Fundamentals of X-ray Spectroscopy

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Outline

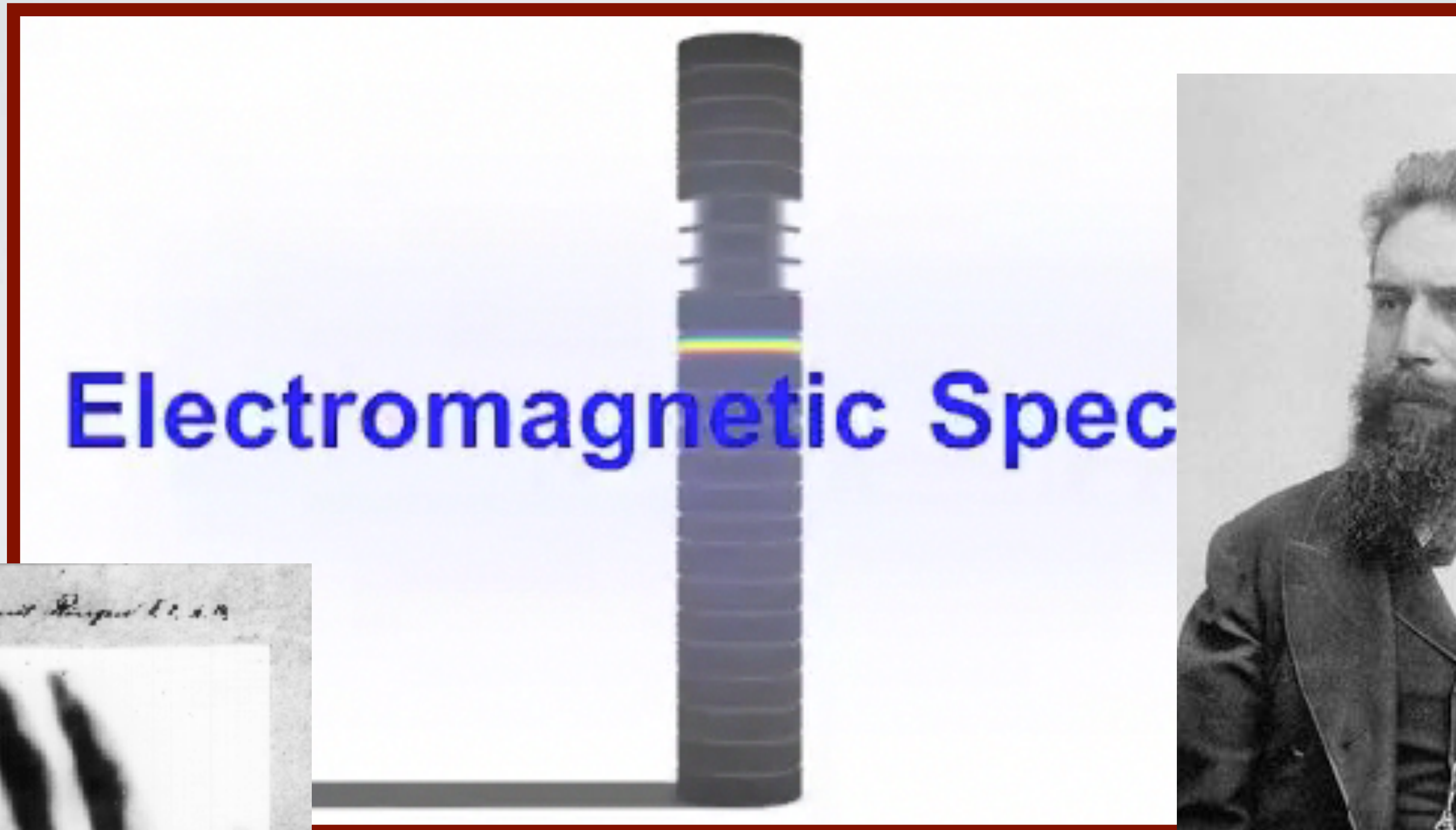
- Introduction to X-rays
- Fundamentals of X-ray production
- The Fe K line in AGN
- Modeling reflection with/without GR
- Reflexion in Black Hole Binaries
- Reflexion in other sources
- Related Topics

What are X-rays?

High Energy Photons
E = 0.1 -- 200 keV
Wavelength = 0.1 -- 100 Å
T = 10^6 -- 10^{10} K

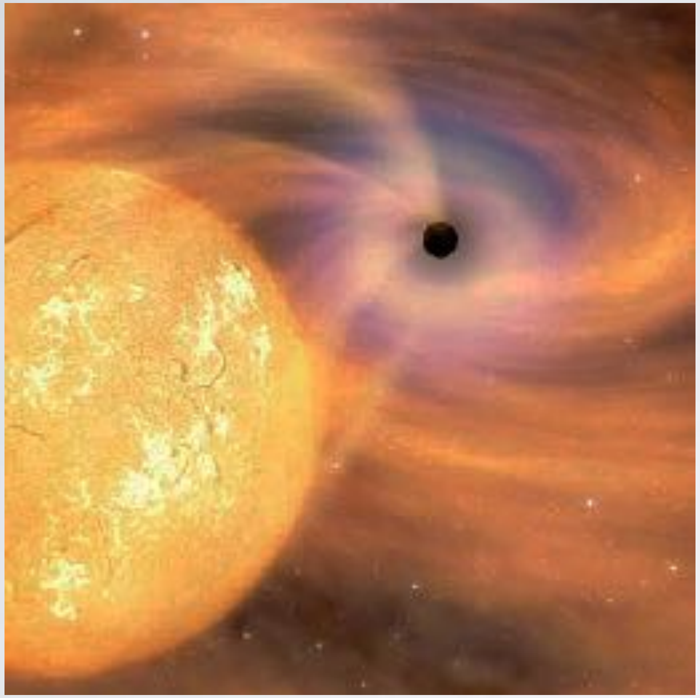
We can see:
Very high temperature
Non-thermal particle acceleration
Atomic Processes

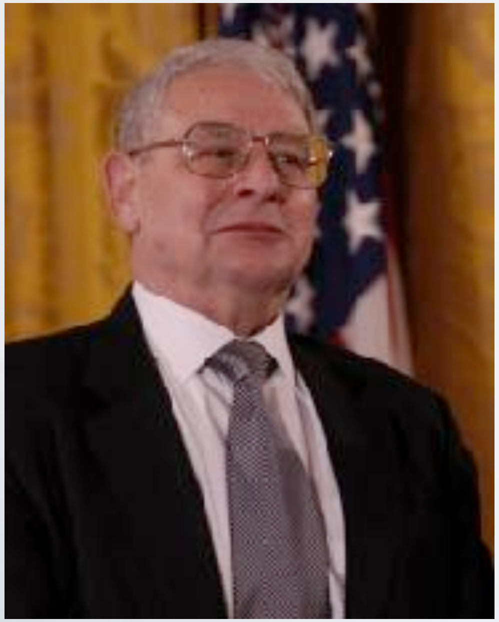
Discovery of X-rays



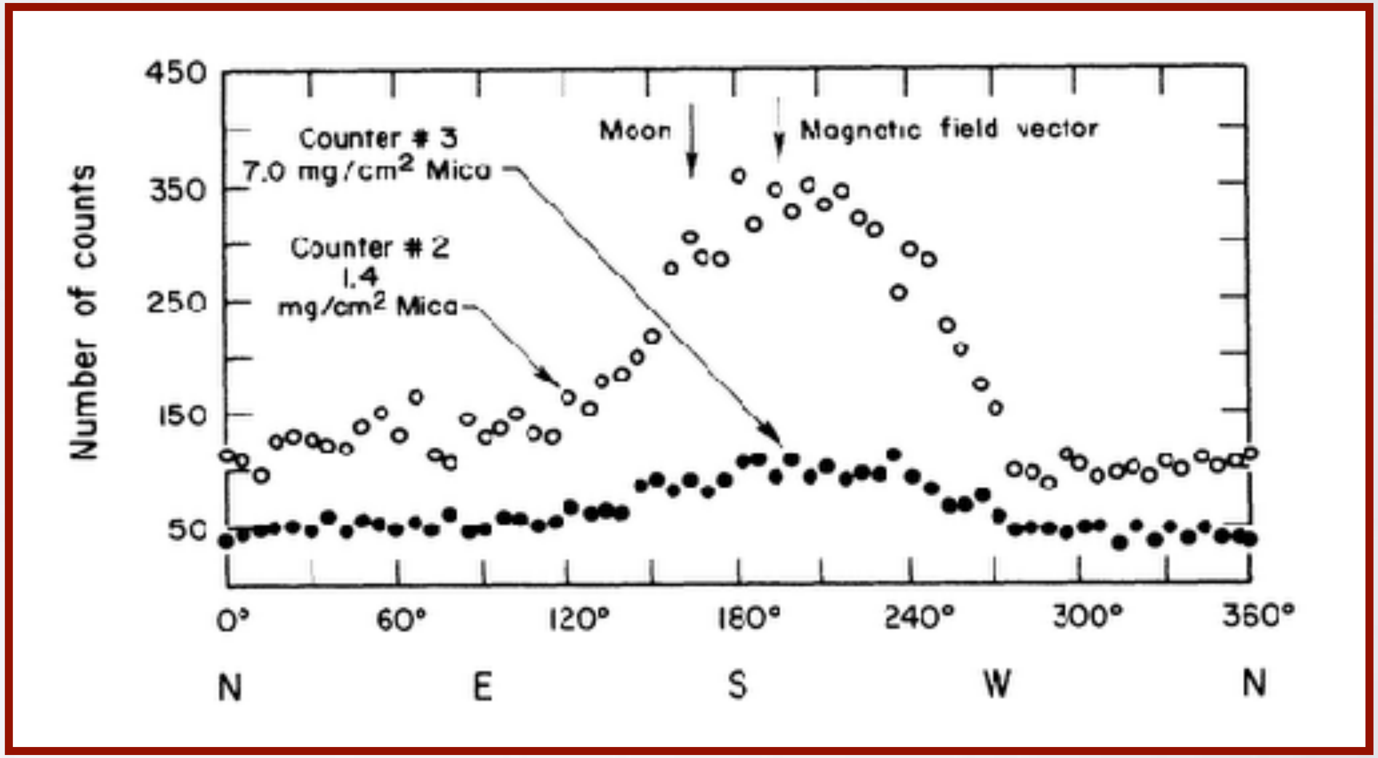
Wilhelm Röntgen's first "medical" X-ray,
of his wife's hand, taken on 22 December 1895

X-rays in Astronomy



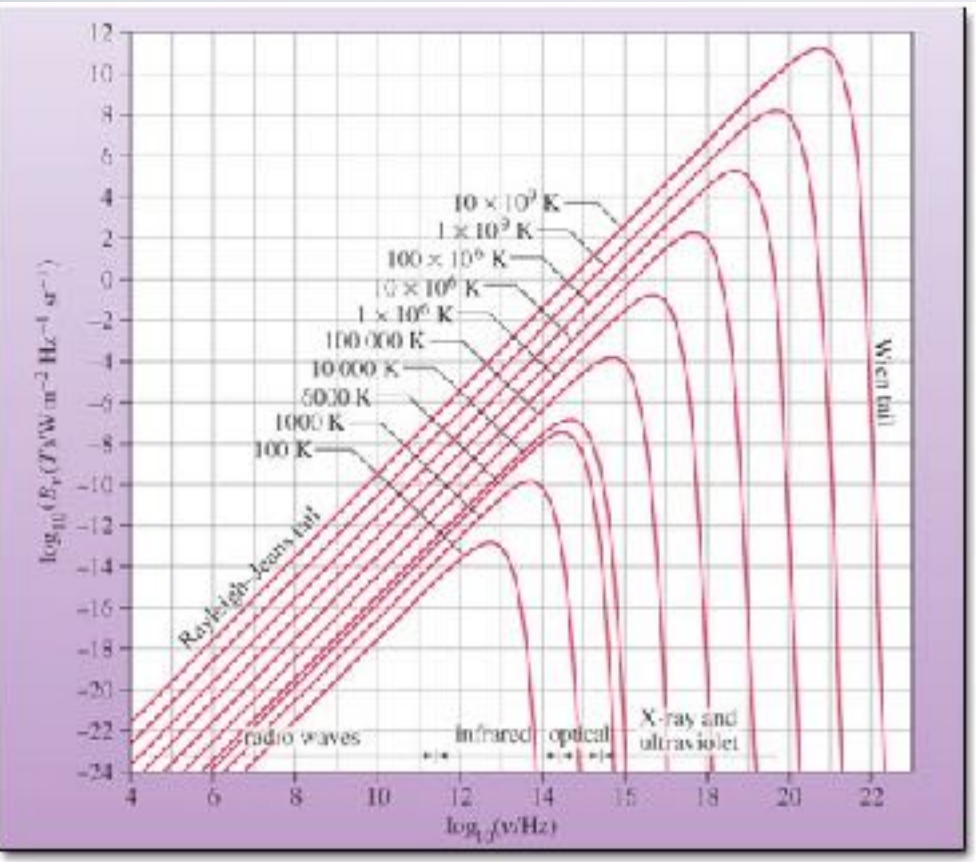


Sco X-1 - First X-ray source detected

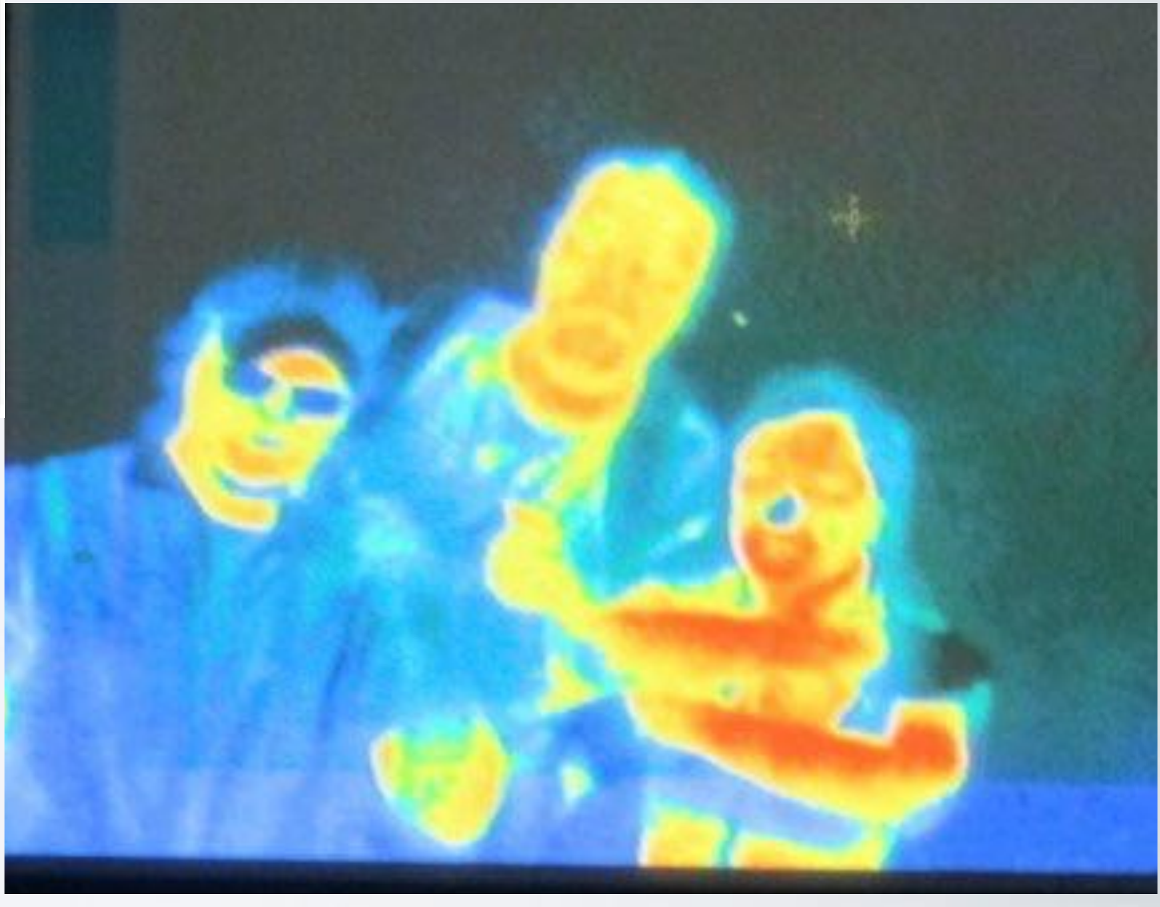


Number of counts versus azimuth angle
(Giacconi et al. 1962)

Temperature and Radiation

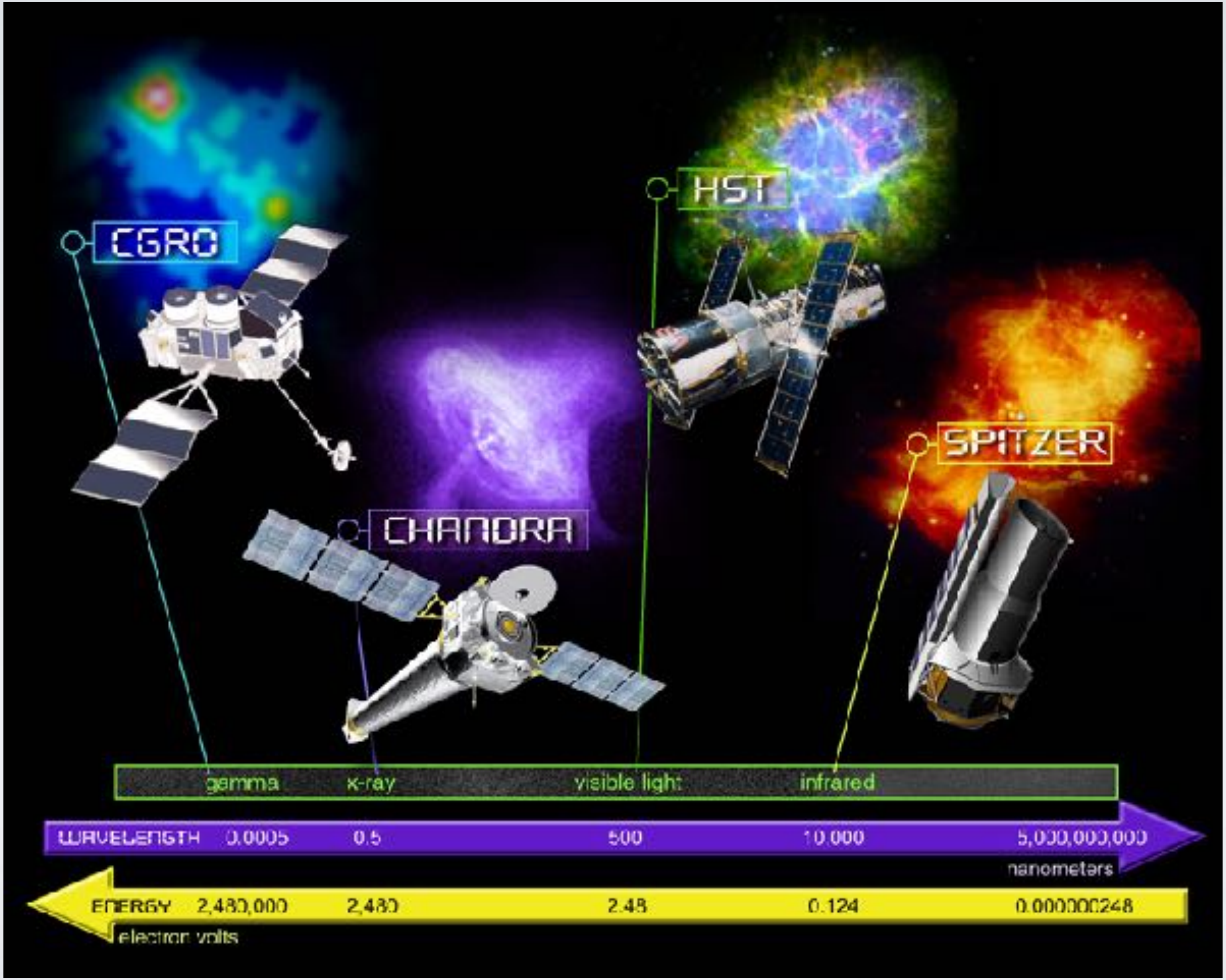


Planck's Function

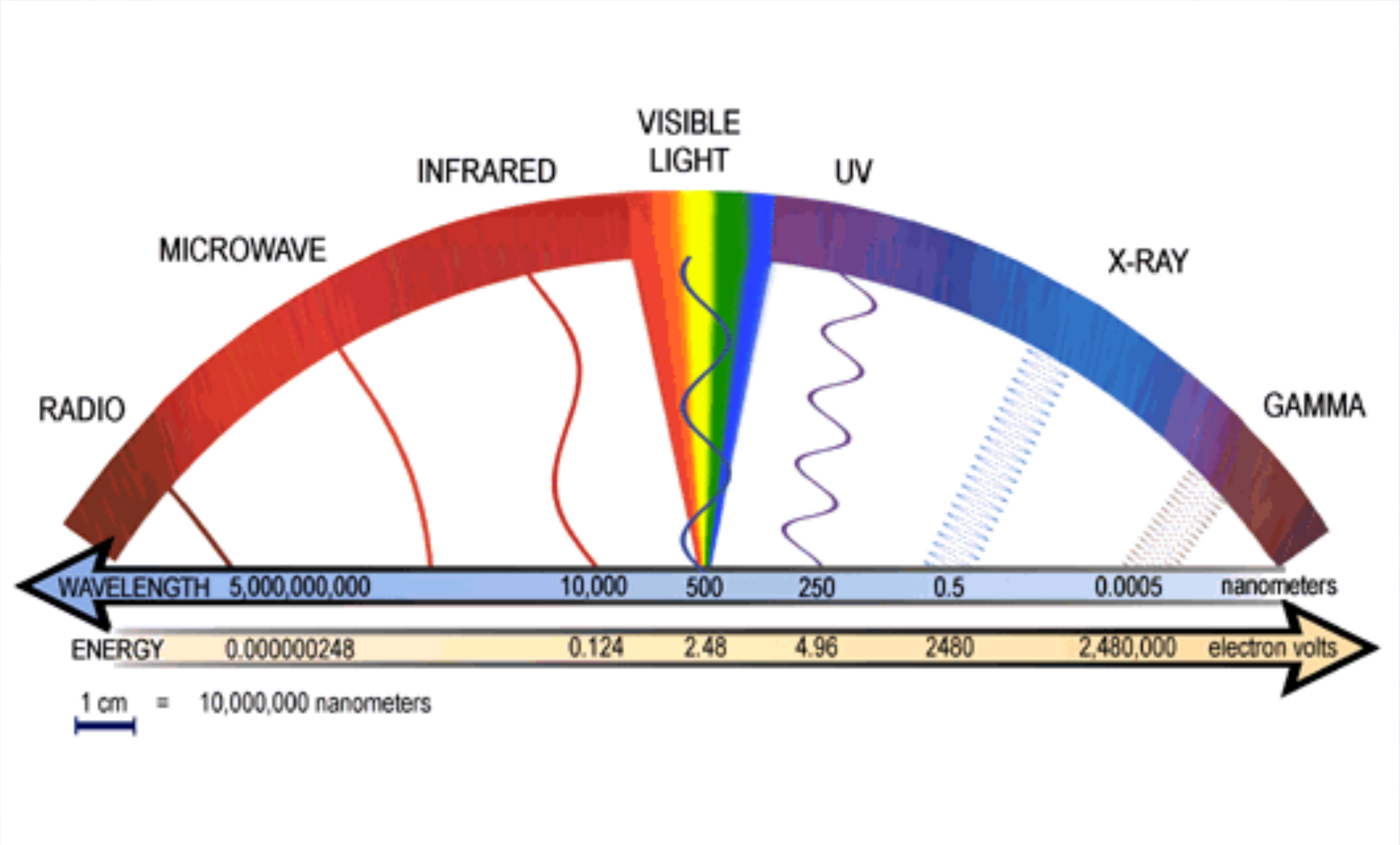


Omar, Javier and Margarita at the Aerospace museum.

Why to Study X-rays?



Why to Study X-rays?



Why to Study X-rays?

Why to Study X-rays?

