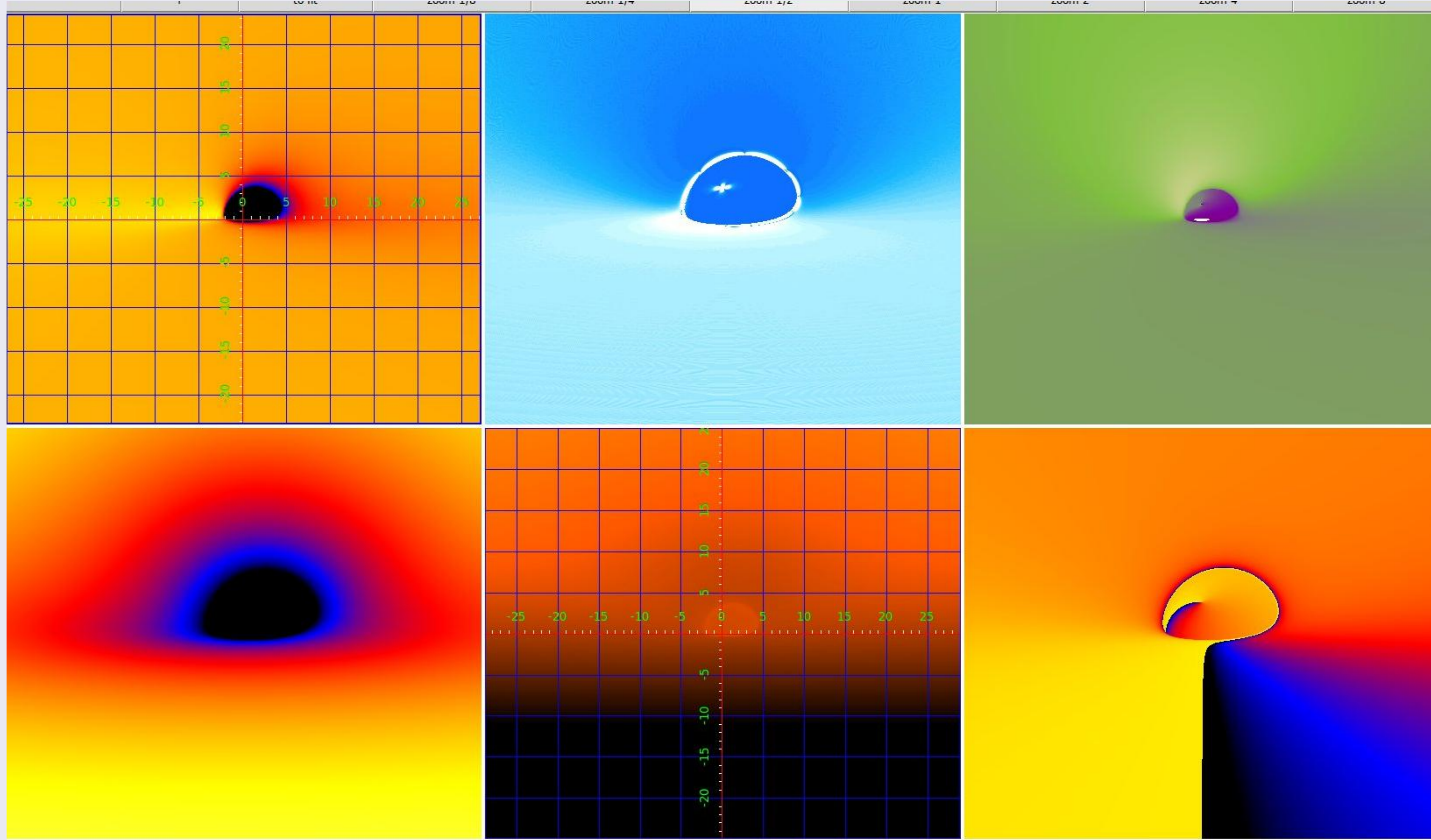
Figure 1 - Edge on Kerr

Figure 1 : Dataset with near-extreme Kerr hole, a = 0.97, edge-on view (89 deg)

Explanation of Figure Panels

Each image (created using *ds9 -multiframe -log file.fits*) represents the values of a different physical quantity as a function of position in the observer image plane:

Redshift g, calculated by integrating the null geodesic	Transfer function value, estimated as product of spacetime effects on emission element (Kerr metric area element) and ray transfer effects (projected pixel area of interpolated geodesics in BL coords)	Geodesic departure cosine μ, (cosine of angle at which geodesic leaves disk)
Boyer-Lindquist radial coordinate of geodesic r,	Boyer-Lindquist coordinate time t from disk to observer plane	BL azimuthal angle coordinate ϕ of geodesic at disk plane.