X-RAY FOCUSING

Requires:

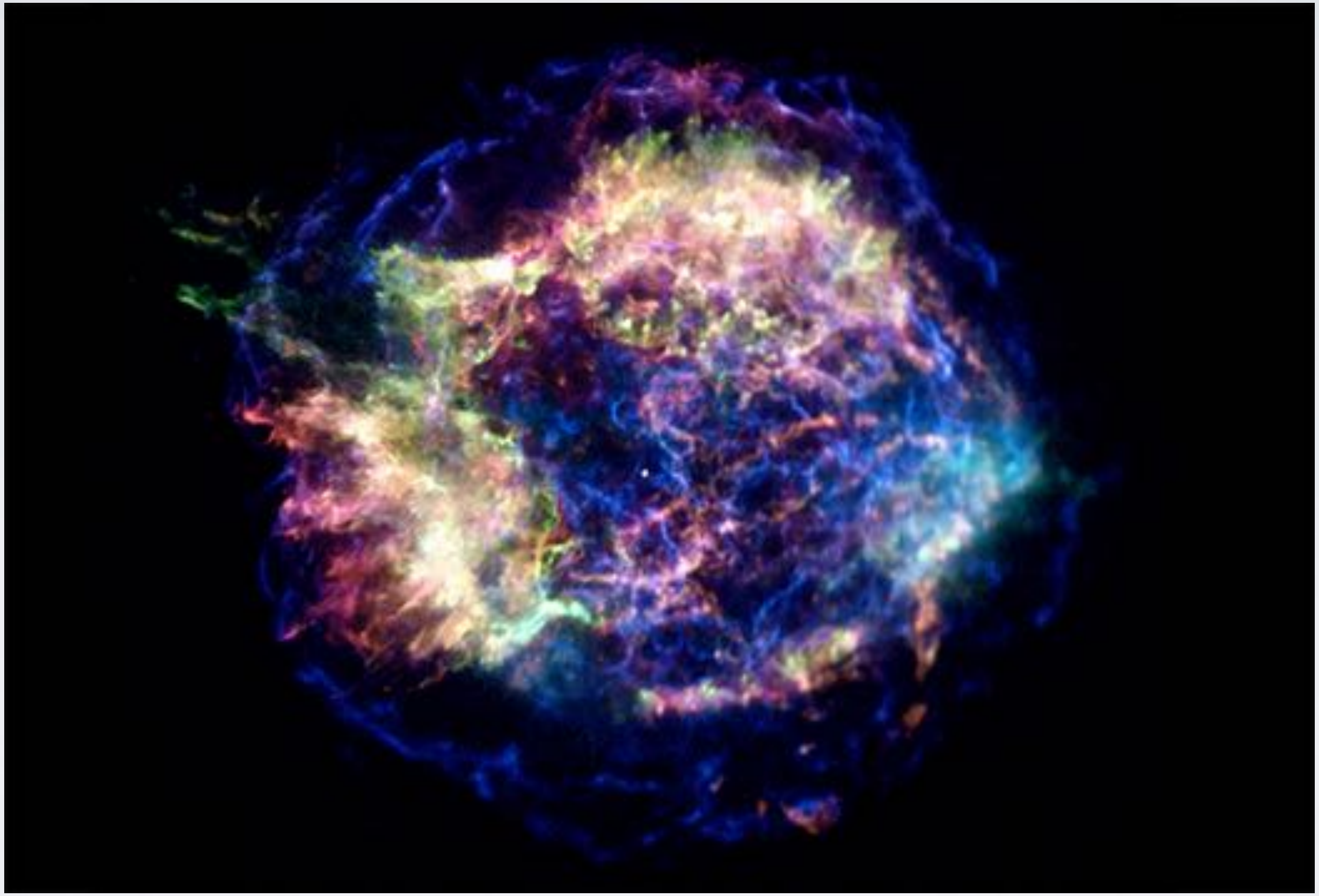
1. Angle of reflection small related to surface (**grazing incidence**)
   - ~1° for 1 keV
2. Highly **polished surface**
   - surface roughness of ~few Å

Slide courtesy of P. Boorman

Supernova remanent Cassiopeia A

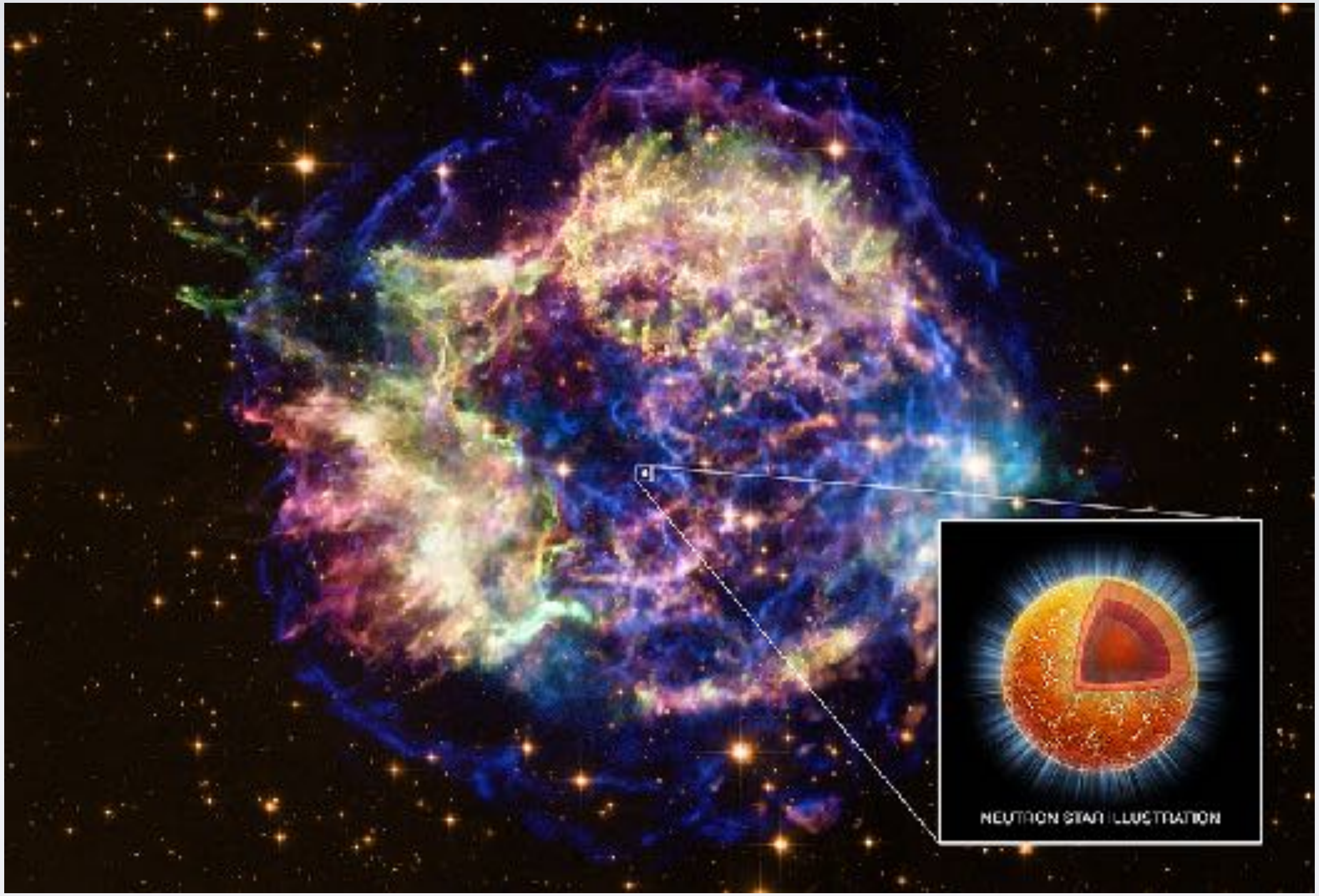
Optical

Supernova remanent Cassiopeia A



X-Ray

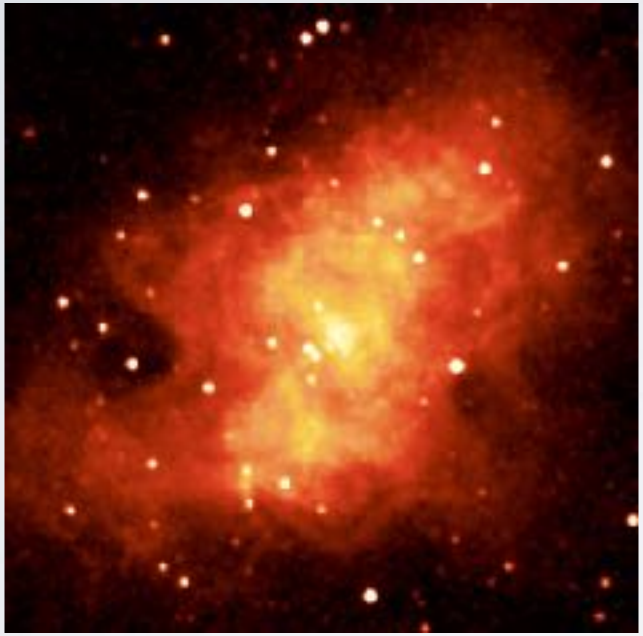
Supernova remanent Cassiopeia A



Optical + X-ray

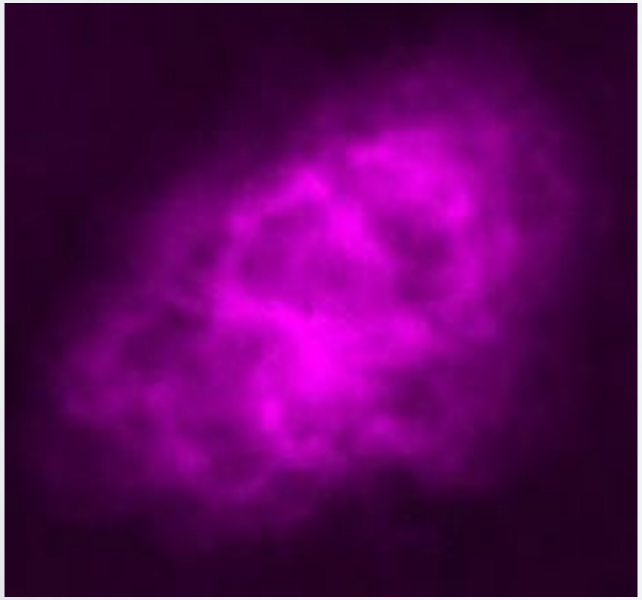
The Crab Nebula

Infrared

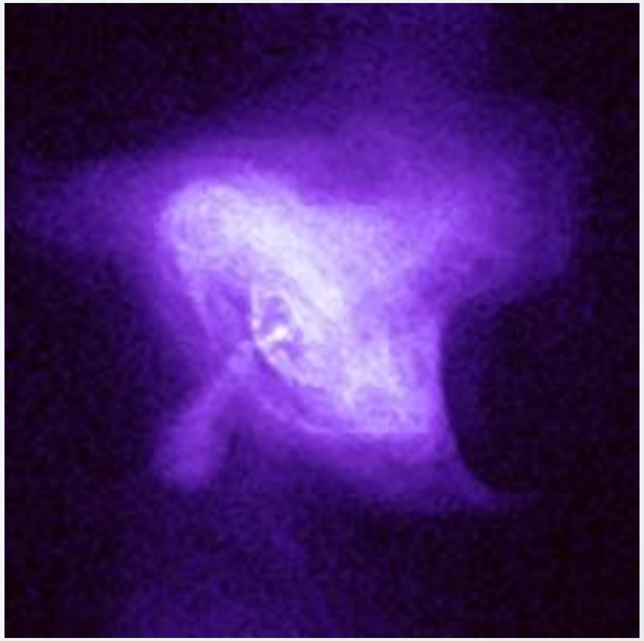


Visible

Radio



X-rays

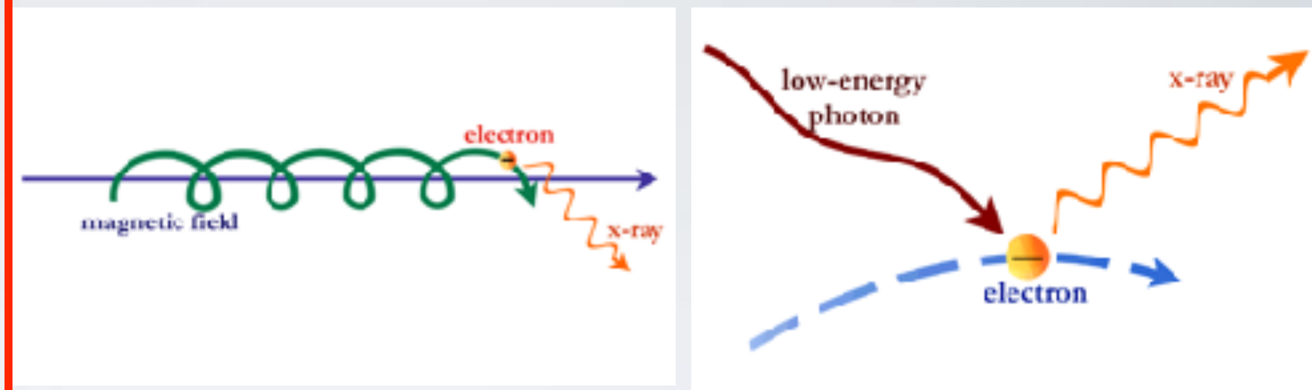


X-ray Emission Mechanisms

Continuum

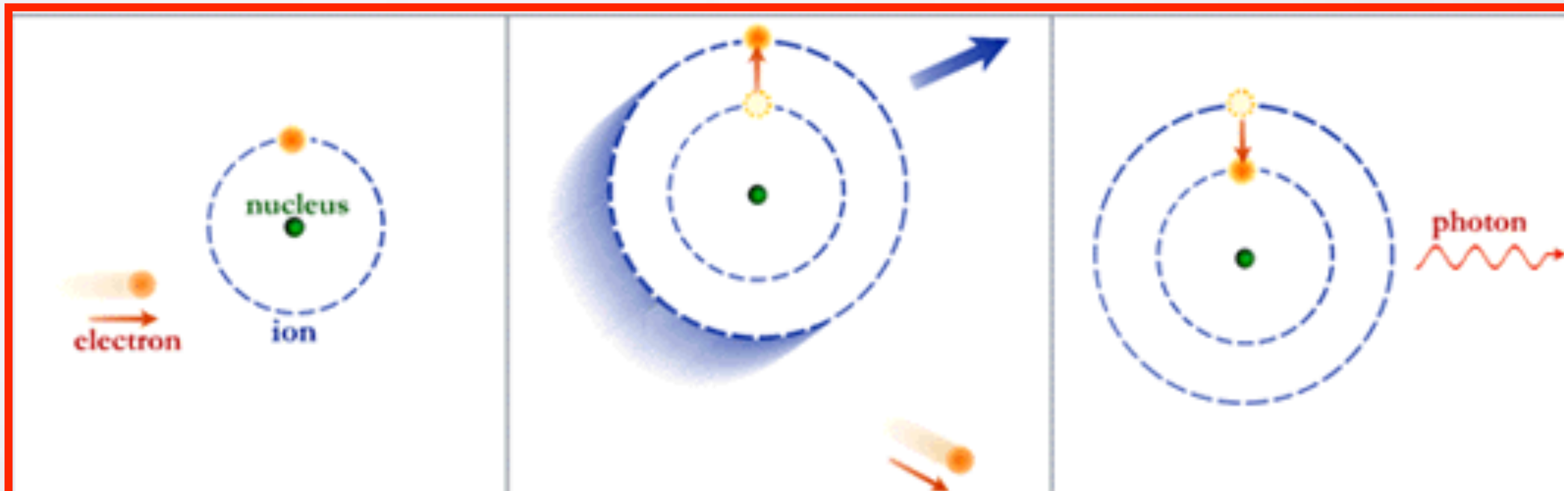
Black-Body
Bremsstrahlung (free-free)

Cyclotron & Synchrotron
Inverse Compton Scattering



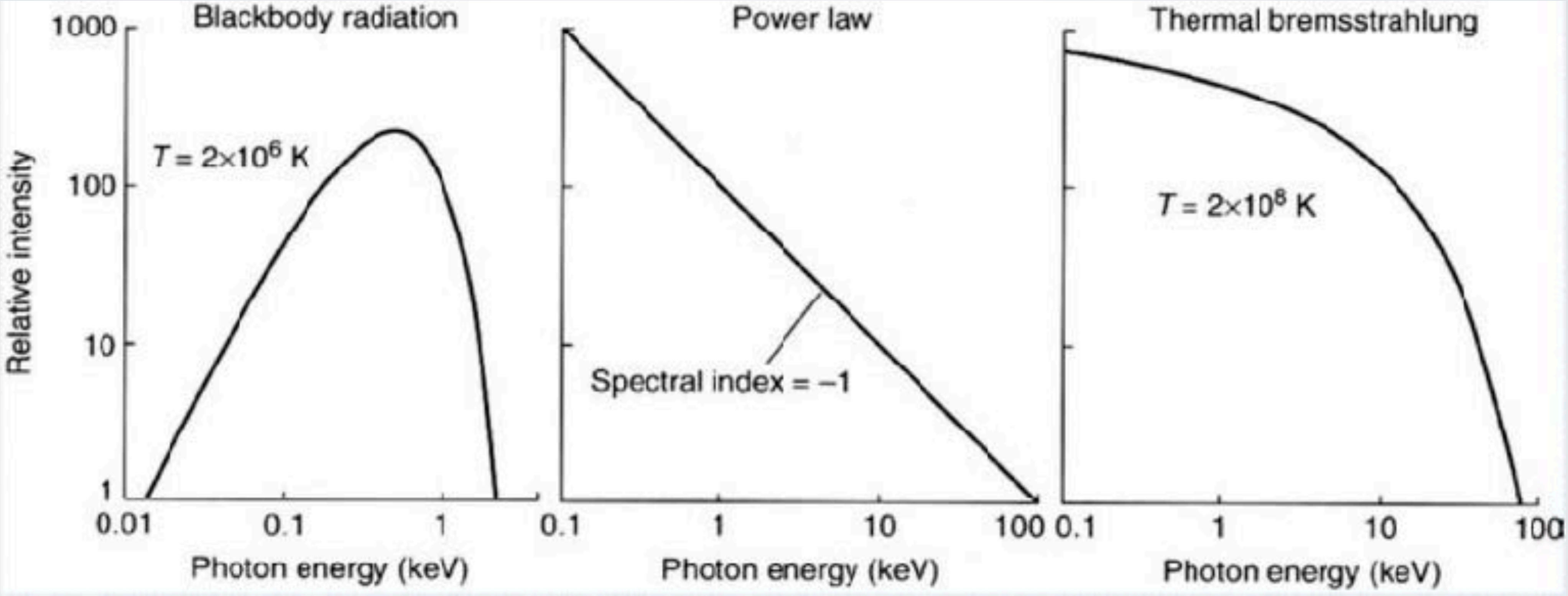
Lines

Bound-Bound
Fluorescence
Charge Exchange
Cyclotron
Exotic Physics (?)



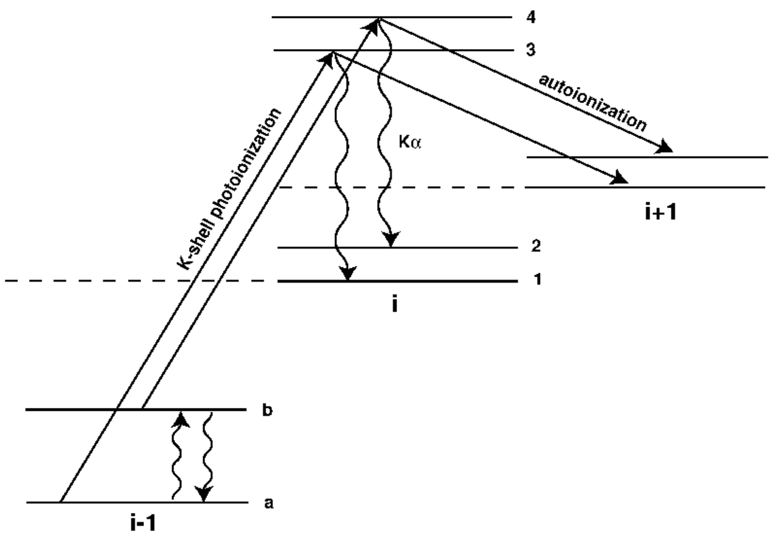
X-ray Emission Mechanisms

Continuum



X-ray Emission Mechanisms

Lines

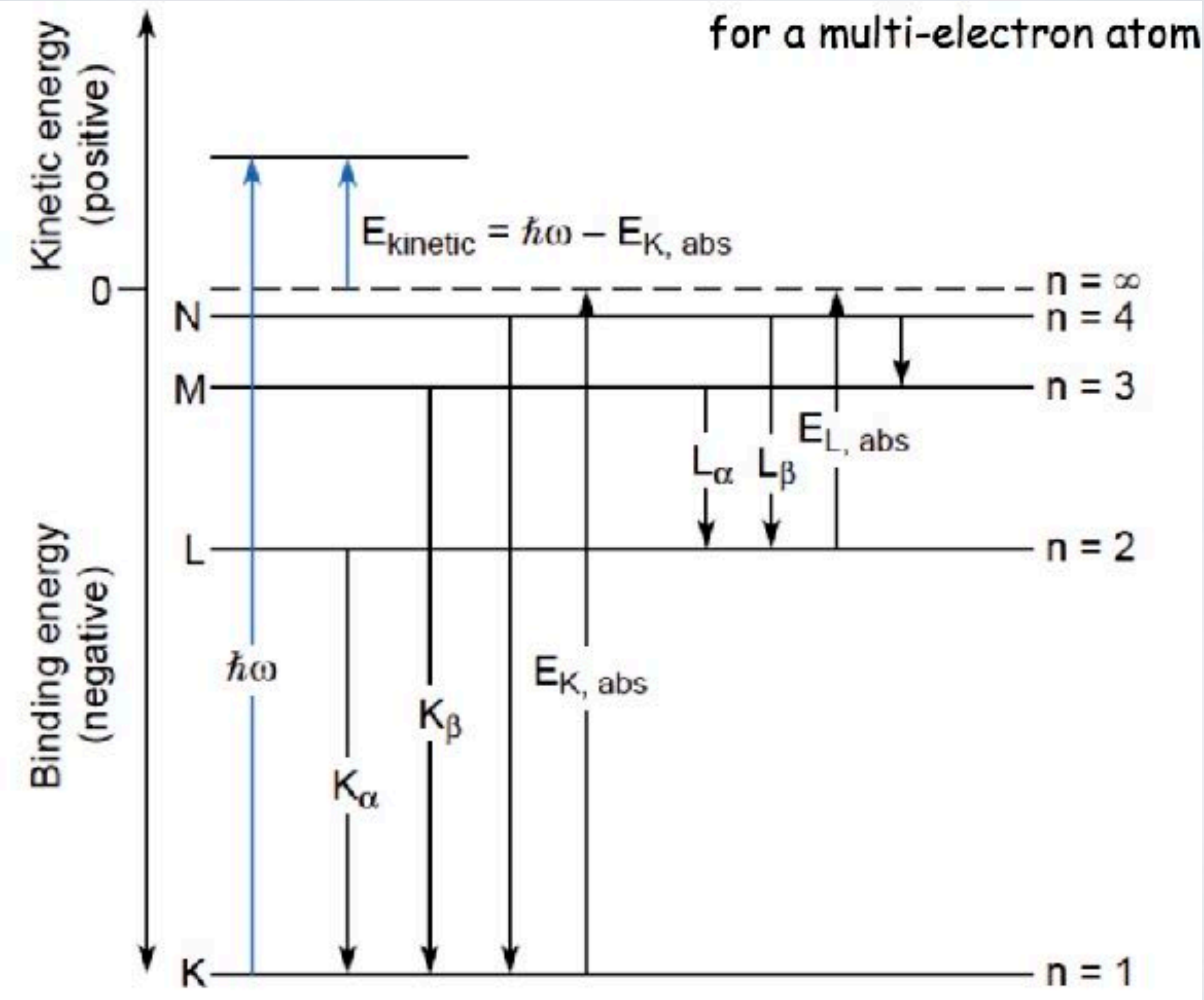


Liedahl+Torres05

The X-ray band ($\sim 0.1 - 10$ keV) covers the emission and absorption produced by the inner-shell transitions of the astrophysically abundant ions (C $\rightarrow$ Ni).

- **Line positions** provide information about the gas composition (identification), as well as about its dynamics (redshifts, gas outflows)
- **Line intensities** provide information about the column of the absorbing material (including ions), constrains on the ionization degree of the gas ($\xi = L/nR^2$), temperature and density
- **Line shapes** provide information about the thermal and turbulent motions of the gas, and can also probe relativistic effects near strong gravitational fields

X-ray Emission Lines



Astrophysical Plasmas

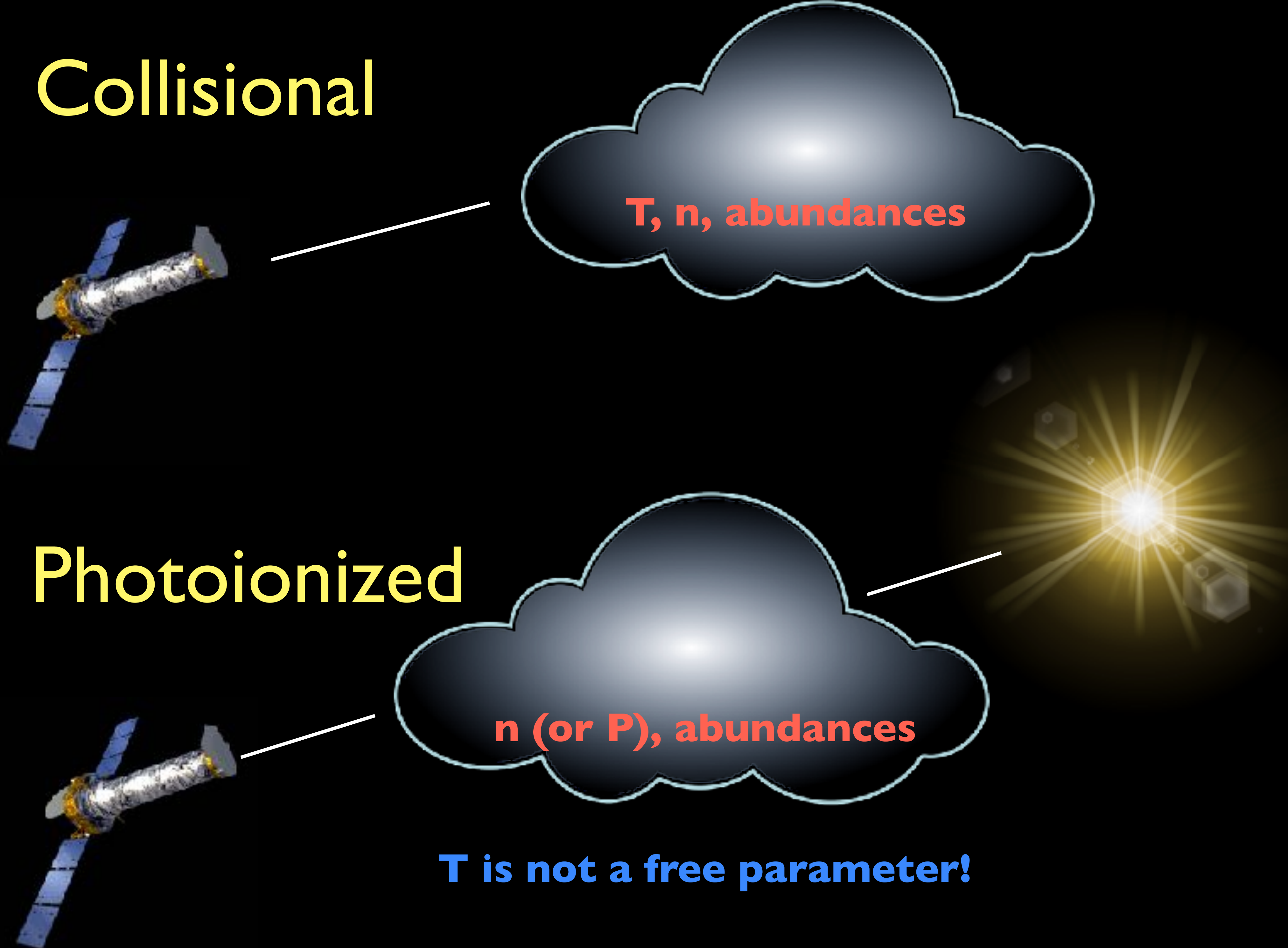
In general, there are two types of X-ray emitting plasmas

Collisional:

kT ~ Ionization energy of the ions in the plasma

Photoionized:

kT << Ionization energy of the ions in the plasma


Collisional
T, n, abundances
Photoionized
n (or P), abundances
T is not a free parameter!

Collisional Plasmas

kT ~ Ionization energy of the ions in the plasma

Collisional Radiative:

$$Ne = 10^{14} - 10^{27}\ \mathrm{cm}^{-3}$$

Collisions compete with photons in de-exciting levels. A level with a small A value may be collisionally de-excited before it can radiate

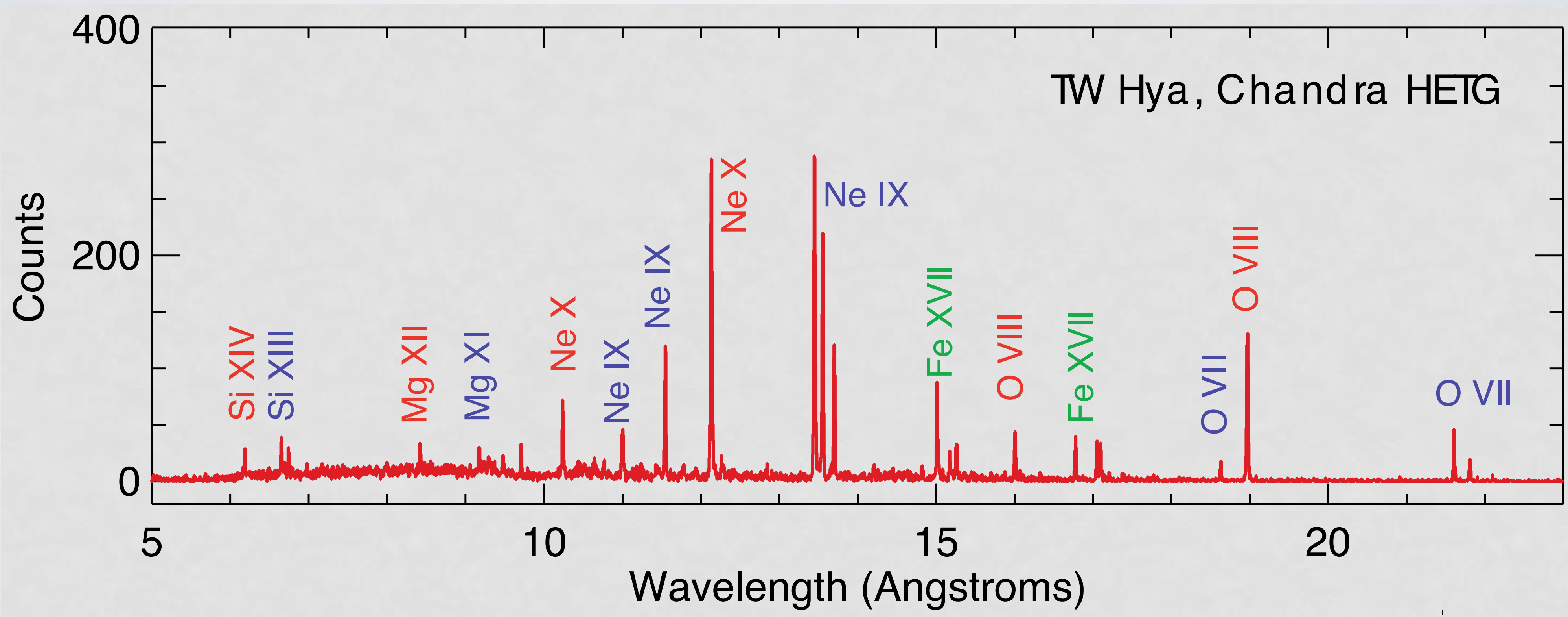
Coronal/Nebular:

$$Ne < 10^{14} - 10^{16}\ \mathrm{cm}^{-3}$$

In a Coronal plasma, collisions excite ions but are too rare to de-excite them; decays are purely radiative. This is also called the “ground- state” approximation, as all ions are assumed to be in the ground-state when collisions occur.

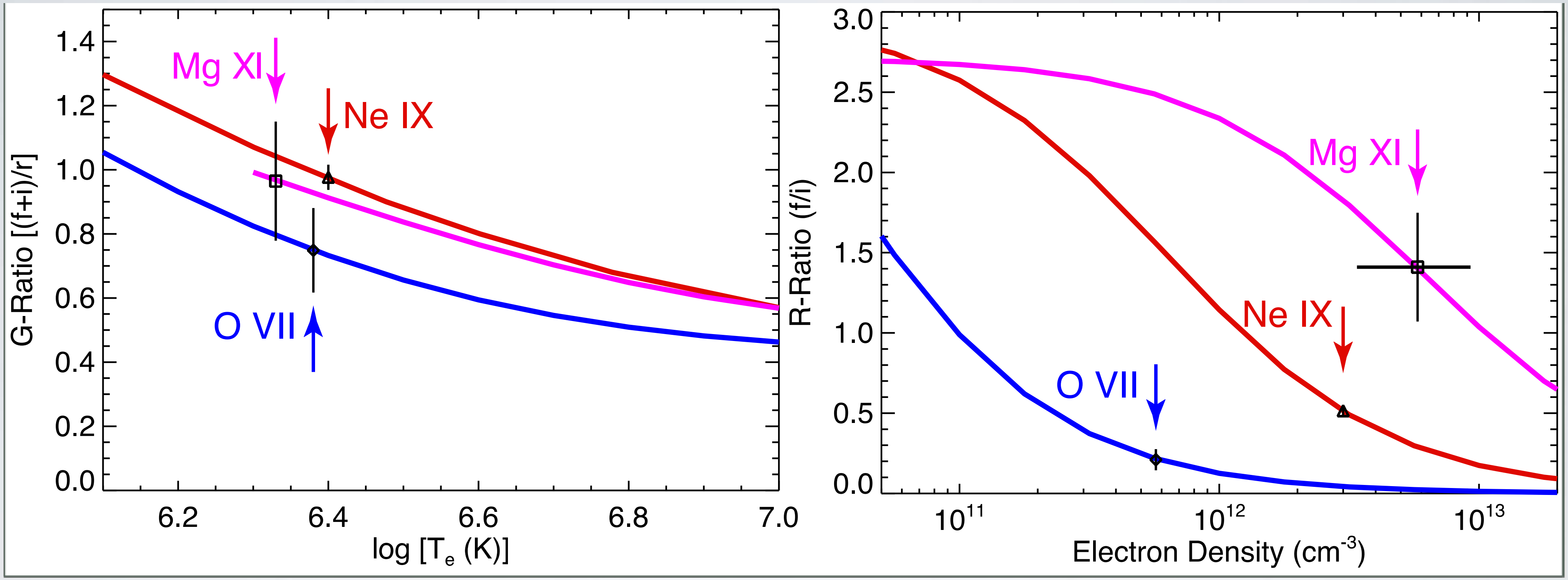
Collisional Plasmas

HETG ~500 ks Chandra observation of the accreting young star TW Hydrae (Brickhouse et al 2010)



Spectrum dominated by H- and He-like emission lines

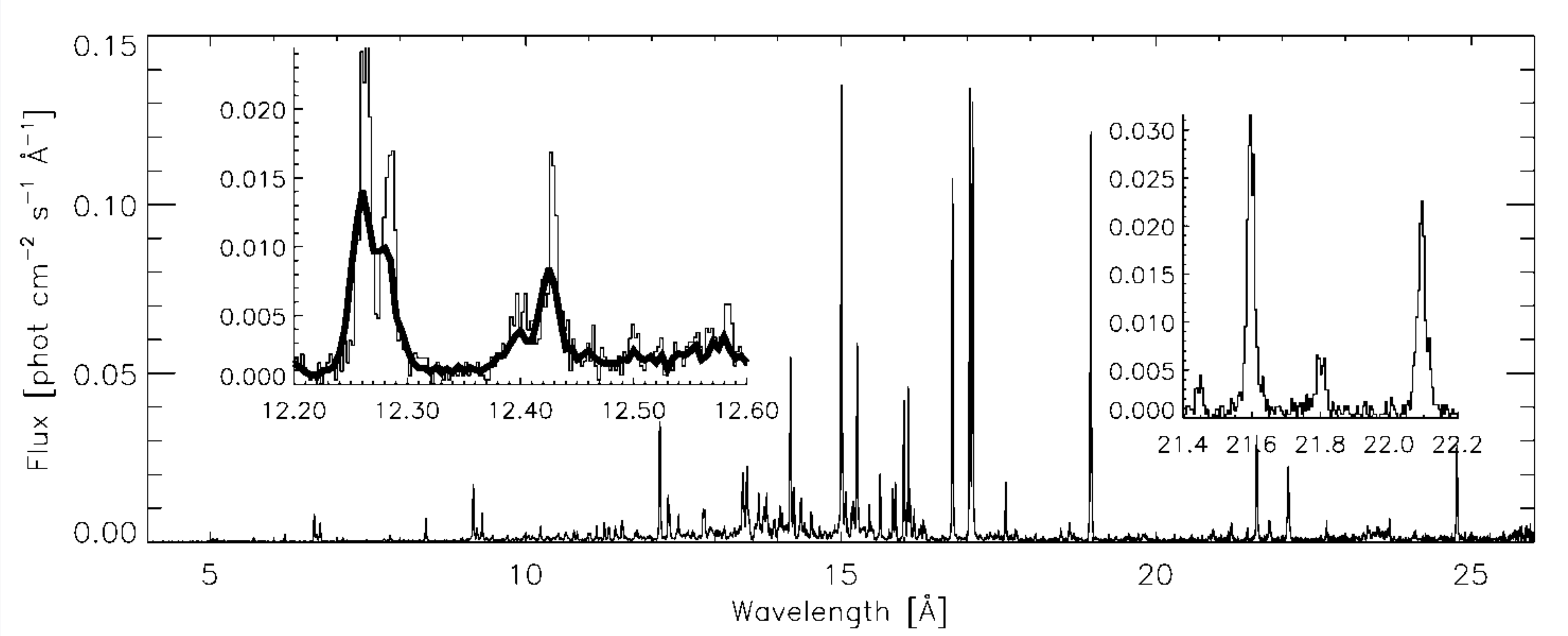
Collisional Plasmas



While the temperature diagnostics for Mg XI, Ne IX, and O VII all give roughly the same result, the density diagnostics are quite different, especially for O VII, leading to the primary result.

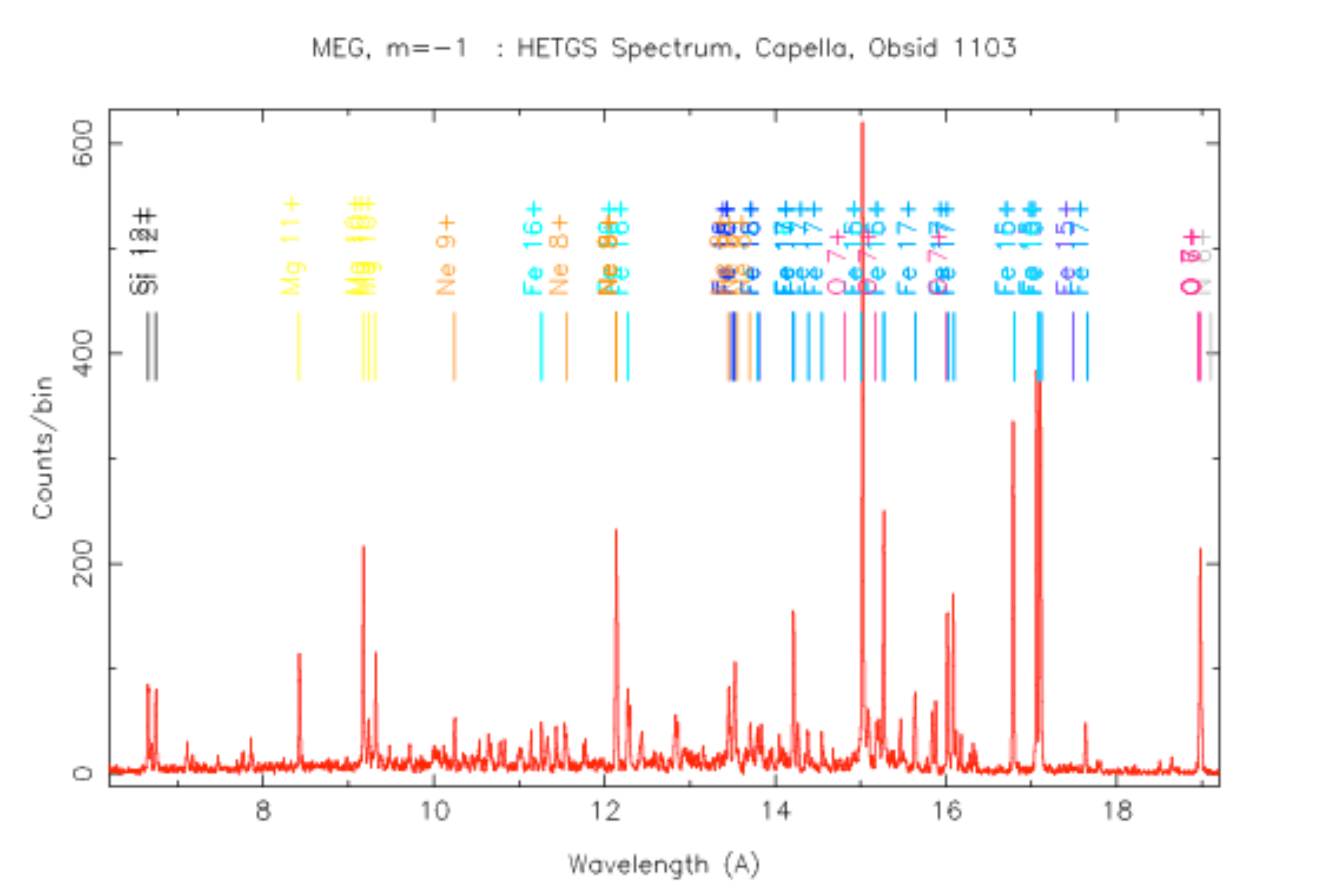
Coronal Plasmas

Capella: Active binary system (G1 and G8 giants) with a rich spectrum of X-ray emission lines



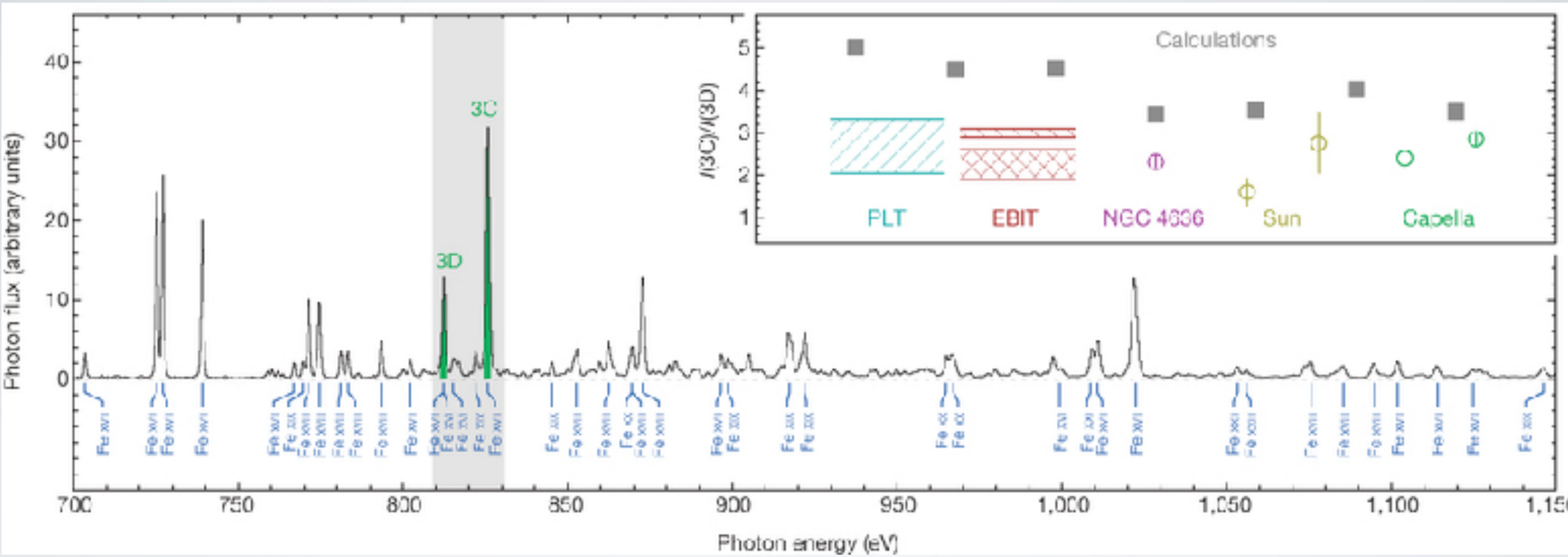
89 ksec Chandra HETG (Canizares et al. 2000)

X-ray Emission from Capella



http://cxc.harvard.edu

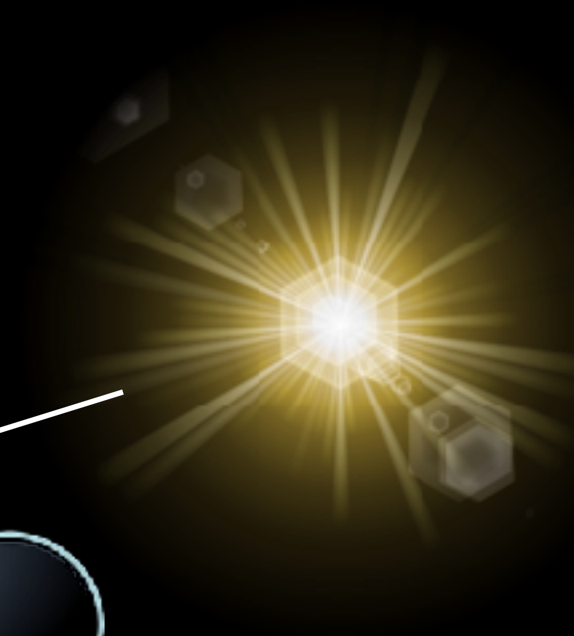
Coronal Lines Testing Atomic Data



An unexpectedly low oscillator strength compared to the theoretical calculations has been proposed as the origin of the Fe XVII emission problem (Bernitt et al. 2012)

Collisional

T, n, abundances



Photoionized

n (or P), abundances

T is not a free parameter!