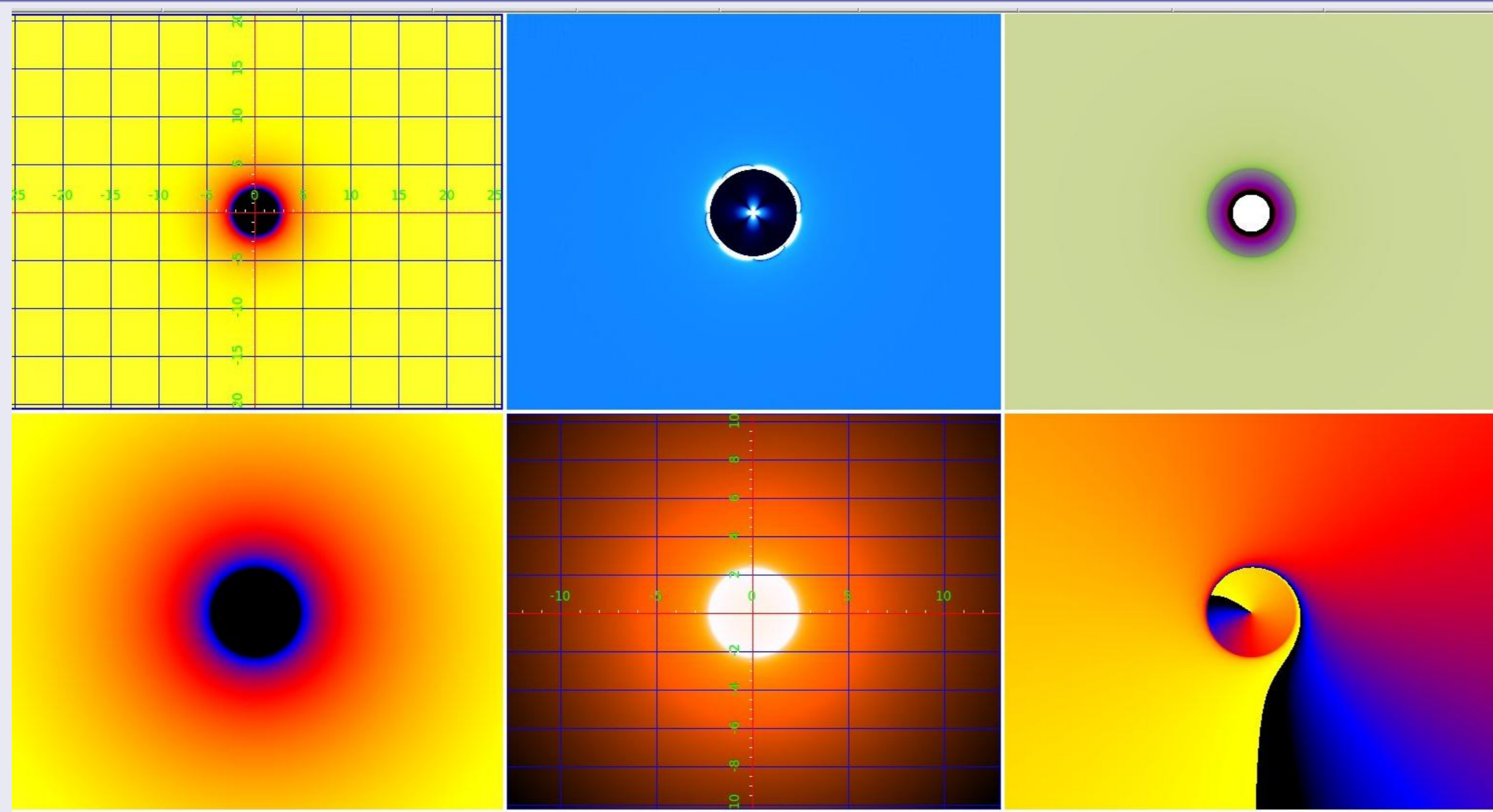## Figure 2 - Transfer Function dataset for face on Kerr example

Figure 2 : Dataset with near extreme Kerr, a=0.97, face on (1 deg)