Photoionized Plasmas

- Photoionization of plasmas occurs when an external source of radiation illuminates a relatively cold material
- Incident photons excite and/or ionize atoms in the gas
- The gas is heated by photo-absorption or scattering of photons by cold electrons
- Cooling is achieved by both continuum and line emission
- In a photoionized gas, equilibrium is reached at a particular temperature where heating balances cooling

Therefore, the gas temperature needs to be calculated self-consistently, and the ionization balance is determined by the strength and shape of the incident radiation (for a given density or pressure)

Photoionized Plasmas

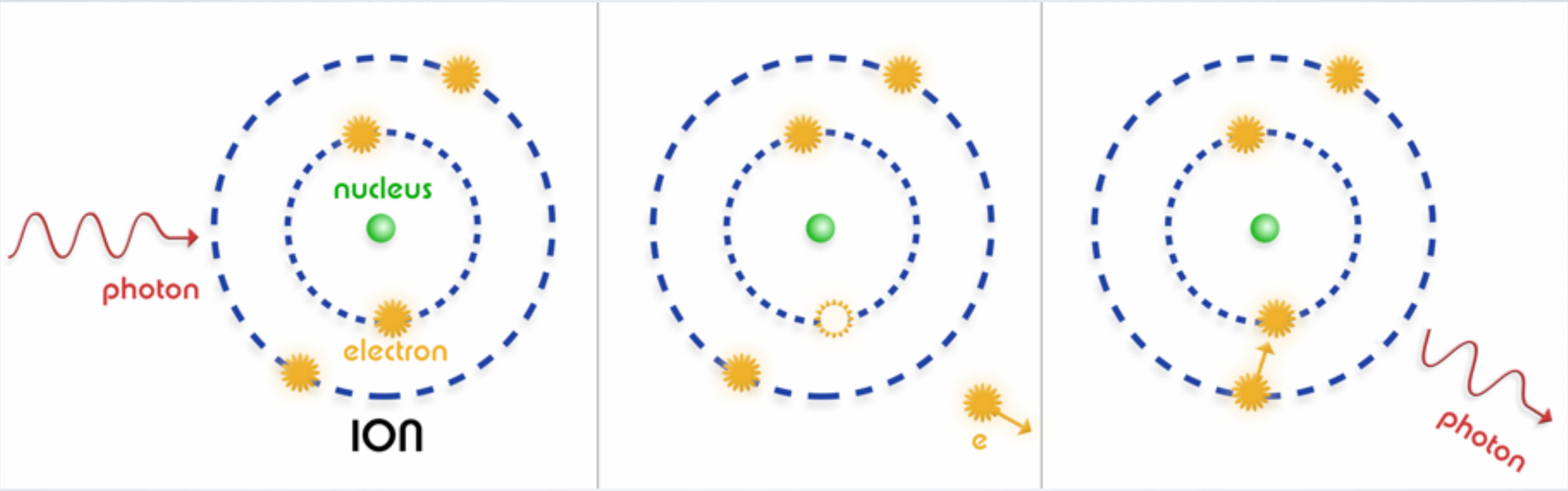
• Ionization balance allows for the possibility of different ionic species to co-exist with similar abundances

• Complex emergent spectrum:

- Absorption: continuous (photoelectric); discrete (lines, resonances and edges)
- Emission: continuous (thermal black-body, bremsstrahlung); discrete (fluorescence lines, radiative recombination continua)

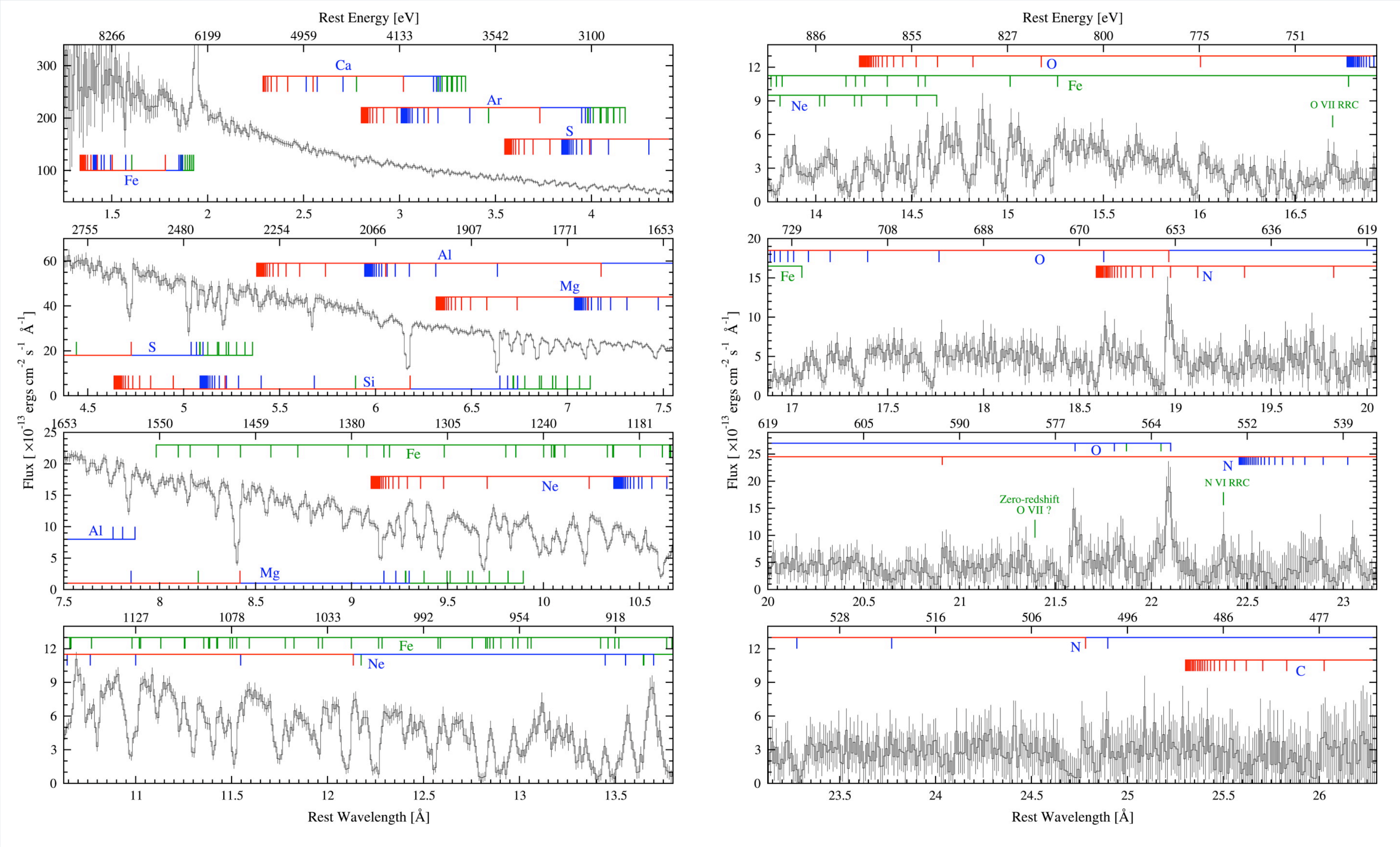
• **Inner-shell** ionization and fluorescence emission particularly important for X-ray astrophysics

K-shell Fluorescence



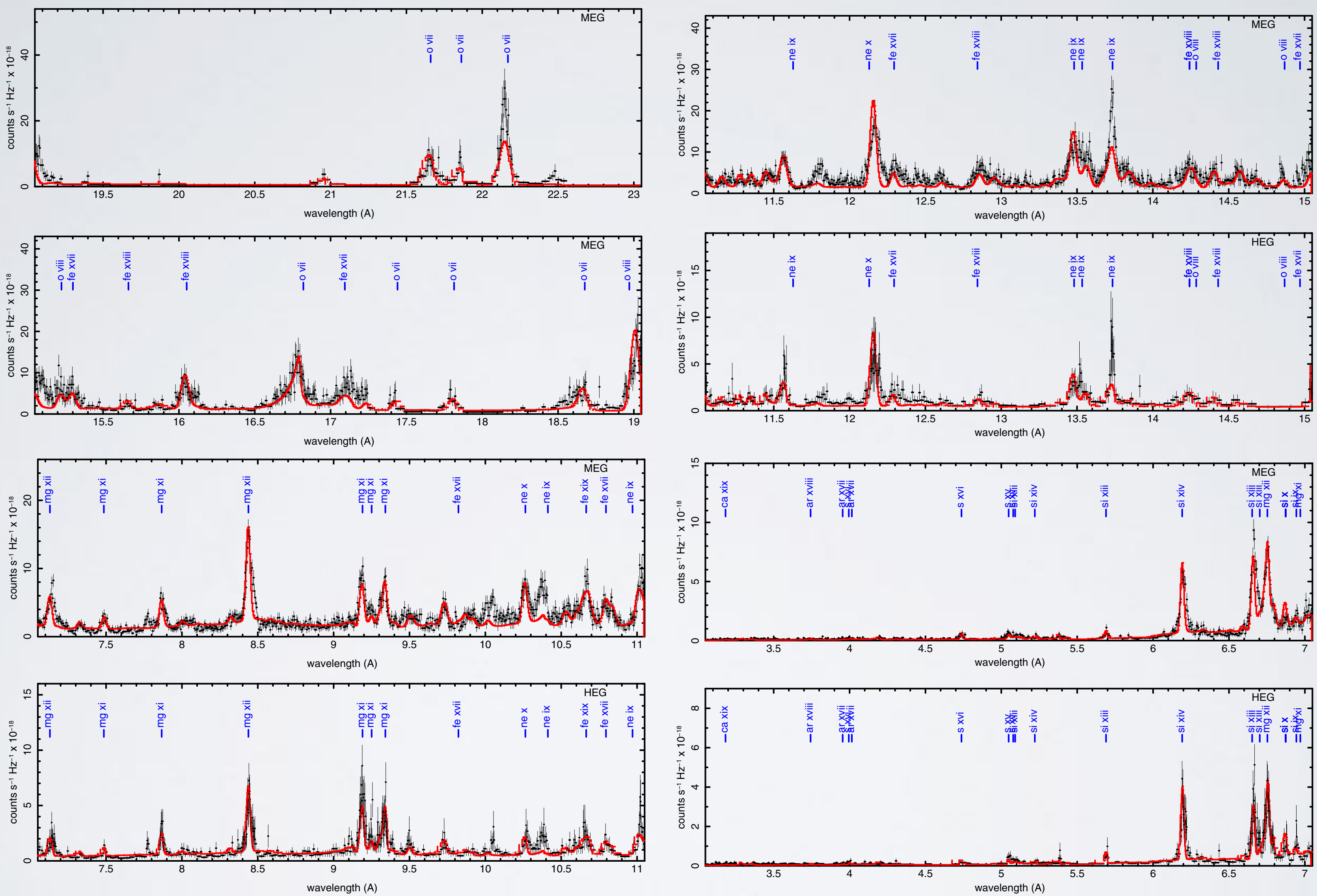
- Needs L-shell electrons
- Photoionization, then either 2p → 1s radiative transition or Auger ionization
- Fluorescence yield ~ Z^4, appreciable for a high-Z element
- Such a process is an important contributor to iron K emission

Photoionized Plasmas



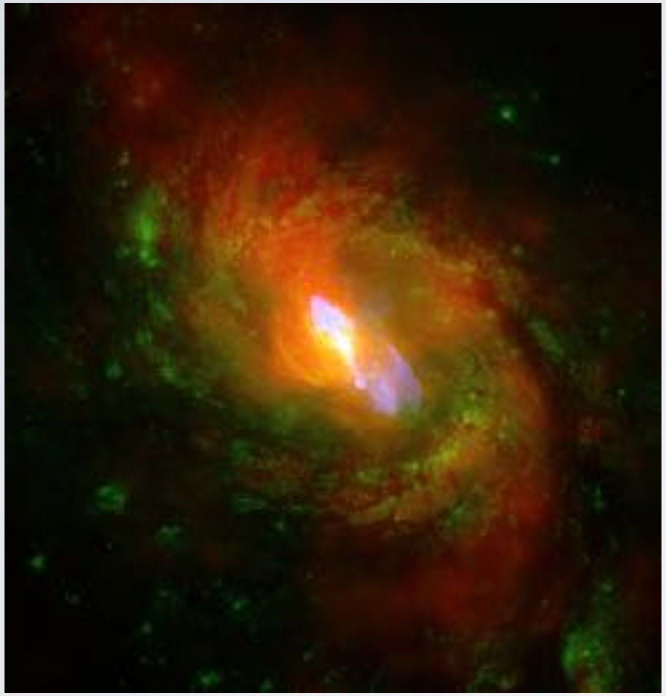
NGC 3783 900 ksec Chandra observation, over 135 lines identified!
Kaspi et al (2003)

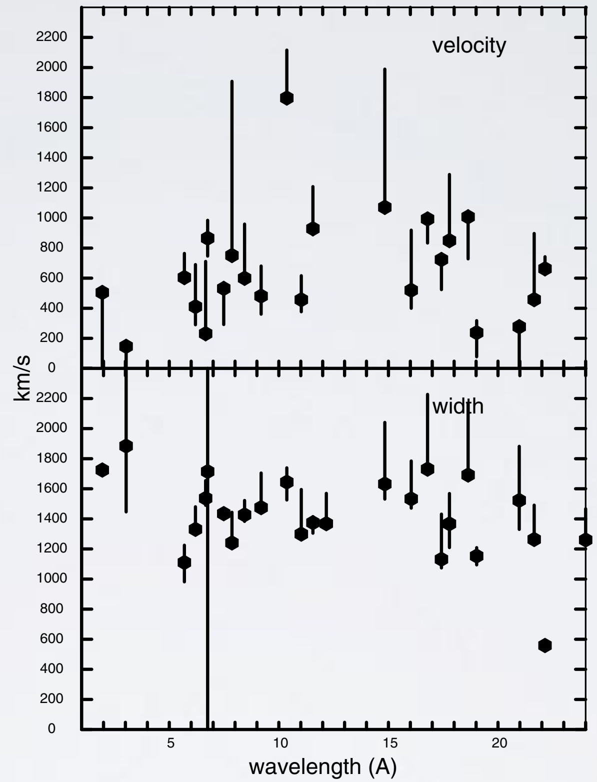
Photoionized Gas in NGC 1068

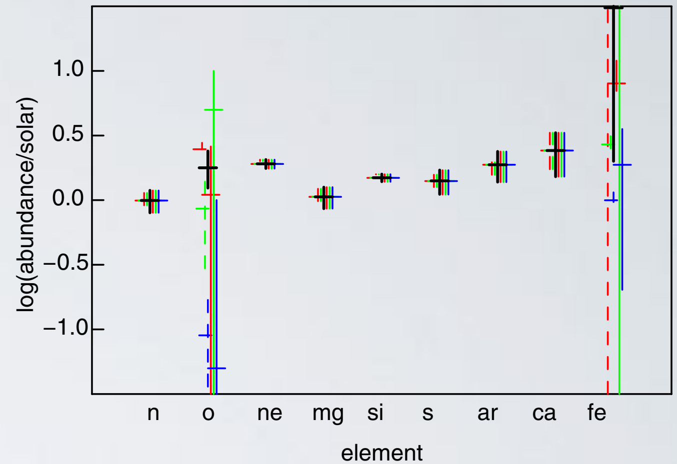


Fits of the XSTAR model to 400 ksec Chandra HETG observation (Kallman et al. 2014)

Photoionized Gas in NGC 1068







Kallman et al. (2014)

- H-like and He-like ions from C to Si, as well as significant emission due to Fe L-shell transitions
- Bright RRC point to the predominance of recombination in a photoionized plasma
- Diversity of ionization parameters ranging from $\xi \sim F_x/n_e$=10 to1000.

Plasma Codes

Understanding a plasma requires a physical model. For these, a large number of atomic lines are needed (hundreds or more). Modern plasma codes have made of the hard work, compiling millions of transitions!

Code	Source
SPEX	http://www.sron.nl/spex
Chianti	http://chiantidatabase.org
AtomDB	http://atomdb.org
CLOUDY	http://www.nublado.org
XSTAR	http://heasarc.nasa.gov/docs/software/xstar/xstar.html

Fitting Codes

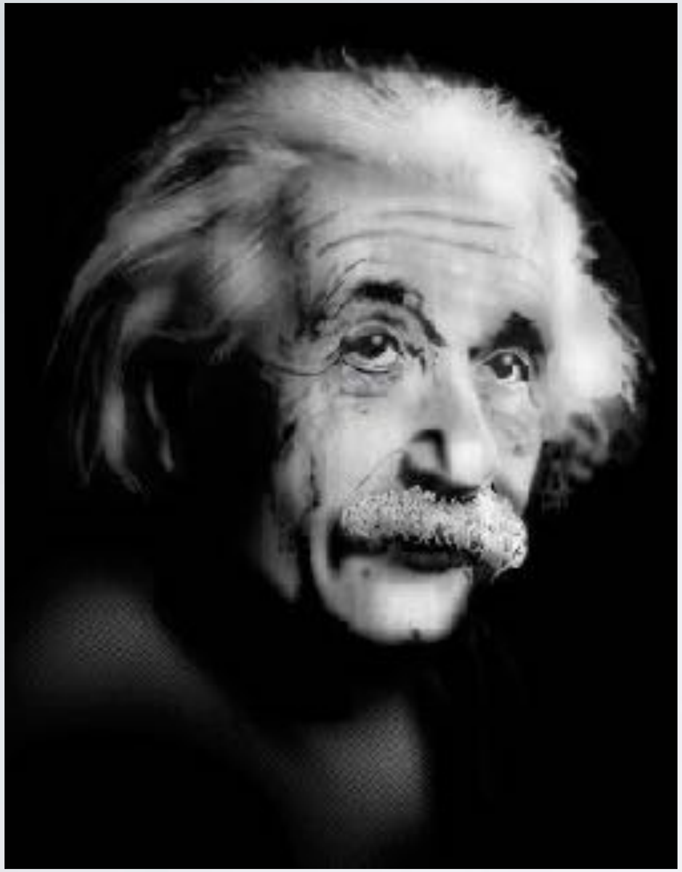
XSPEC	https://heasarc.gsfc.nasa.gov/xanadu/xspec/
ISIS	http://space.mit.edu/asc/isis/
Sherpa	http://cxc.harvard.edu/sherpa/

Summary

Although moderately complex, there are relatively few processes that dominate X-ray emission; analyzing the observed spectrum from each can reveal the underlying parameters. These processes are:

- Line emission
  - Collisional ⇒ temperature, abundance, density
  - Photoionized ⇒ ionization state, abundance, density
- Synchrotron emission ⇒ relativistic electrons, magnetic field
- Inverse Compton scattering ⇒ relativistic electrons
- Blackbody ⇒ temperature, size of emitting region / distance^2
- Absorption ⇒ abundance, density, velocity

Einstein and the Space-Time



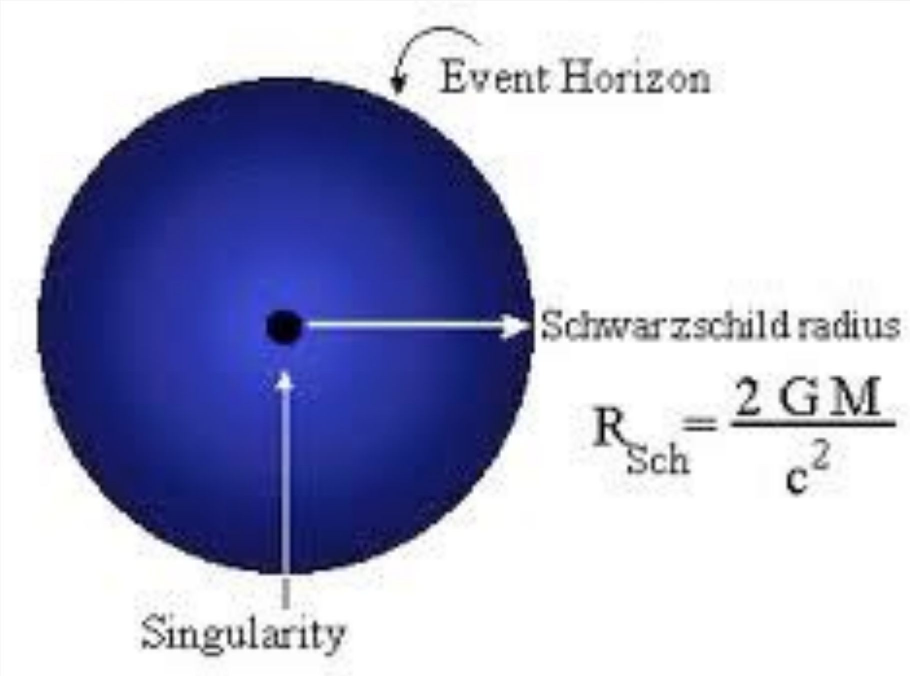
In 1915 Albert Einstein develops the theory of General Relativity.

The Persistence of Memory, by Salvador Dali

Theoretical prediction of Black Holes

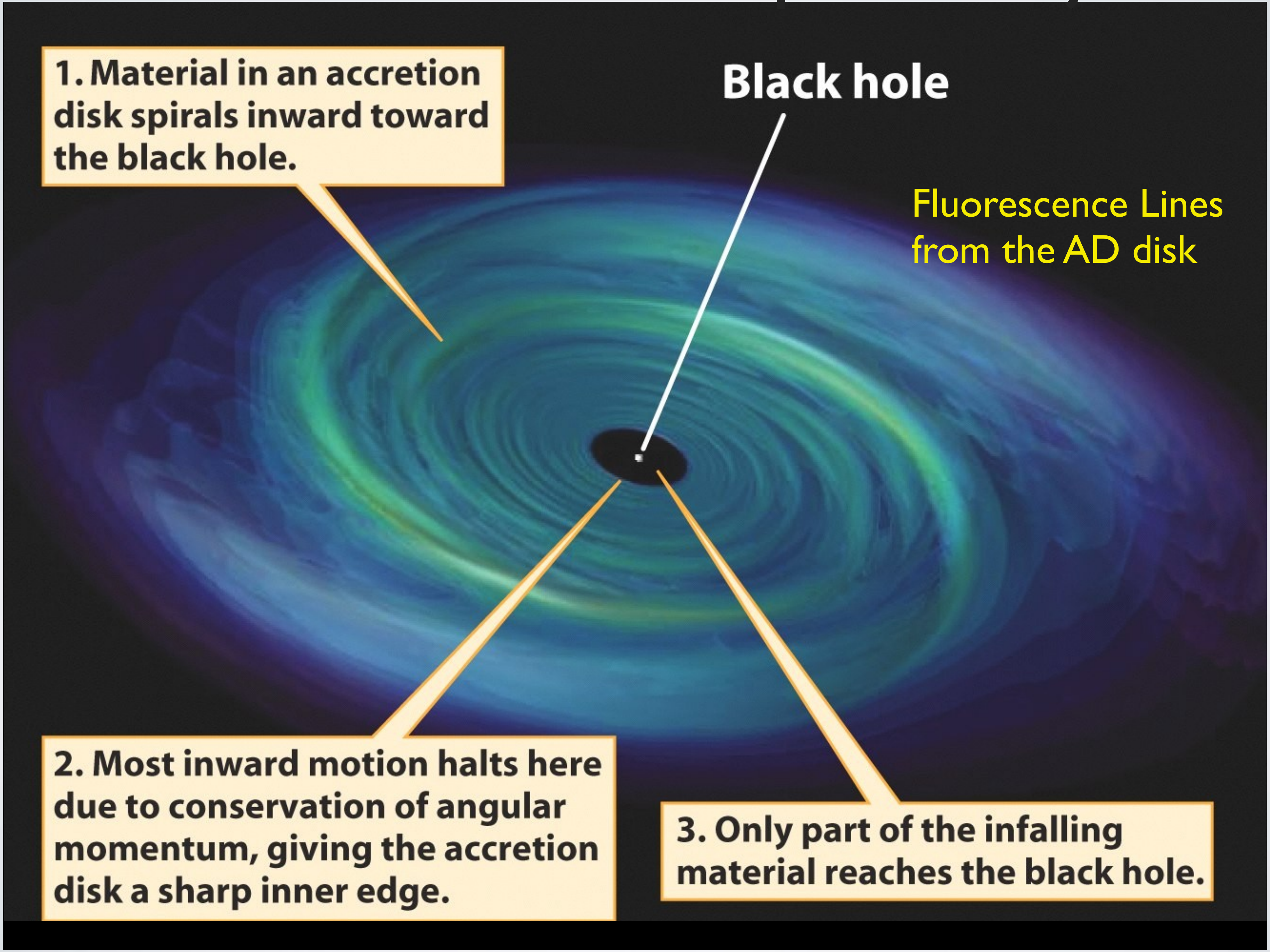
"As you see, the war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas."

- Schwarzschild to Einstein, December 1915.



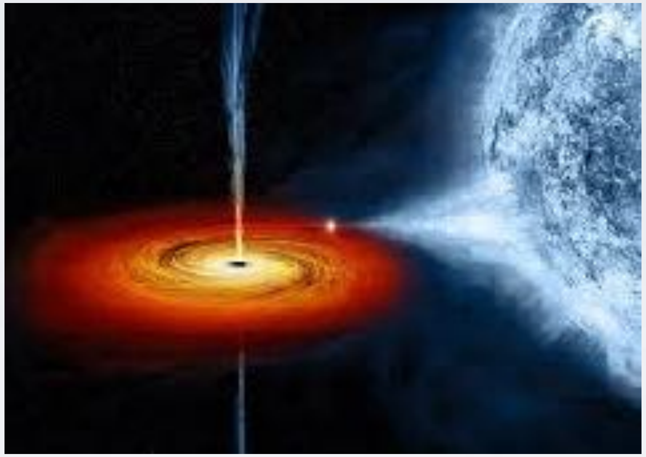
In 1915, provided the first exact solution to the Einstein field equations of general relativity (for non-rotating mass).

Accretion Into Compact Objects



Accretion Physics is the Same!

Neutron Star



Stellar-mass BH

Supermassive BH

Mass of the Compact Object

1.4 - 3 Msun

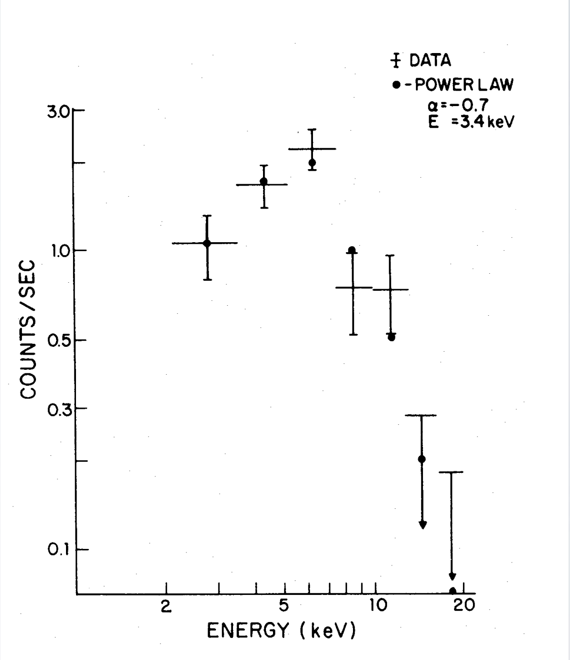
3 - 100 Msun

10^6 - 10^9 Msun

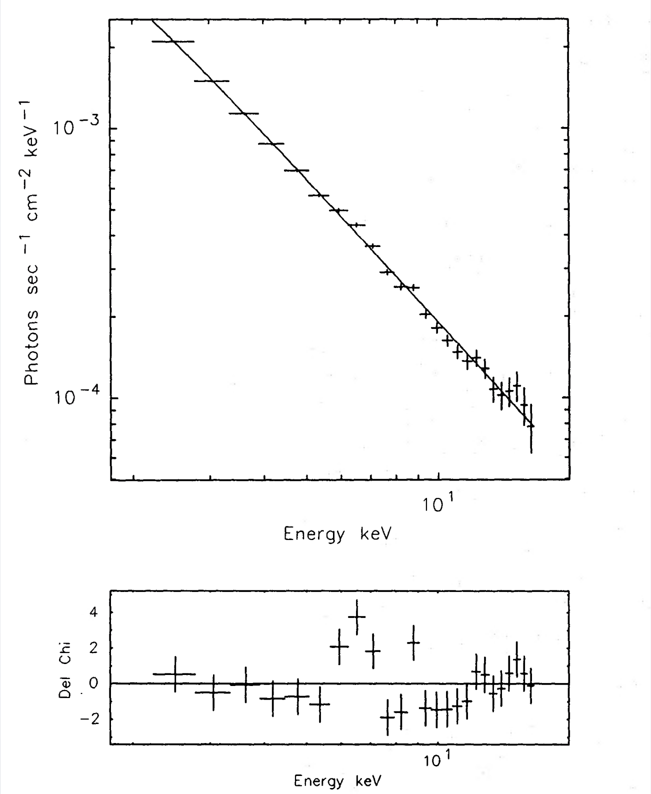
X-ray Reflection First Detections

1960-1970's: First X-ray observatories were launched: *Uhuru, Ariel-V, OSO-8, HEAO-1*.

Several X-ray sources were associated with AGN, with a power-law continuum with Gamma ~ 1.7 (e.g., Tucker et al. 1973; Mushotzky, 1976, 1984).



UHURU Observation of NGC 5128 (Tucker et al. 1973)



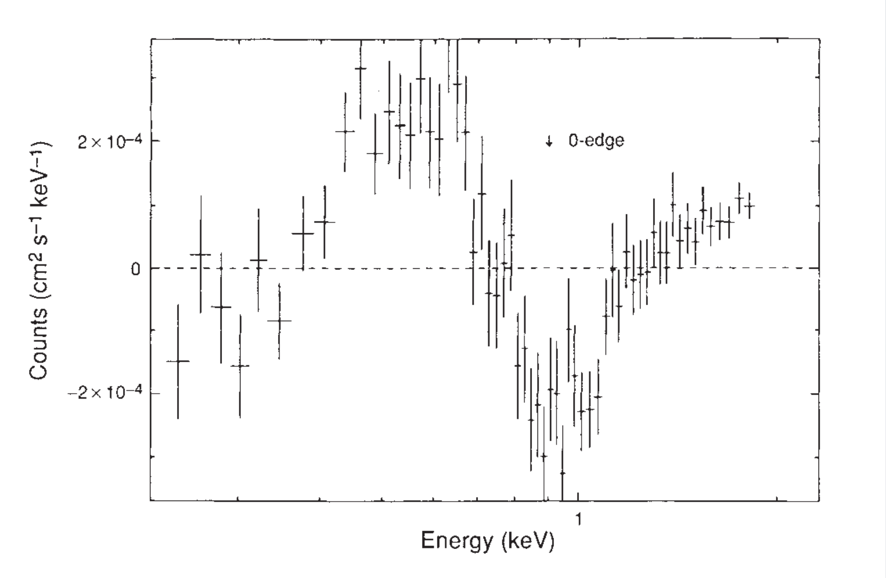
Ginga Observation of NGC 5548 showing one of the first clear detection of Fe K emission near 6.4 keV (Pounds et al. 1989)

1980's: *Einstein, EXOSTAT, Tenma, Ginga.*

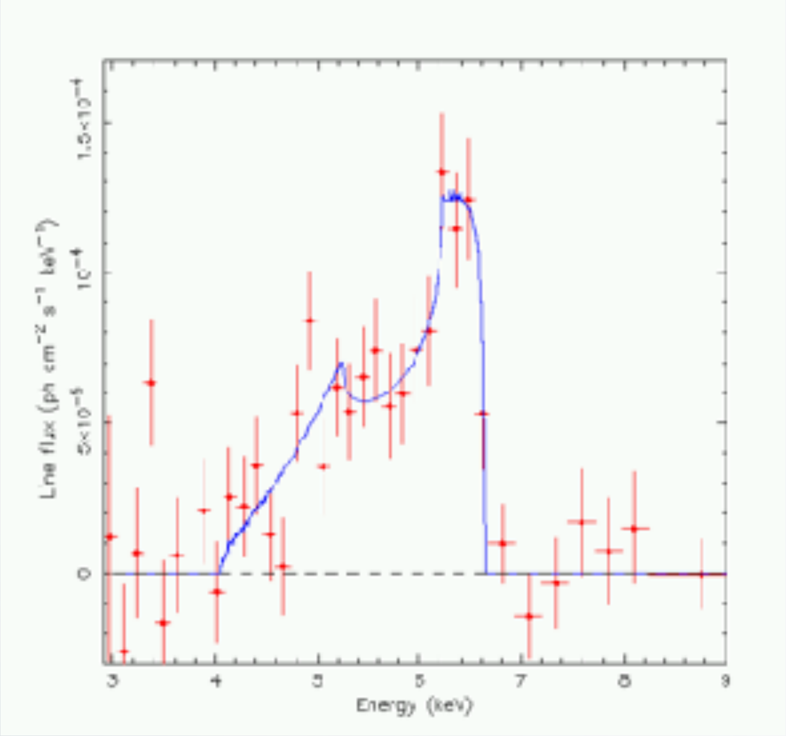
Detection of Fe K emission and absorption as a common property of Seyfert galaxies (Pounds et al. 1989, 1990; Matsuola et al. 1990; Nandra & Pounds 1994).

X-ray Reflection First Detections

1990's: *ROSAT, ASCA.* First CCDs flying on X-ray observatories. First detections of a distorted Fe K line, which was interpreted as emission affected by relativistic effects near the BH (Tanaka et al. 1995; Nandra et al. 1997; Fabian et al. 2000).



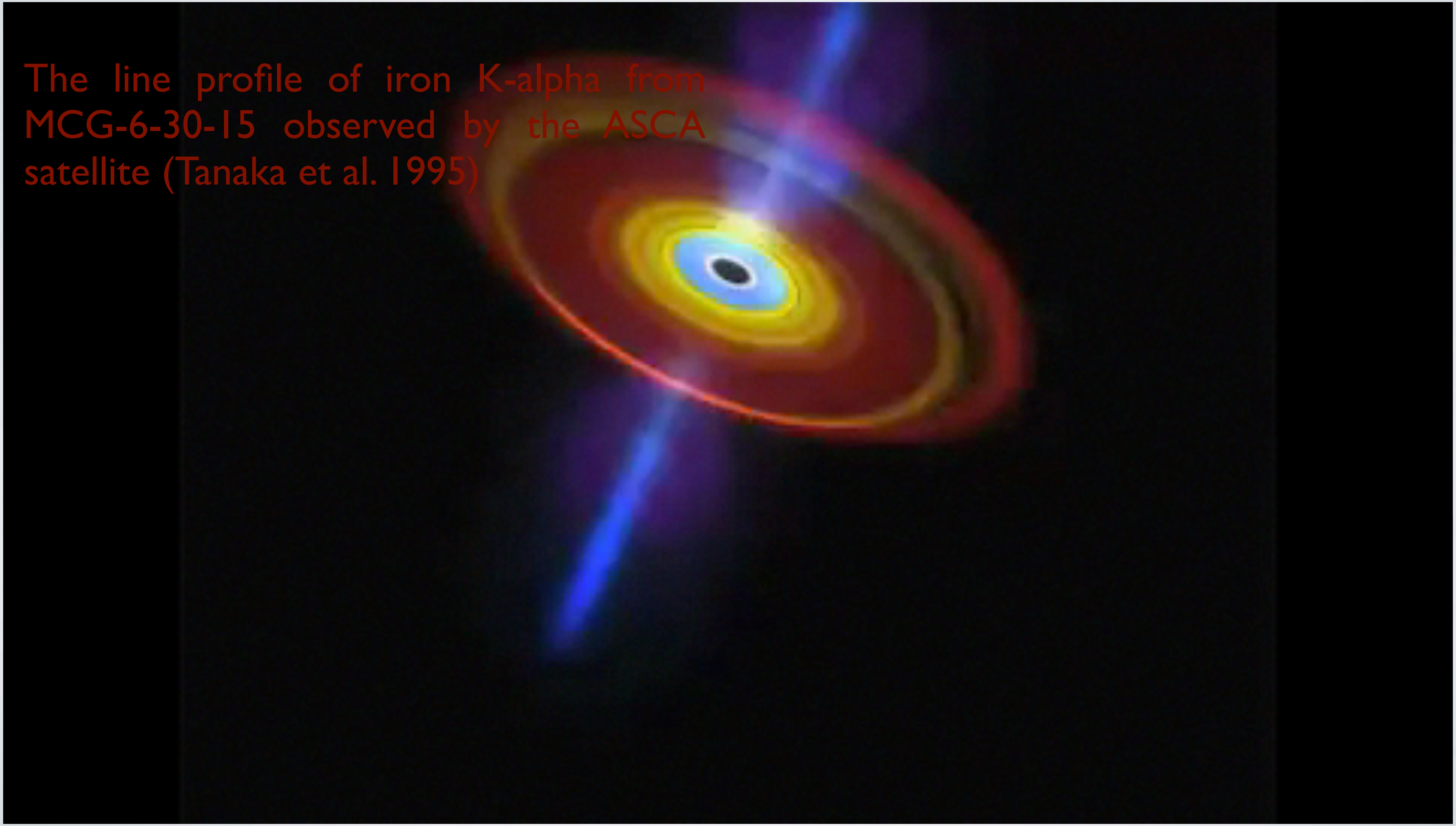
Residuals from a power-law fit to the ROSAT spectrum of MCG-6-30-15, showing a strong absorption feature at ~0.8 keV due to iron.



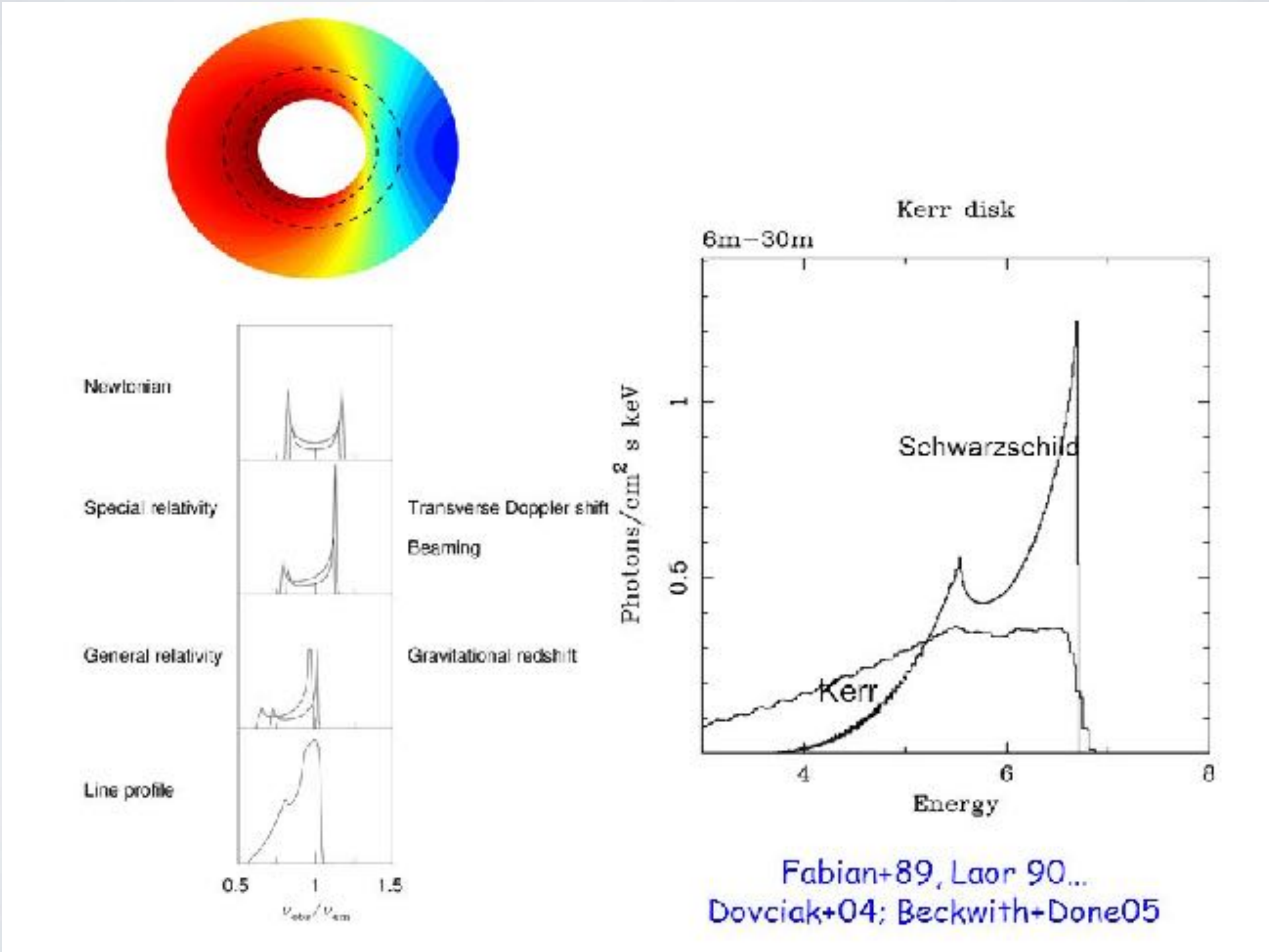
The line profile of iron K-alpha from MCG-6-30-15 observed by the ASCA satellite (Tanaka et al. 1995)

X-ray Reflection from the Inner-Disk

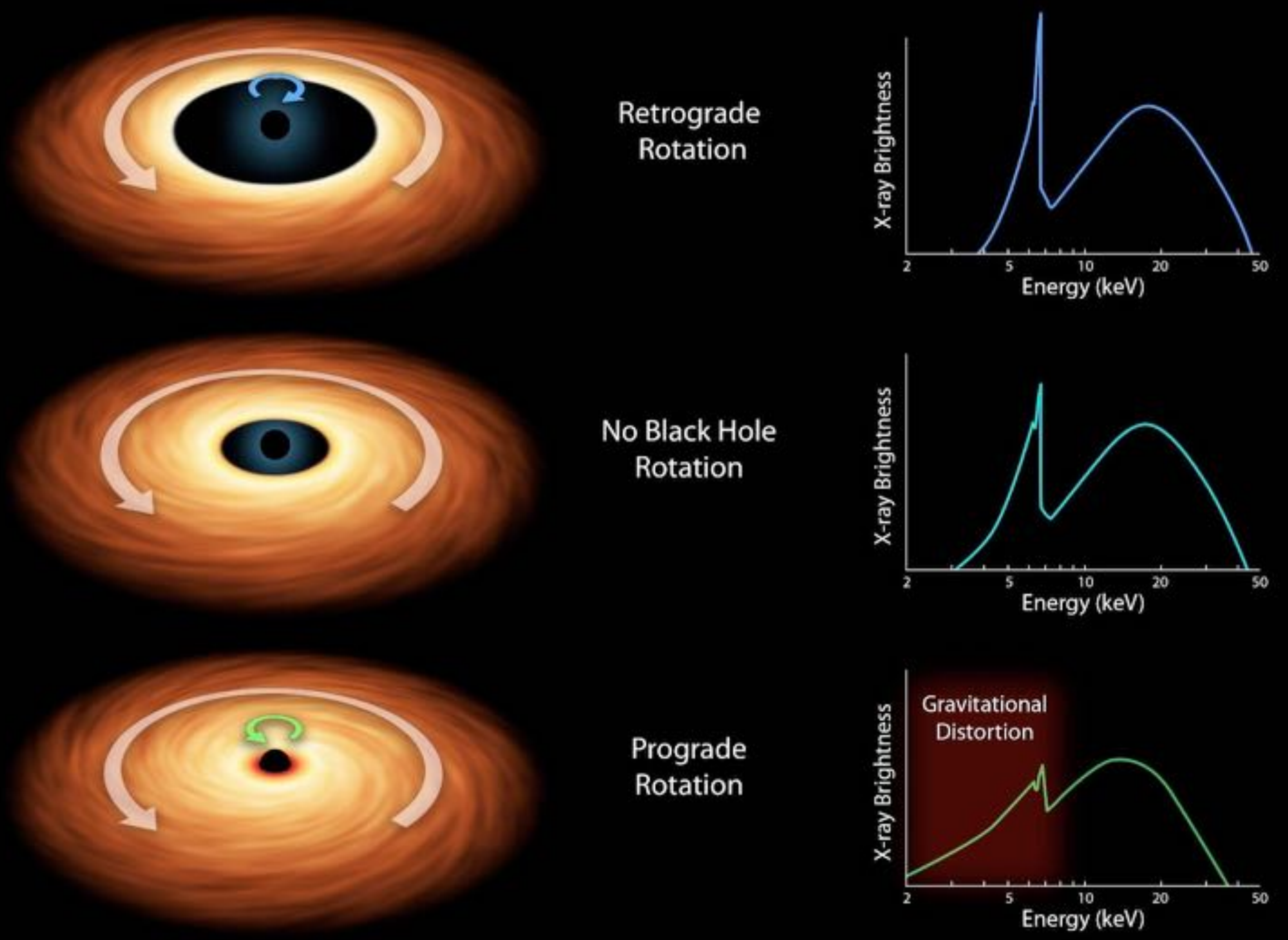
The line profile of iron K-alpha from MCG-6-30-15 observed by the ASCA satellite (Tanaka et al. 1995)



Relativistic Effects (Special + General)

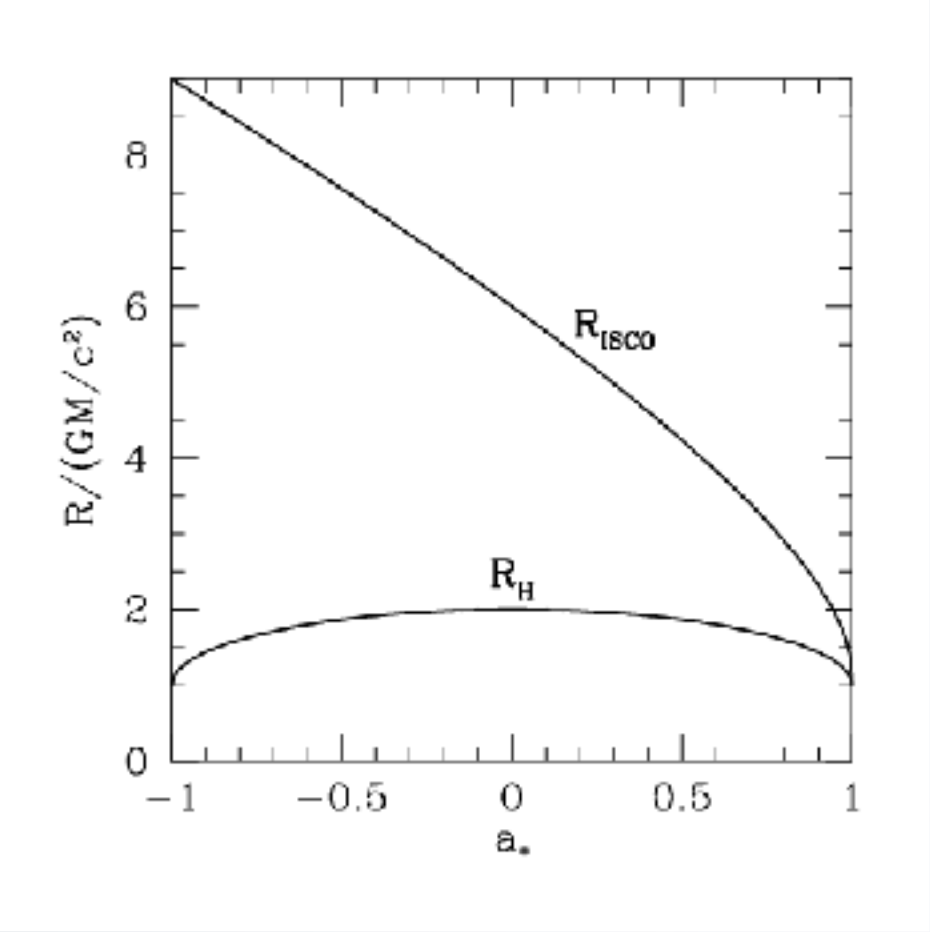


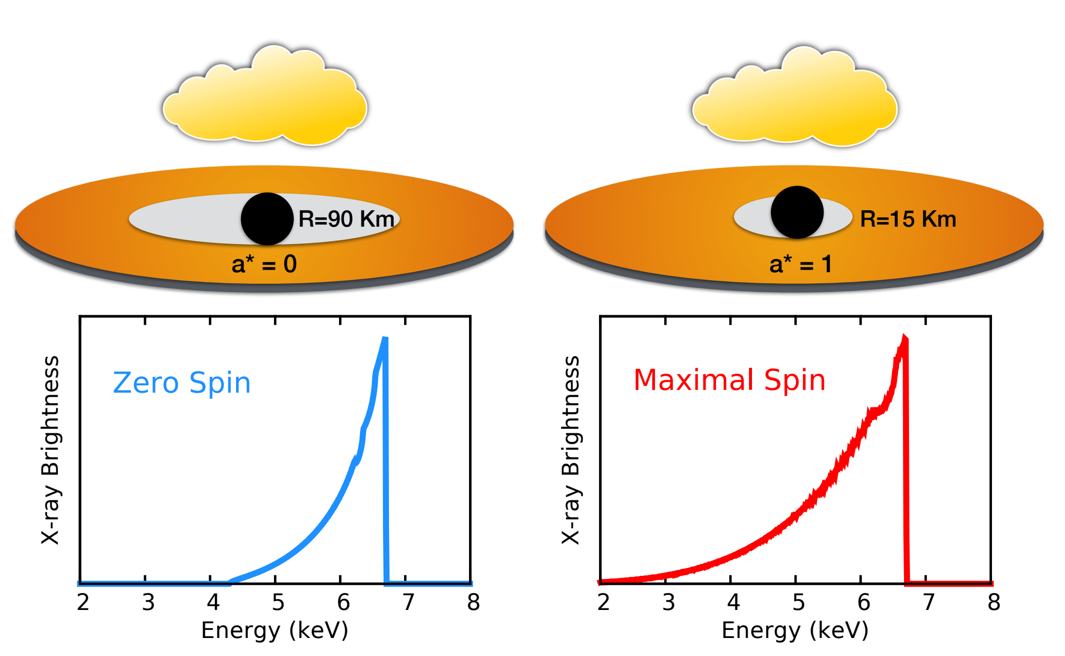
But Why X-ray Reflection is Important?



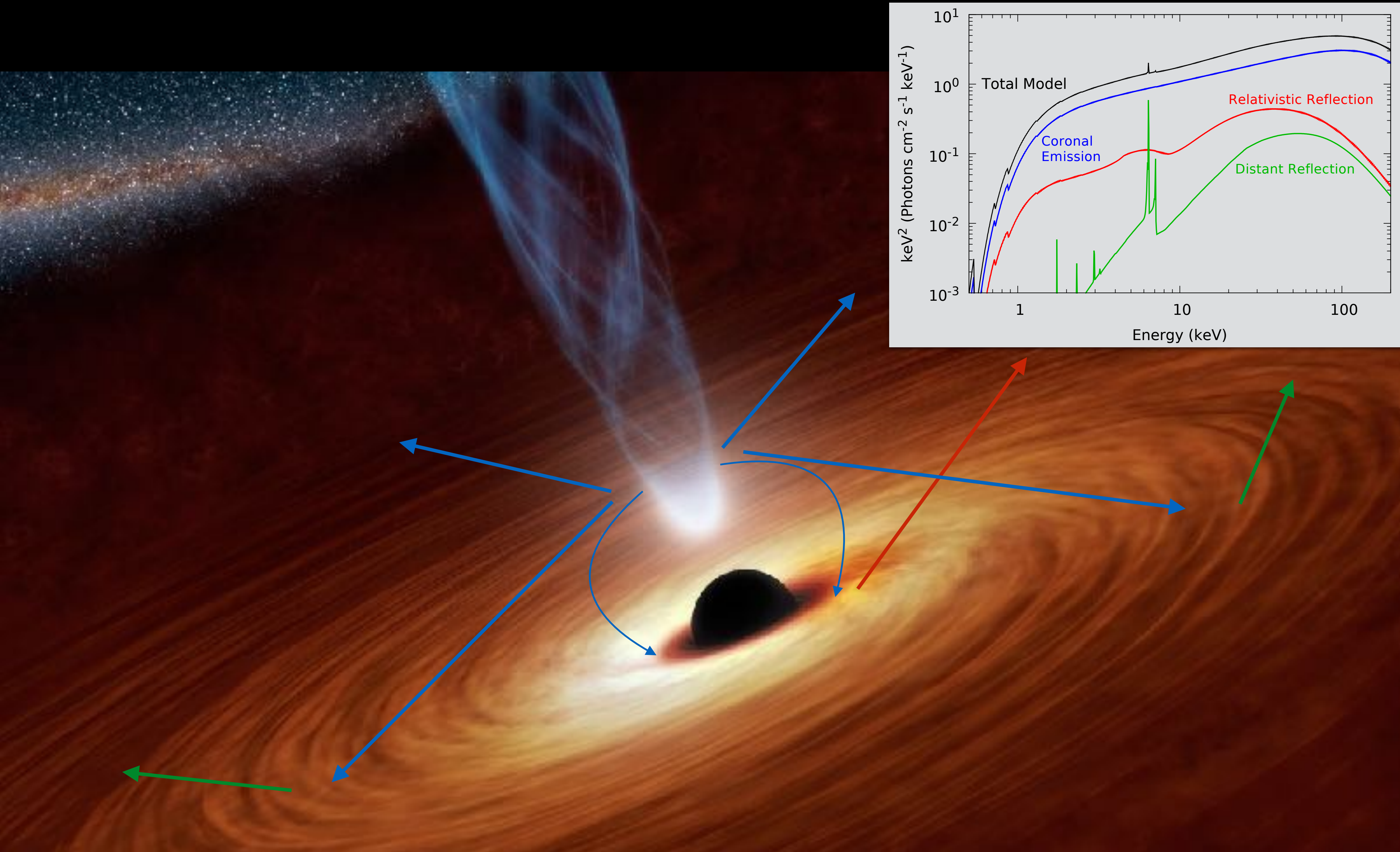
But Why X-ray Reflection is Important?