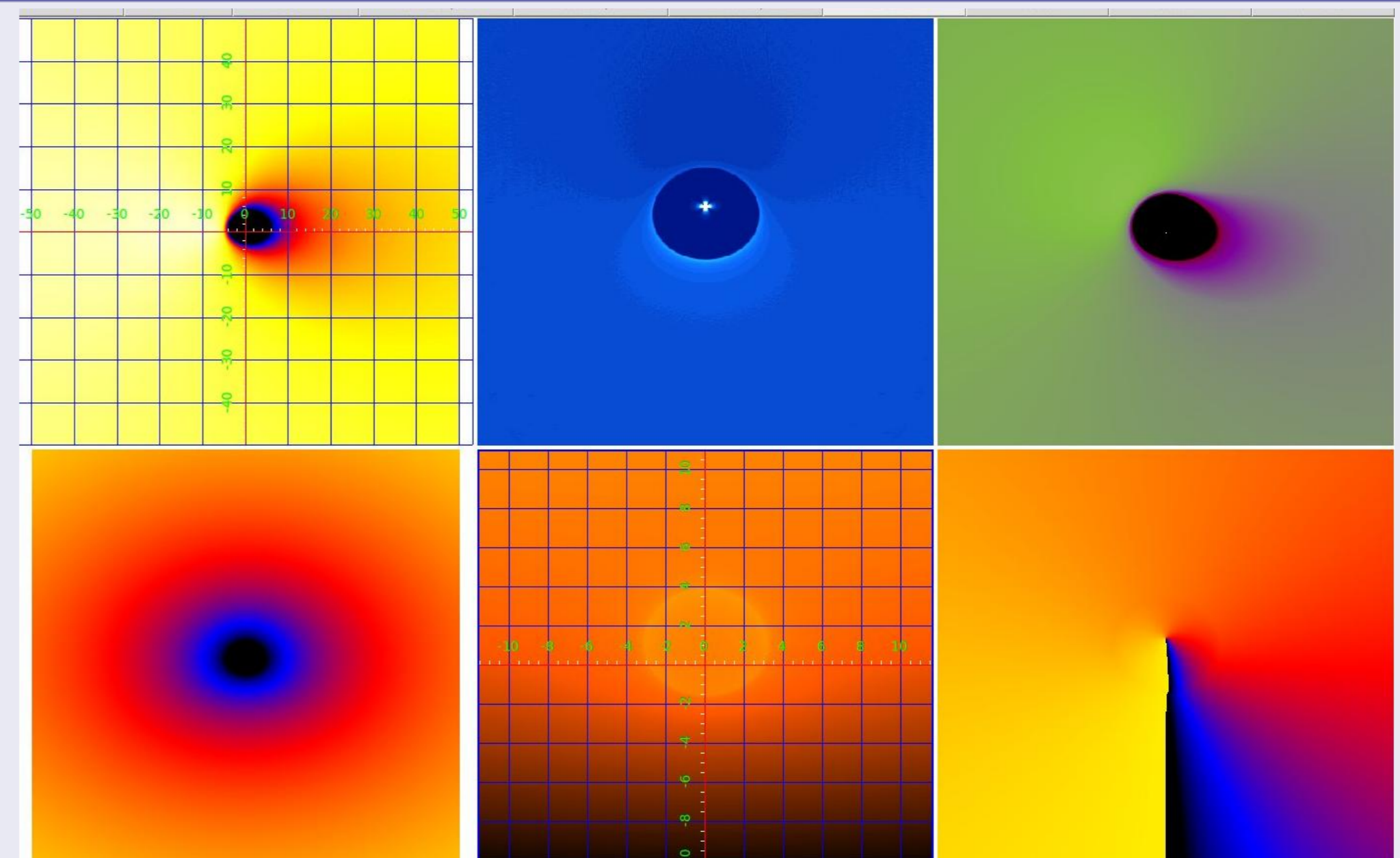## Figure 3 - Low spin example

Figure 3 : Dataset with near-Schwarzchild hole, a = 0.05, 45 degree-on view

Abstract

- We separate the energy-independent physics of black hole geometry from the spectrally complex astrophysics of the accretion disk emission code by precomputing the geometry effects.
- We leverage what we've learned designing Chandra/CIAO data files and analysis systems to define a data format for these precomputed datasets.
- Multiply these files by your emission model - using the precomputed redshift in each pixel - and then sum to get the observed spectrum. Unlike earlier approaches we do not rebin to redshift-radius space at this stage.

Introduction

Data formats for a library of Kerr metric transfer functions

Light rays emerging from an accretion flow around a black hole don't travel in straight lines - they follow *null geodesics* in the Kerr metric. To calculate the spectrum of emission seen by a distant observer at a given apparent position in the sky we must track these geodesics back to their origin in the flow (e.g. the accretion disk) and correct for both redshift and lensing (compression or expansion of the geodesics). The flux correction factor from the space (coordinate system) in which the light is emitted to that in which it is observed is called the *transfer function* (Cunningham 1975, ApJ 202, 788). (Warning: different authors have used different definitions of this function).