X-ray reflection is the corner stone of the Fe-line method to measure the spin of Black Holes





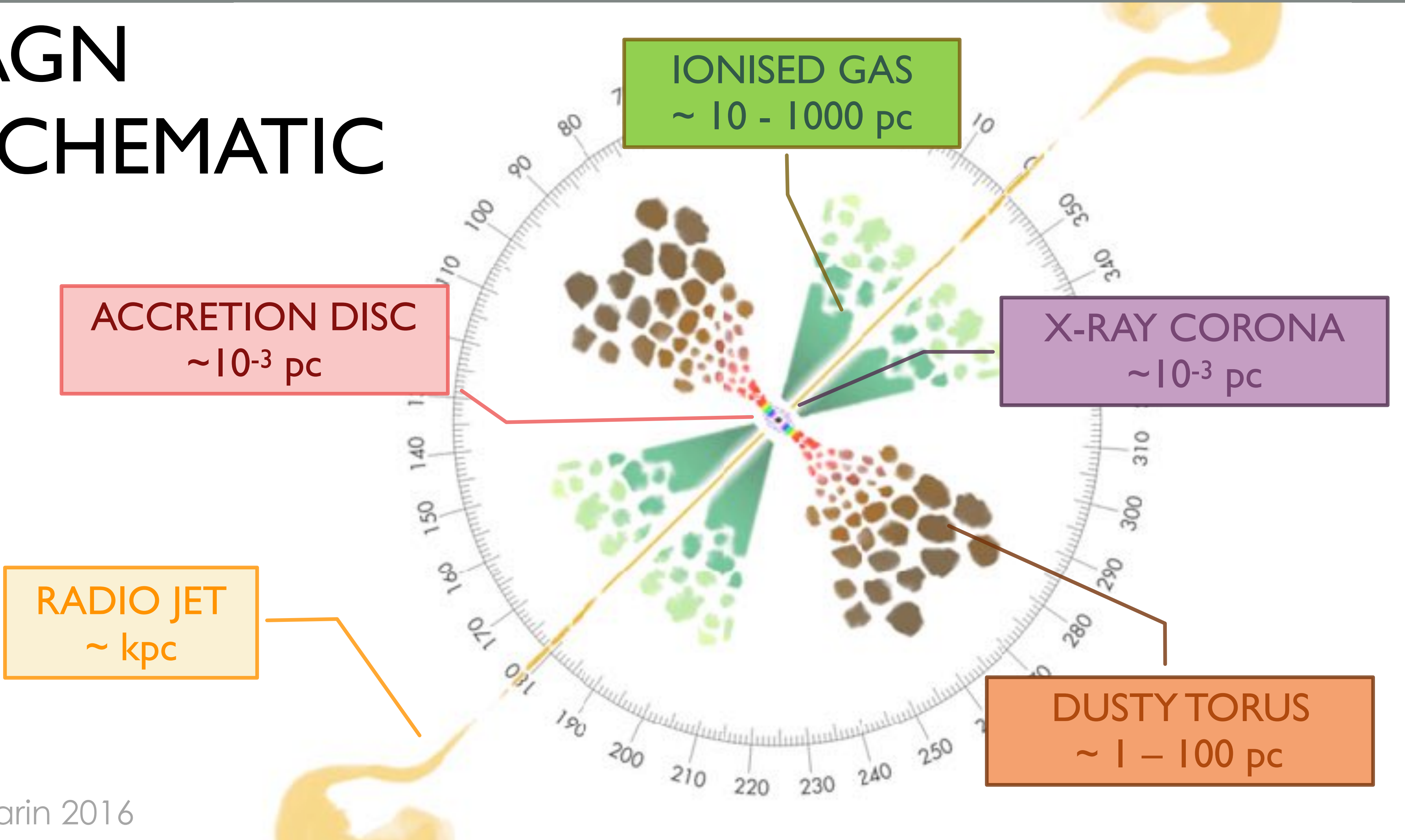
But also see the continuum fitting method in L. Gou's talk tomorrow!



X-ray Reflection from Accretion Disks

The Complex AGN Structure

AGN SCHEMATIC



Marin 2016

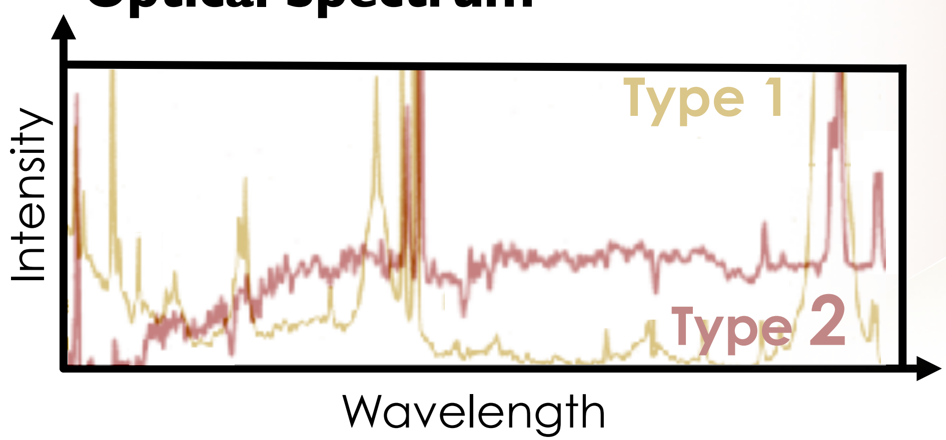
Slide courtesy of P. Boorman

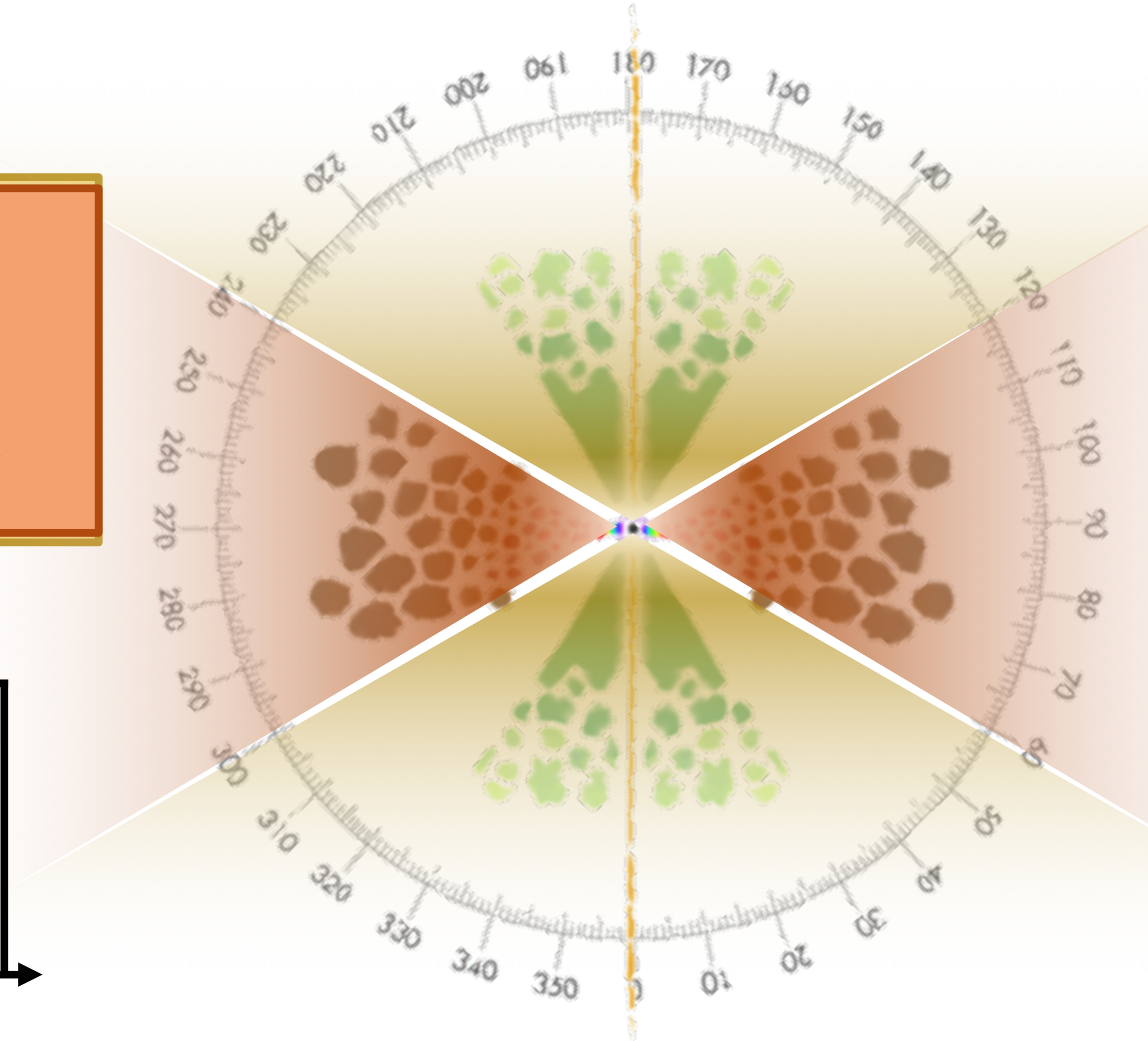
UNIFICATION

TYPE 2

BLR **HIDDEN**
NARROW LINES ONLY

Optical Spectrum





Marin 2016

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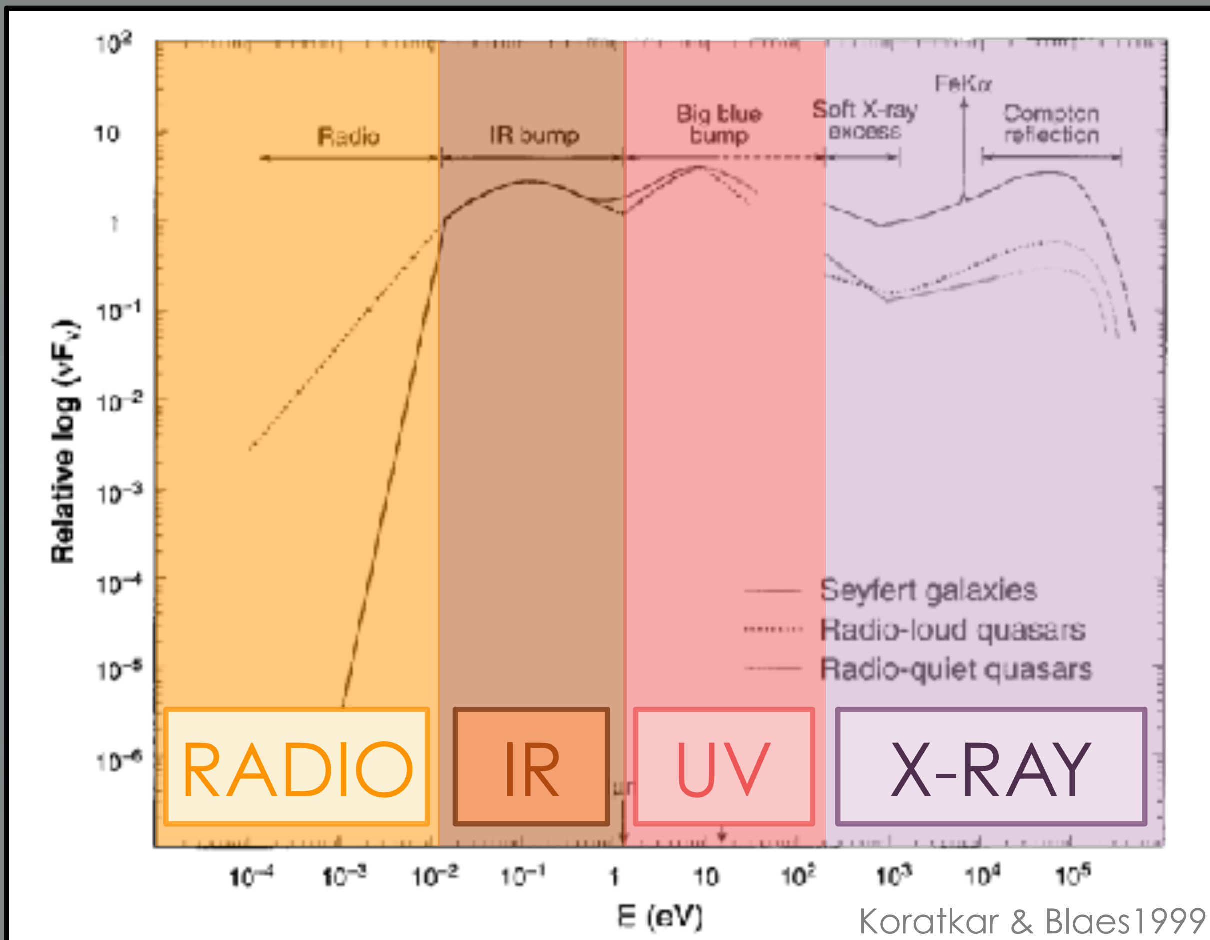
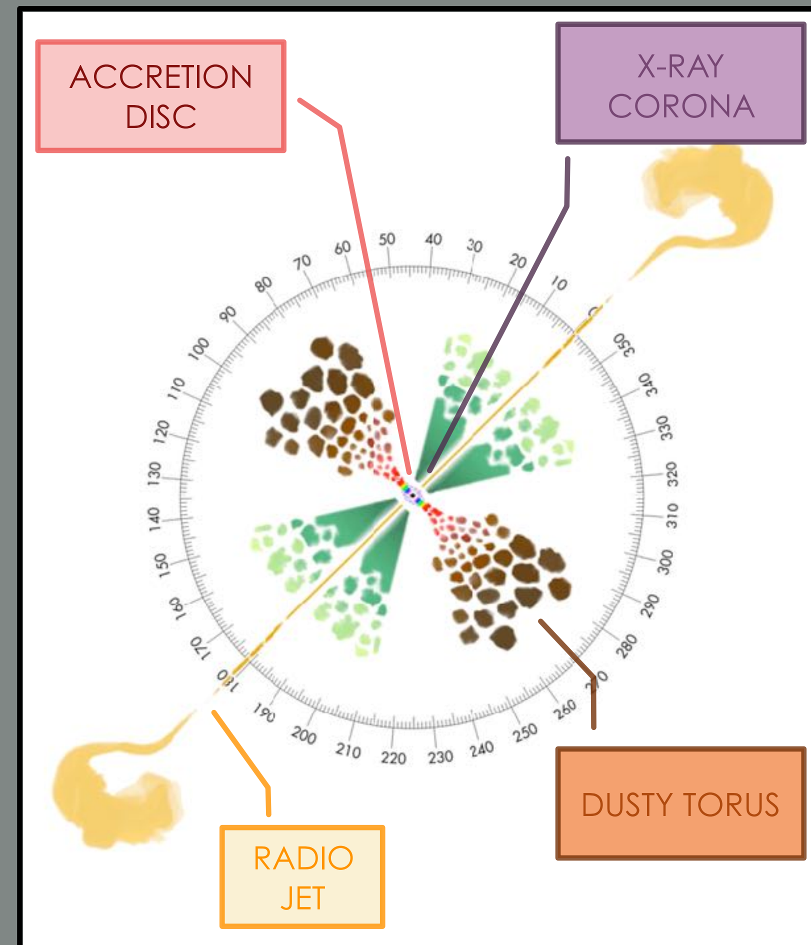
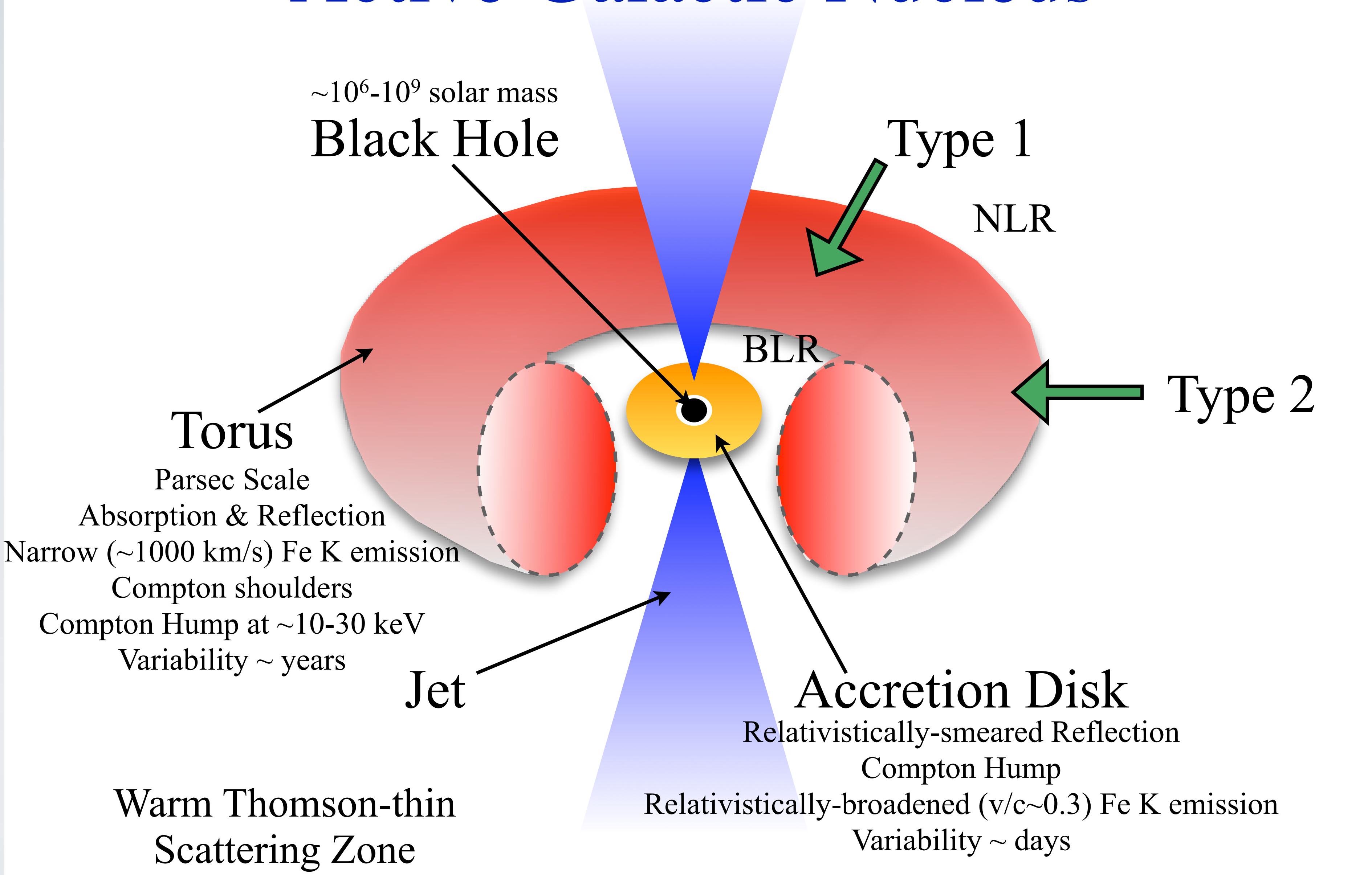
BROADBAND SPECTRUM





Slide courtesy of P. Boorman

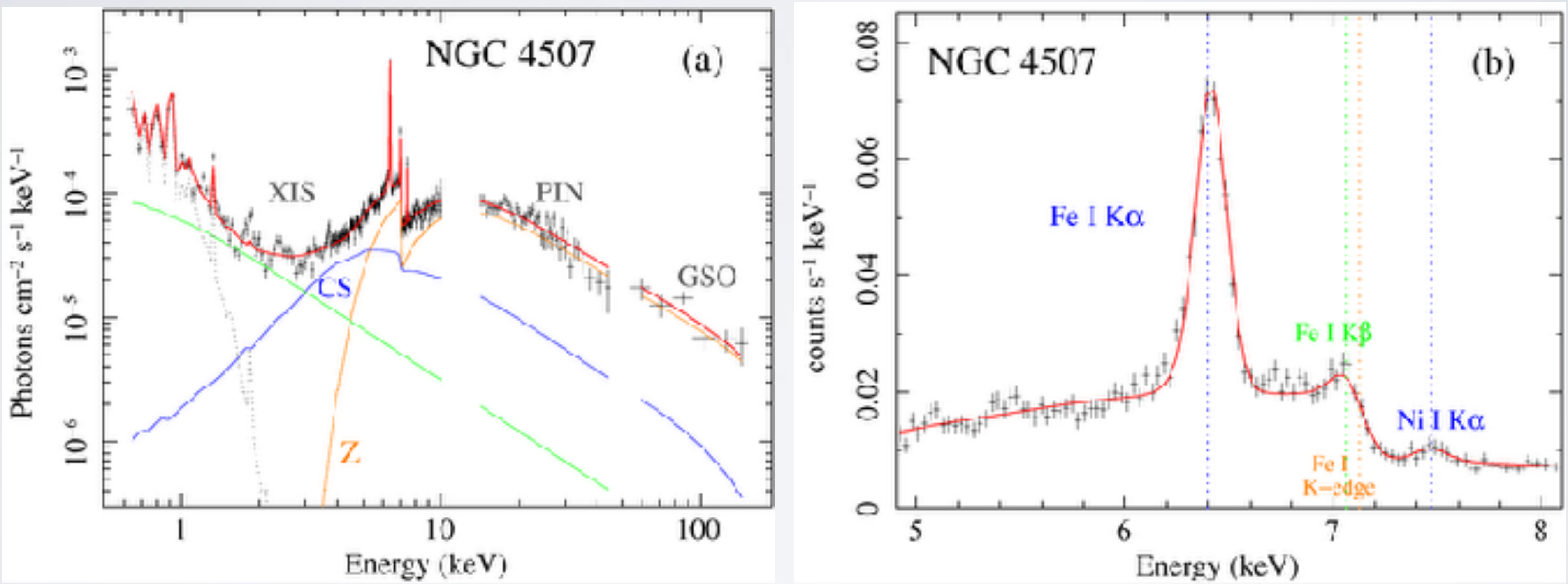
Active Galactic Nucleus



Murphy & Yaqoob (2008)

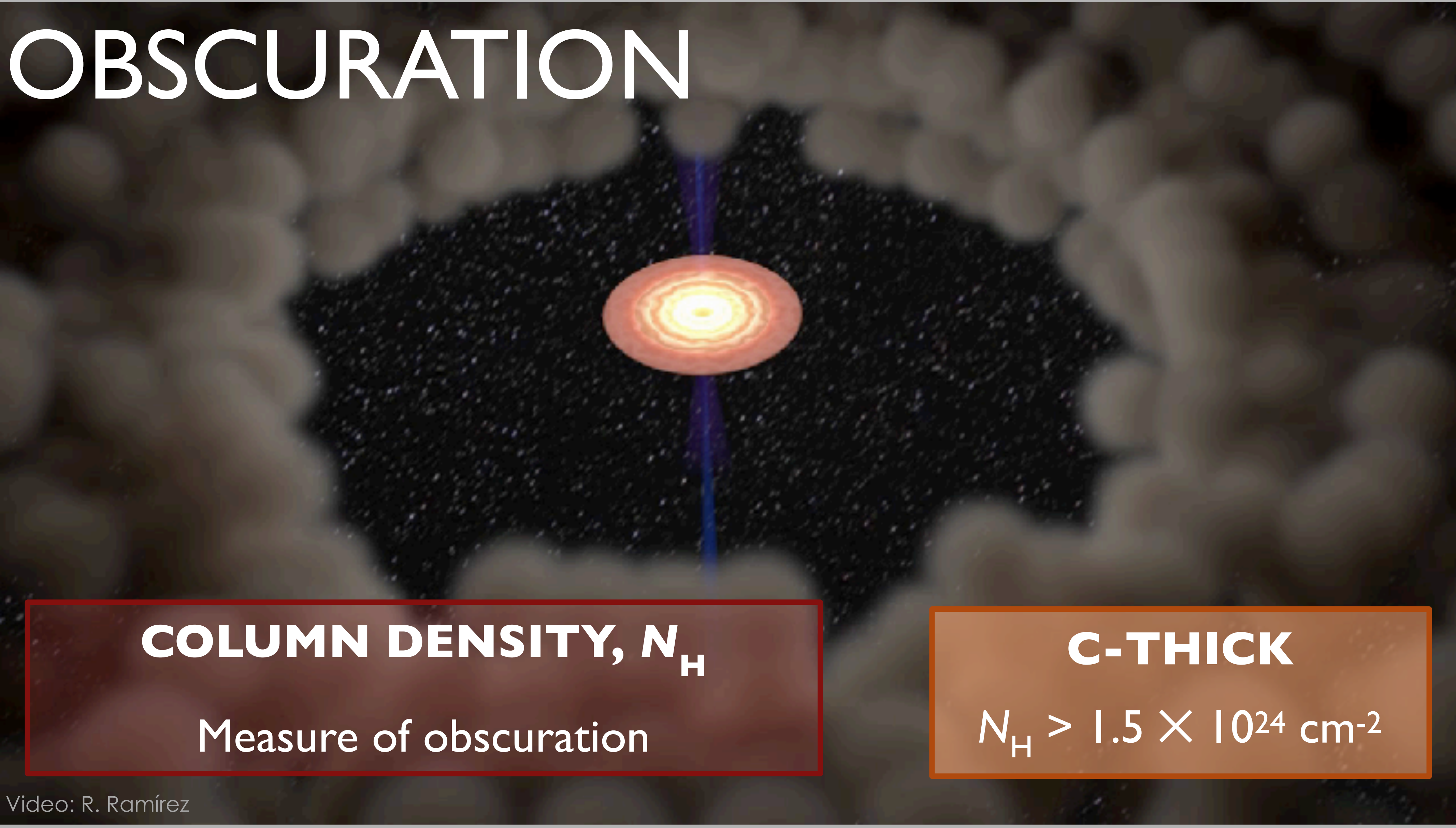
X-ray Reflection from the Torus

- X-rays produced in the central region illuminate the distant torus
- The photons excite the cold-neutral material, producing fluorescence (remember the photoelectric effect?)
- Iron K emission is the most prominent (yield ~ Z^4)



Suzaku data fitted with the MYTORUS model. The spectral shape depends on the geometry of the system, inclination angle, and column density, providing important diagnostics. See www.mytorus.com

OBSCURATION



COLUMN DENSITY, N_H

Measure of obscuration

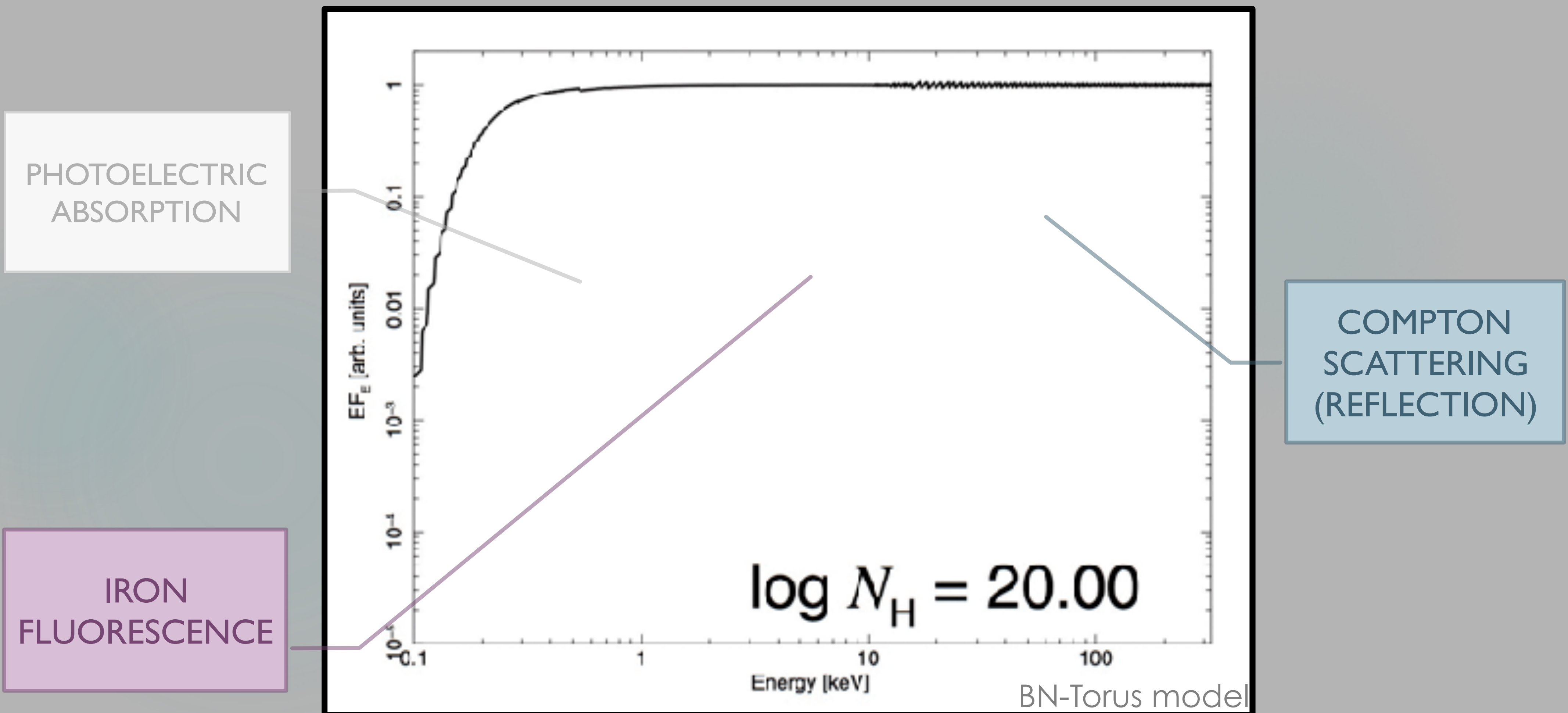
C-THICK

$N_H > 1.5 \times 10^{24}$ cm^{-2}

Video: R. Ramírez

Slide courtesy of P. Boorman

OBSCURED X-RAY SPECTRA



Slide courtesy of P. Boorman

Neutral & Distant Reflection

* PEXRAV (Magdziarz & Zdziarski)
* PEXMON (Nandra)

Provide very simplistic calculation of the reflection spectra. No geometrical information.

* TORUS (Brightman & Nandra)
* MYTORUS (Murphy & Yaqoob)

Provide very simplistic calculation of the reflection spectra, but good geometrical information

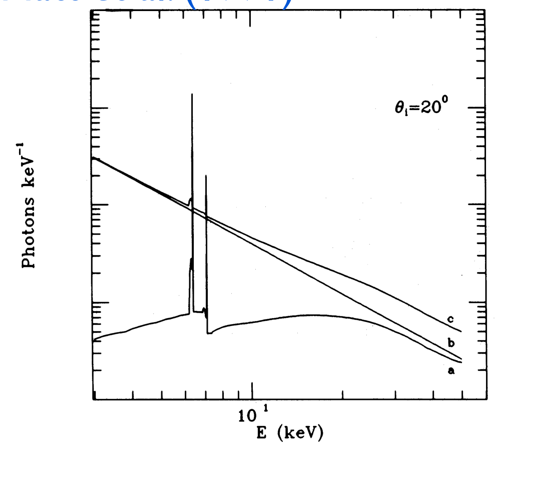
* REFLIONX (Ross & Fabian)
* XILLVER (Garcia & Kallman)

Provide detailed calculations of the reflection spectra (also including ionization). No geometrical information.

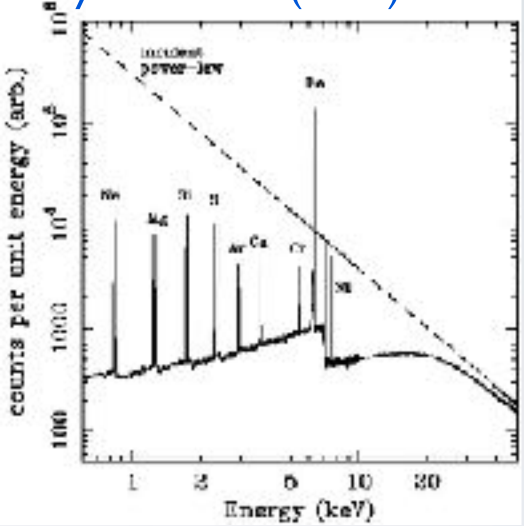
X-ray Reflection from Cold Material

Reflection modeling is being around for a long time…

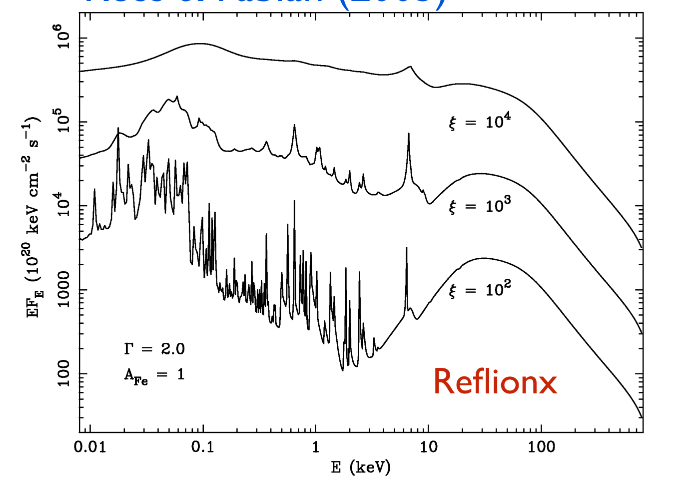
Matt et al. (1991)



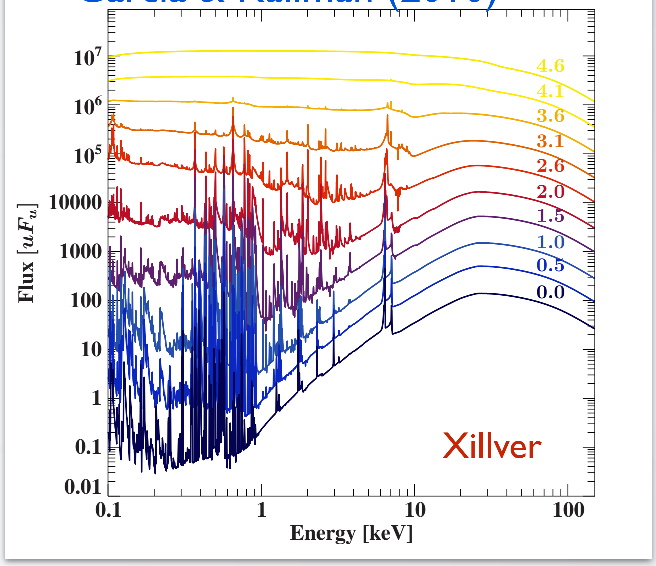
Reynolds et al. (1996)



Ross & Fabian (2005)



García & Kallman (2010)

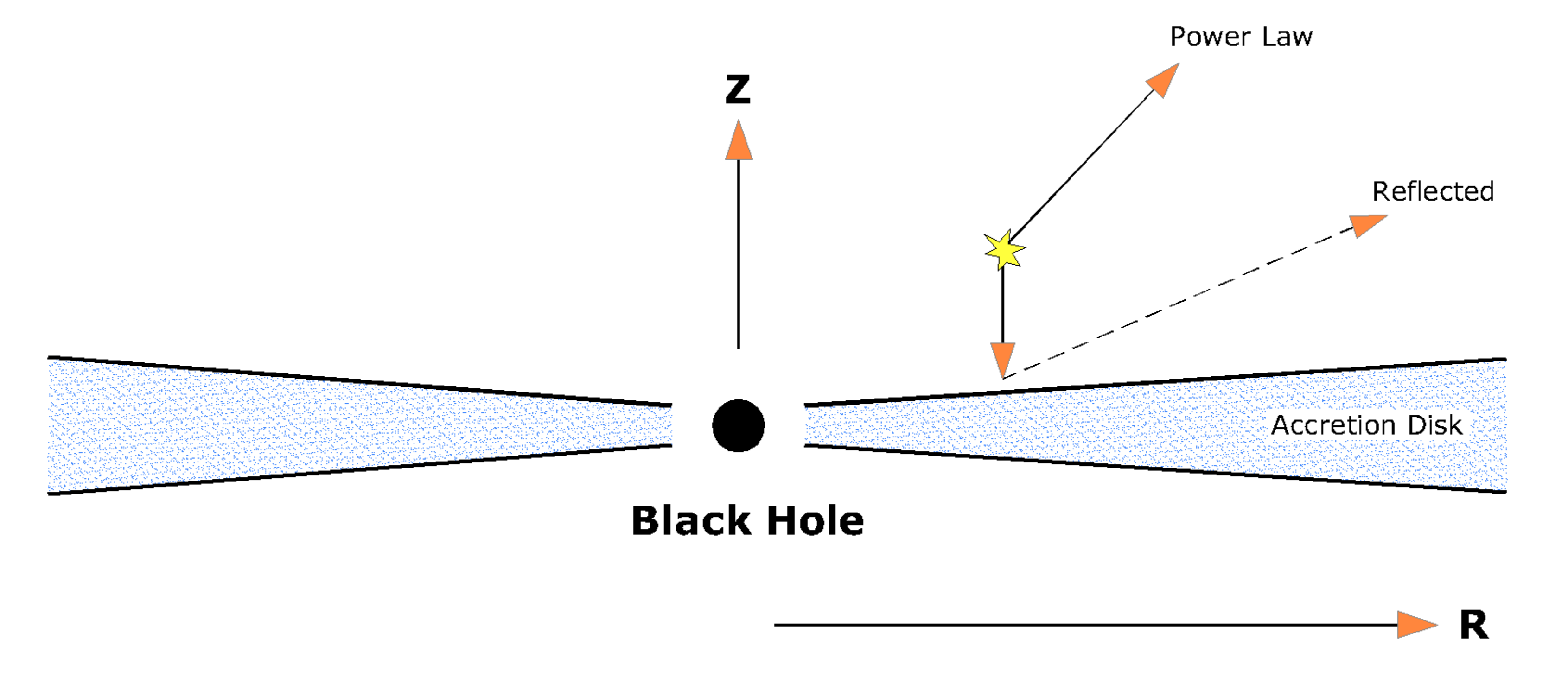


Current models allow for ionization structure (thus, not so cold material)

Calculation of the Reflected Spectrum

Simplistic assumptions regarding the geometry of the system:

- The illumination is prescribed
- The calculation is done at one single place in the disk
- Gas density is constant in the vertical direction
- No magnetic fields



Ionized Reflection in a Nutshell

In any photo ionized plasma, one needs to solve at least 3 basic equations:

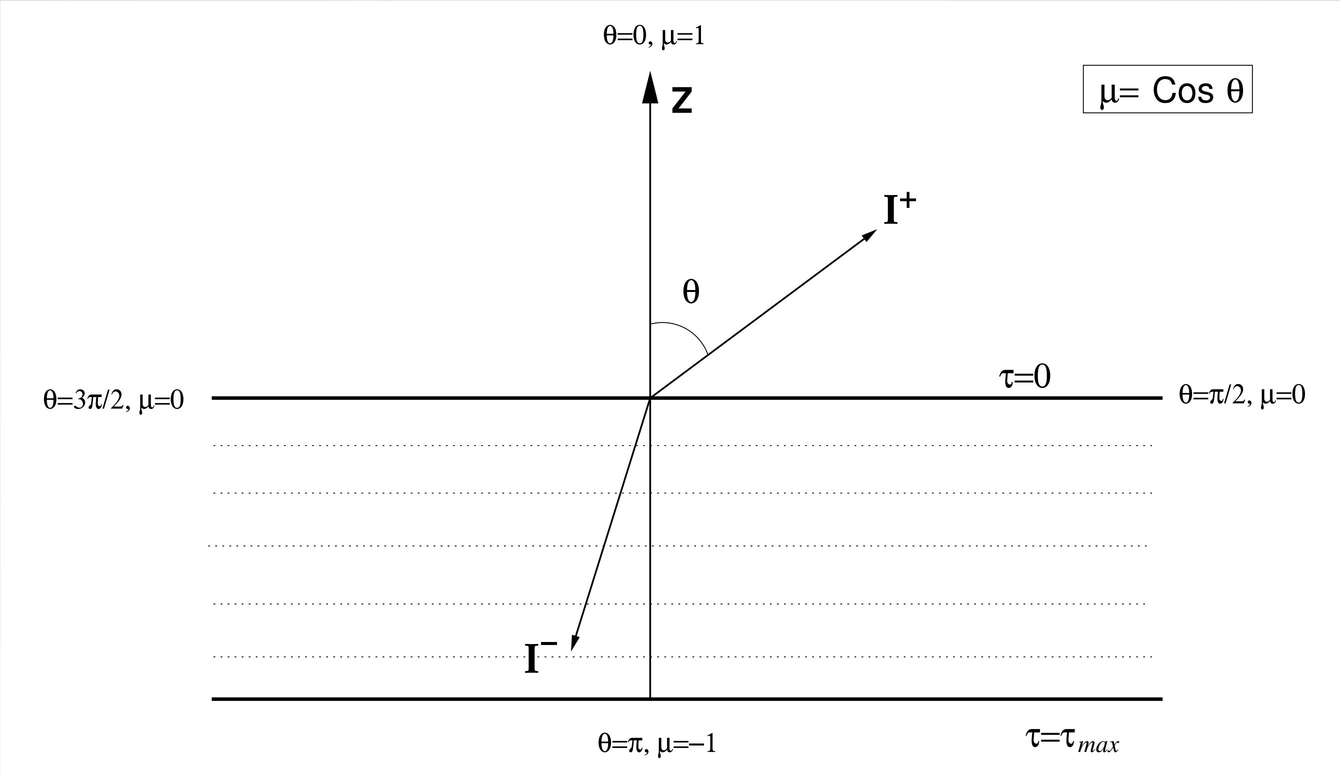
1) Level Populations: All processes populating an atomic level are balanced by those depopulating it.
2) Energy: All heating processes are balanced with the cooling processes
3) Radiation Transport: Interaction of the incident radiation field with the matter in the gas.

* Incident photons excite and/or ionize atoms in the gas
* The gas is heated by photo-absorption or scattering of photons by cold electrons
* Cooling is achieved through both continuum and line emission
* Equilibrium is reached at a particular temperature where **Heating = Cooling**

* Thus, gas temperature needs to be calculated self-consistently, and the ionization balance is determined by the strength and shape of the radiation field.

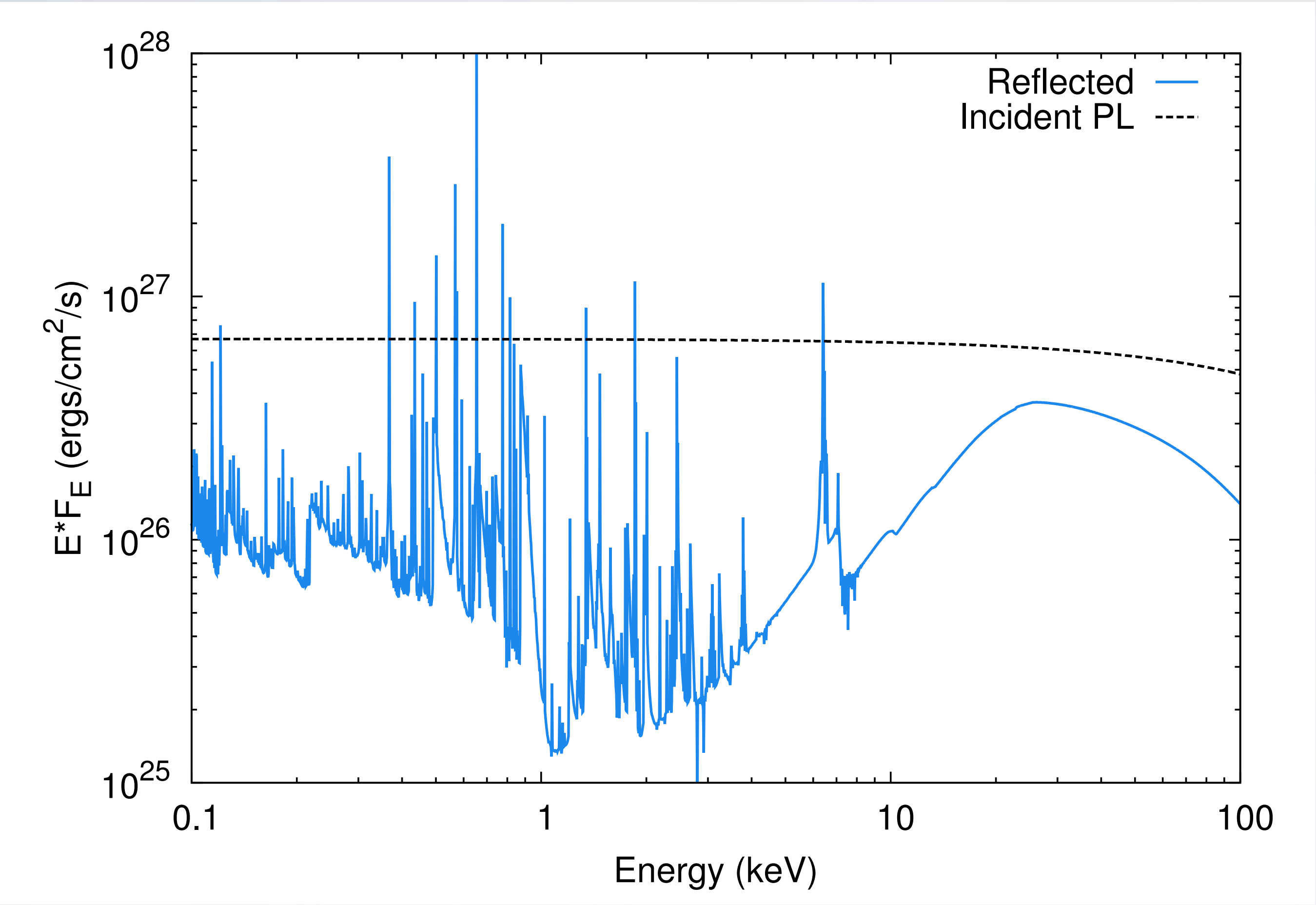
The result is a very complex emergent spectrum, with both absorption and emission features!