- As part of a project to model time-resolved X-ray obscuration in AGN, we have reimplemented and improved the Reynolds et al. (1999, ApJ 514, 164) code
- We calculate spatially resolved transfer functions which give the redshift and projected orientation of an accretion disk element in the observer frame. These can be used for integration over either spectral or spatial source models.
- We define a multi-extension FITS image array format which contains the computed transfer function for a given value of observation angle and black hole spin parameter. Each extension contains an image, in observer plane coordinates, of a different physical quantity: redshift, transfer function value, direction cosine, geodesic coordinates, etc. This allows us to build up a library of transfer function files for different observation angles.
- Use of the FITS format allows us to record the associated model parameters and coordinate systems in a standard way and to visualize the results using standard analysis tools such as ds9 (Joye and Mandel 2005, ADASS XIV, 110).

Advantages of the multi-image FITS representation

- Separate computation of transfer functions from specific end use (e.g. disk model)
- Standardize product to make it easy to share results among and between researchers
- FITS allows header keywords so the file is 'self-documenting' - can give details of parameters associated with the computation.
- FITS coordinate systems accurately record system and units of computation
- Standard analysis tools (e.g. ds9) exist to visualize the file, allowing deeper insight into the results. Although the screen captures don't show this, in the ds9 images shown, function values and coordinates for the current cursor position appear in the window.
- The visualization is helpful to reveal bugs and numerical artifacts - for example, the spurious cross-shaped structure at the center of the TF is a numerical artifact (but does not affect our spectral application since the disk is not emitting there).
- The current code uses numerical integration of geodesics as in Reynolds et al. (1999). But the format is equally suitable for analytic work using elliptic integrals as advocated by Beckwith and Done 2004 (MNRAS 359,1217; Prog. ThPhys. 155, 259).

Technical details

- 'Multiextension FITS Image' file has 6 FITS image extensions, with transfer functions for one choice of a,α
- Example files are 168M; each image is 2000 x 2000 pixels
- Each example image covers the coordinates -50 to +50 R_g (gravitational radii) with 0.05 R_g pixels (the FITS WCS allows users of the files to determine this)
- Header keys: model parameters KERR_A, TF_ALPHA (deg); useful values KERR_RMS, KERR_RH (marginal stability and horizon radii).

Previous similar work

Previous attempts to use FITS files to record transfer functions are to our knowledge only documented implicitly by their use in the XSPEC source code. The Laor model (Laor 1991, Ap J 376, 90) for an a=0.998 extreme Kerr hole is implemented in XSPEC (Arnaud 1996, ADASS 17, 101) using coarsely tabulated azmiuthally-averaged transfer functions for a set of 31 angles in a multiextension FITS binary table file. The RELLINE model (Dauser et al. 2010, MNRAS 409, 1534) gives 600 choices of (a,cos theta), each of which gives TF and geodesic cosine values in a 100 x 20 radii vs redshift array. We have also defined a version of our image format to accomodate these integrated transfer functions and plan to carry out crosschecks with the RELLINE results.
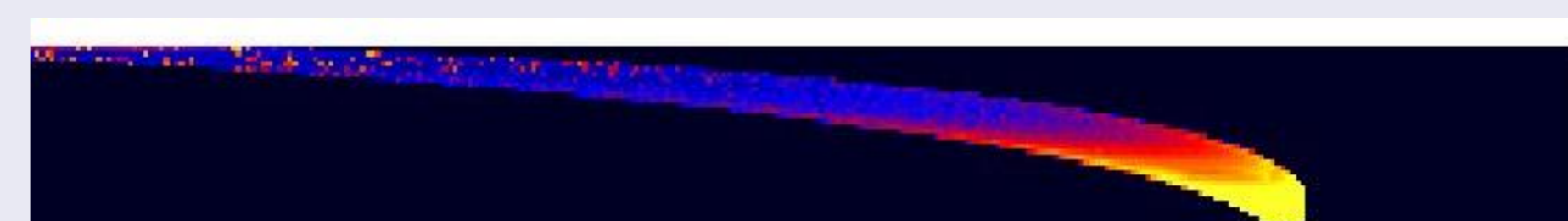

Figure 4 : Example integrated transfer function for a=0.998, theta = 25 deg. X-axis is redshift, Y-axis is emission radius.

Acknowledgments