The XILLVER Code for Ionized Reflection



- Solves the Radiation Transfer equation for every energy and angle at all depths, assuming plane-parallel geometry
- Solves the ionization balance using the XSTAR routines (Kallman & Bautista 2001)
- Includes the most complete and updated atomic data for inner-shell transitions
- Includes Comptonization of the radiation field within the disk

XILLVER: Reflected Spectrum



Input Parameters

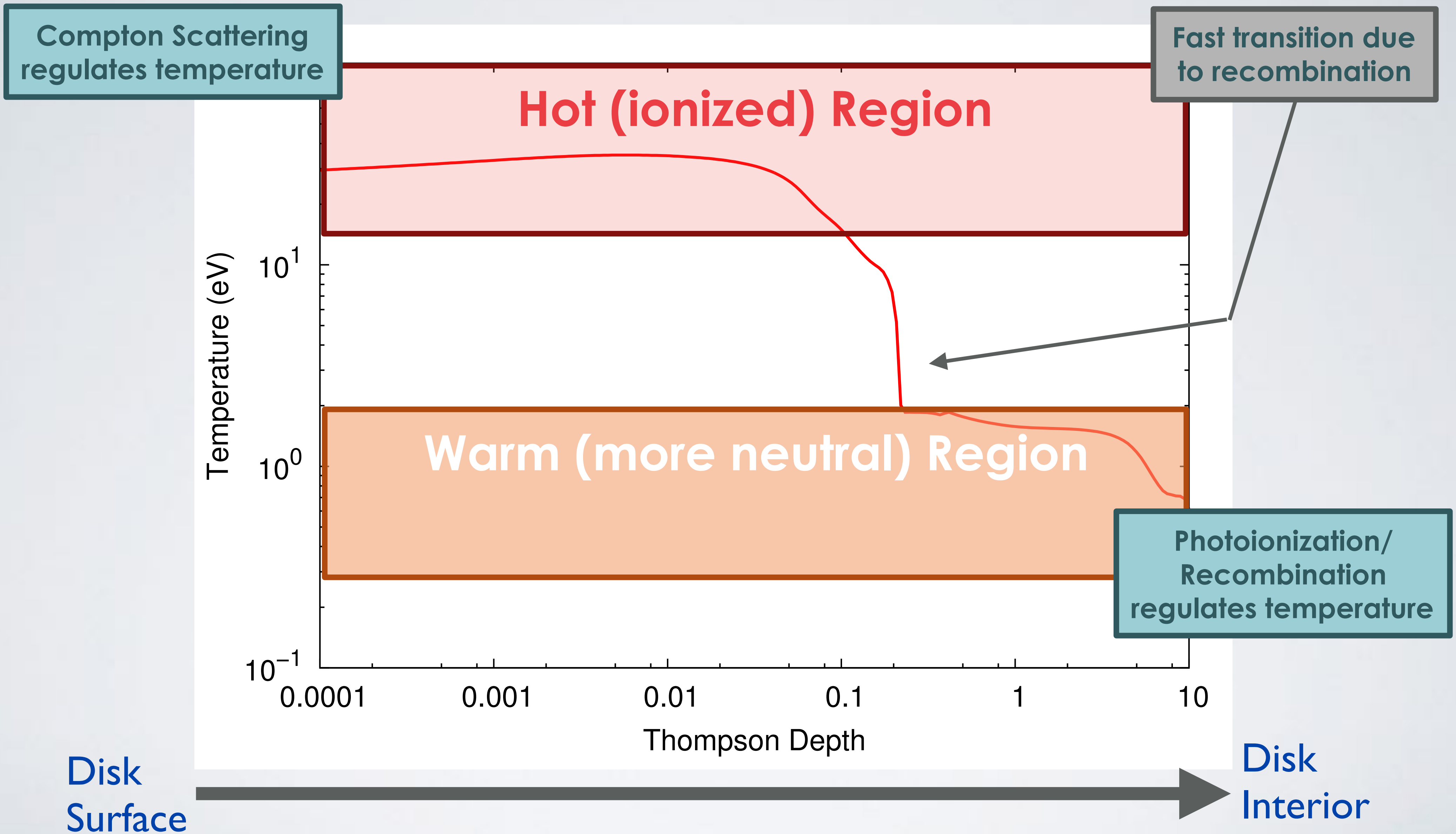
Ionization: Sets how strong is the illuminating field (Xi = 4pi Fx/ne), where ne=const is the gas density

Gamma: Sets the shape of the incident spectrum by assuming a E^-Gamma power-law

Afe: Sets the abundance of iron in Solar units

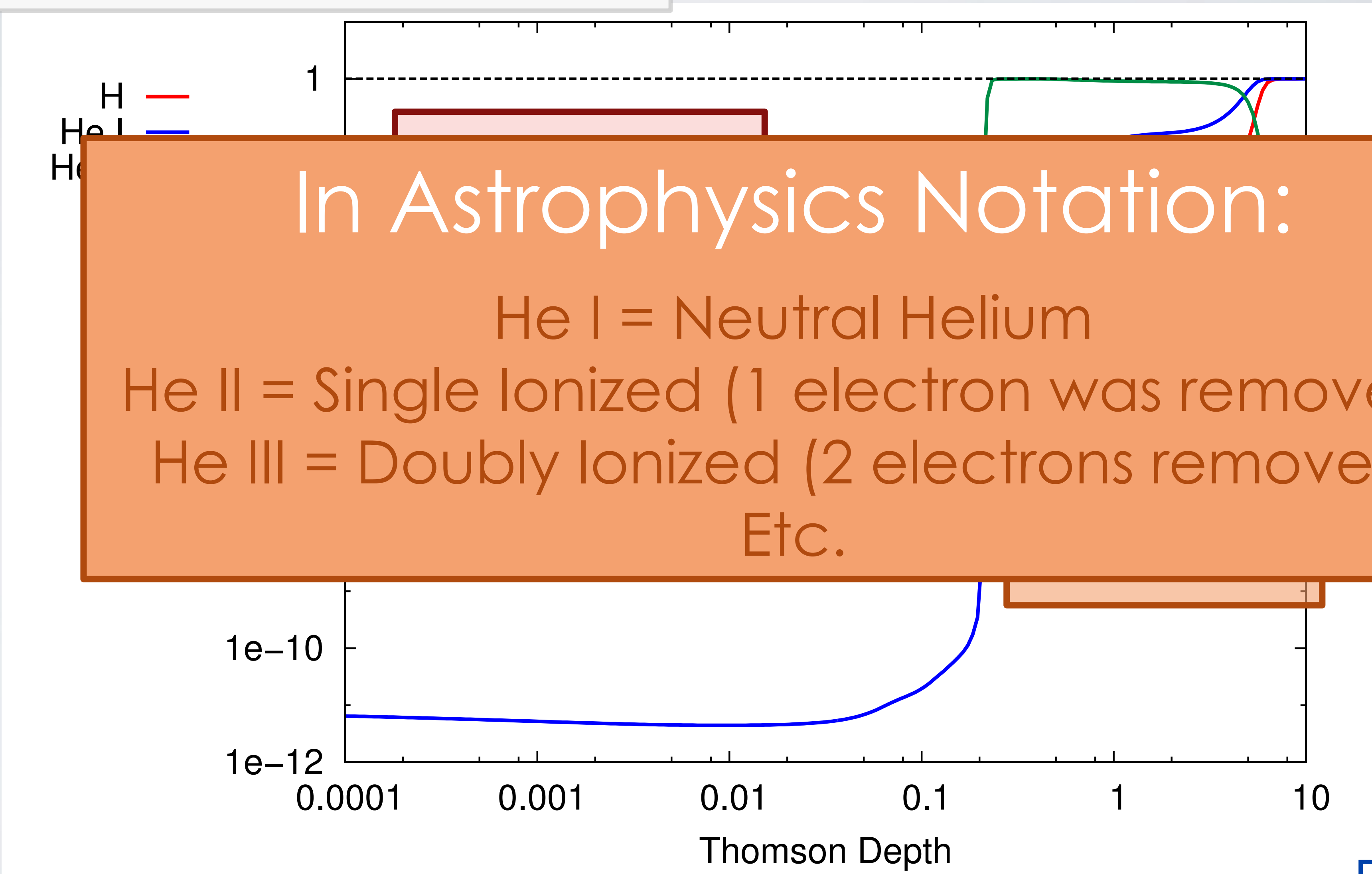
Gamma=2, log Xi = 2, Afe = 1

XILLVER: Temperature Profiles



XILLVER: Ionization Balance

The relative amount of each ion changes with the conditions of the gas



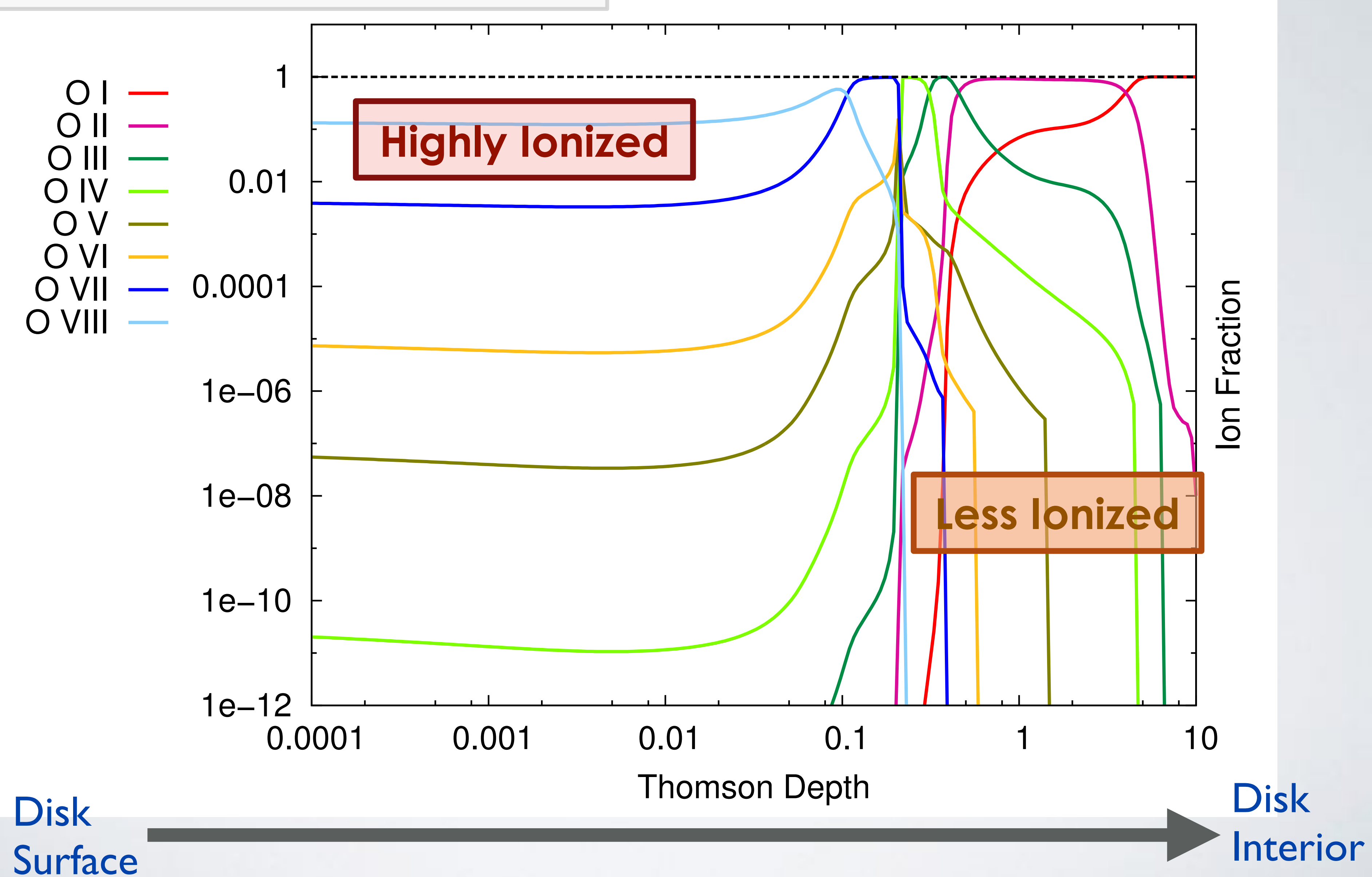
In Astrophysics Notation:

He I = Neutral Helium
He II = Single Ionized (1 electron was removed)
He III = Doubly Ionized (2 electrons removed)
Etc.

Disk Surface → Disk Interior

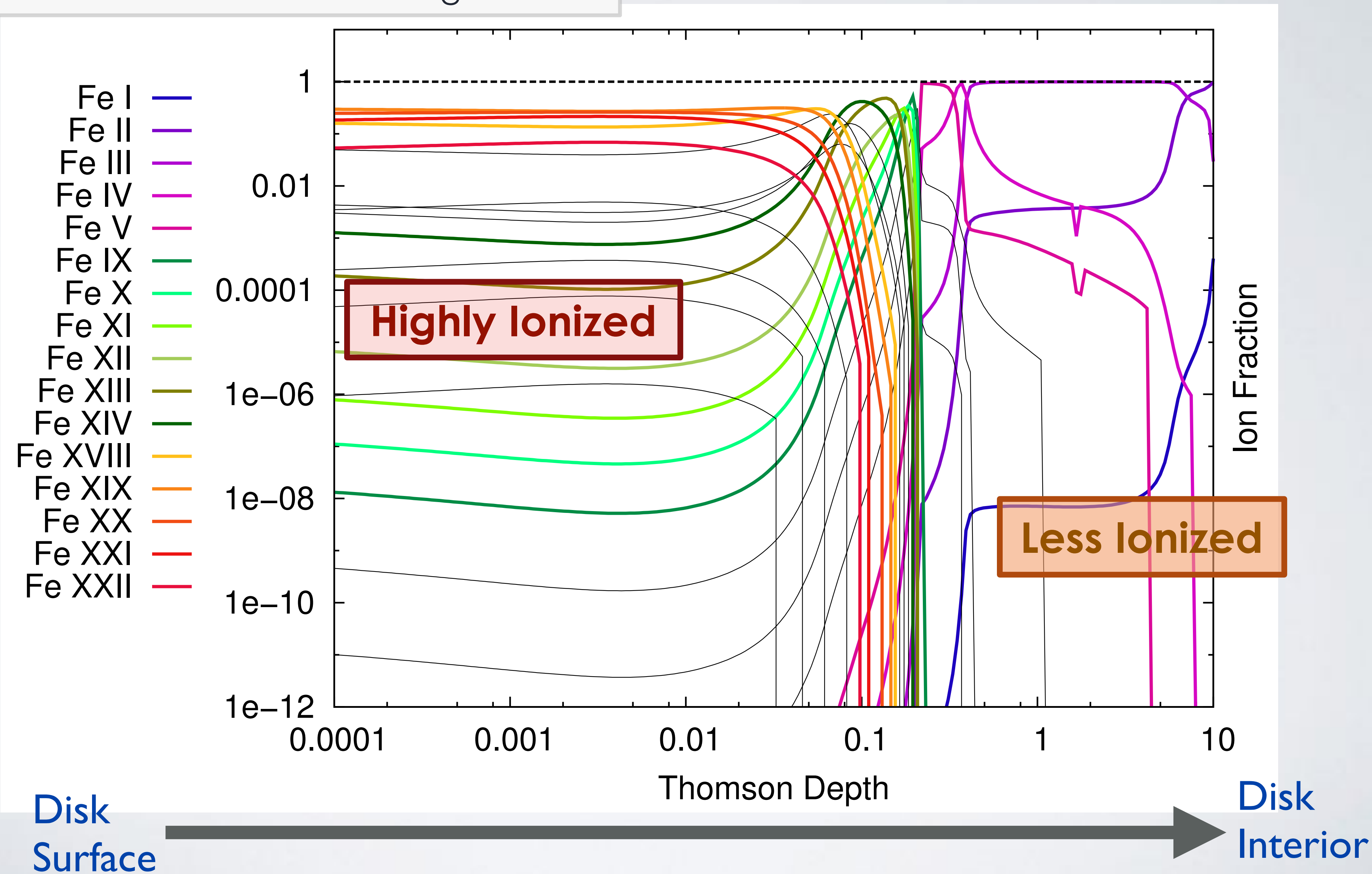
XILLVER: Ionization Balance

The relative amount of each ion changes with the conditions of the gas



XILLVER: Ionization Balance

The relative amount of each ion changes with the conditions of the gas



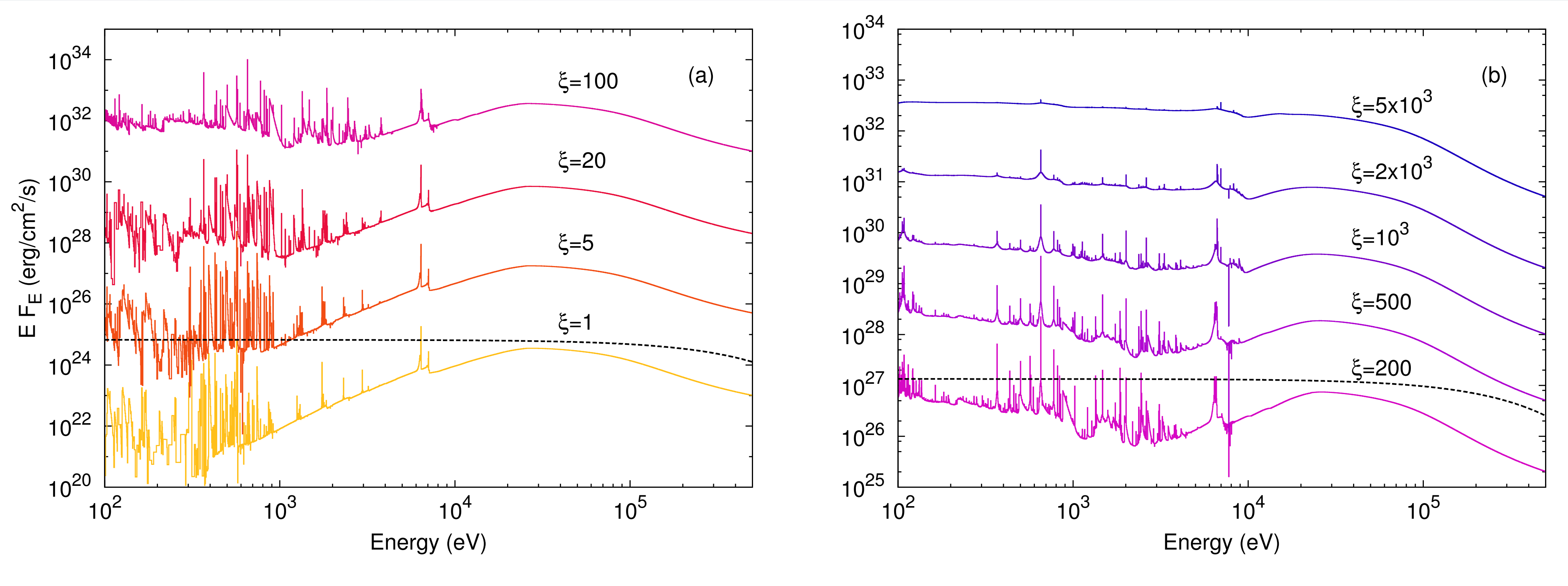
XILLVER: Changing the Ionization

The Ionization Parameter

$$\xi = \frac{4\pi F_x}{n_e}$$

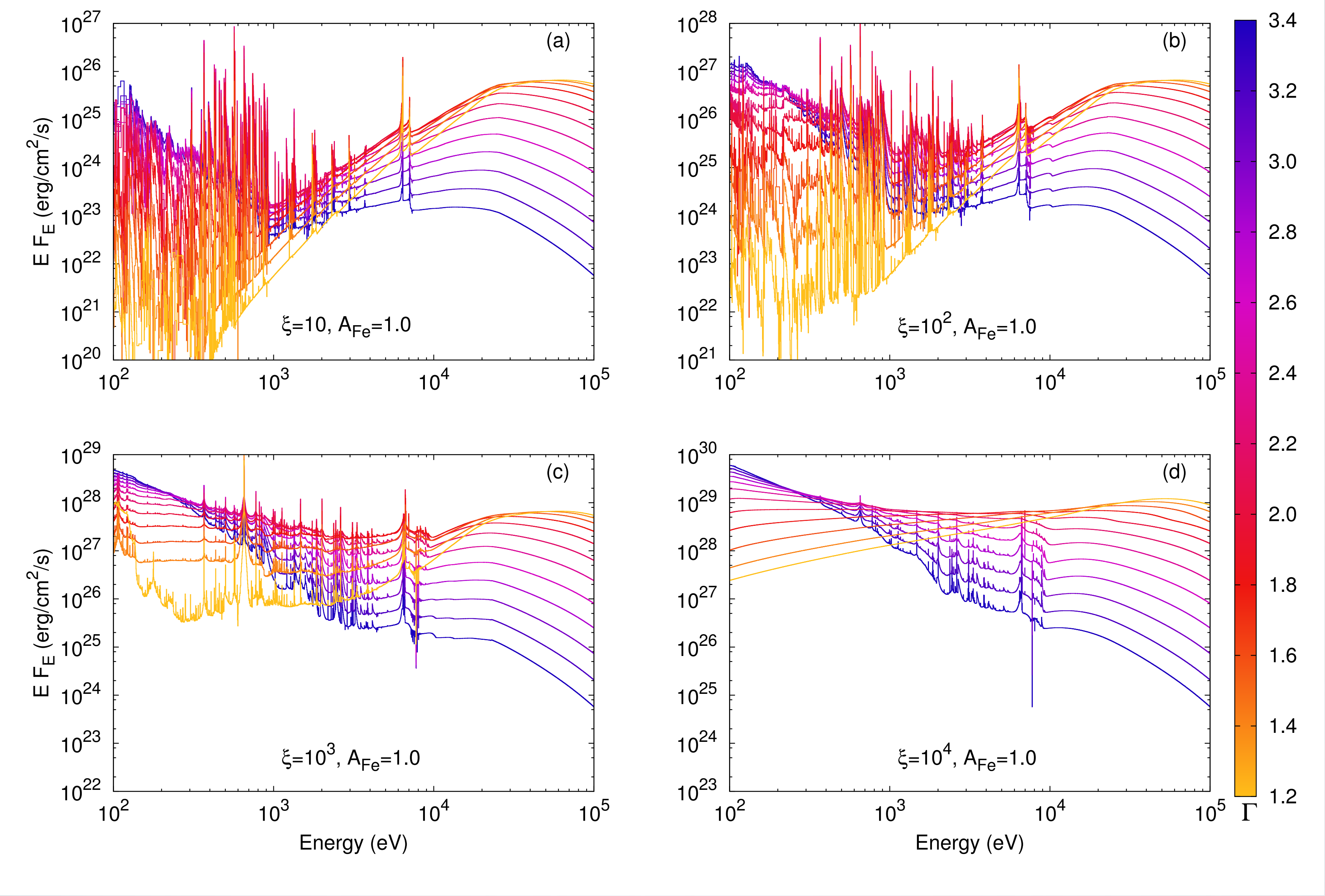
Integrated incident flux

Gas density (held fixed)

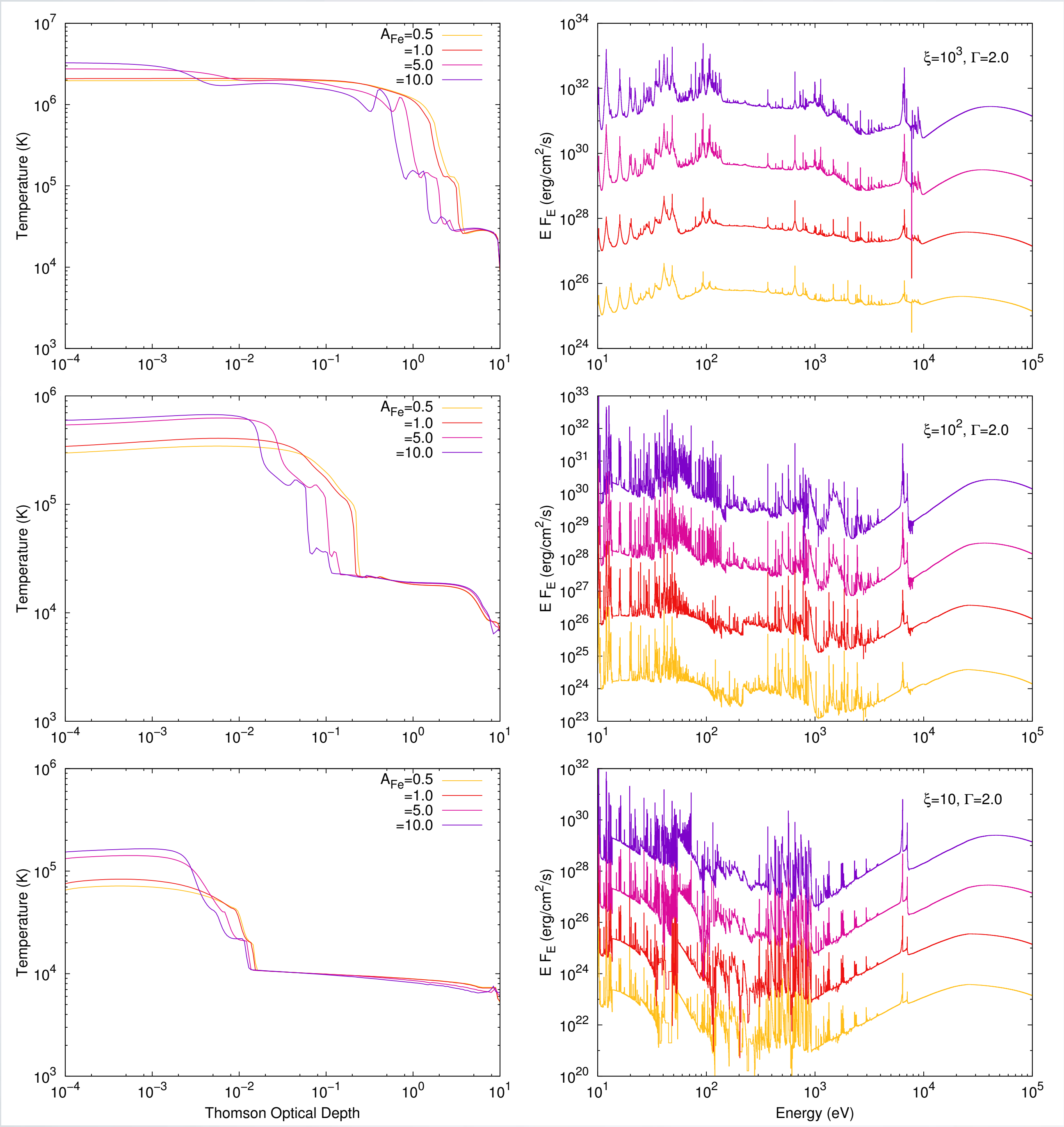


XILLVER: Changing the Photon Index

The ionization parameter is the same, yet the changes are dramatic!



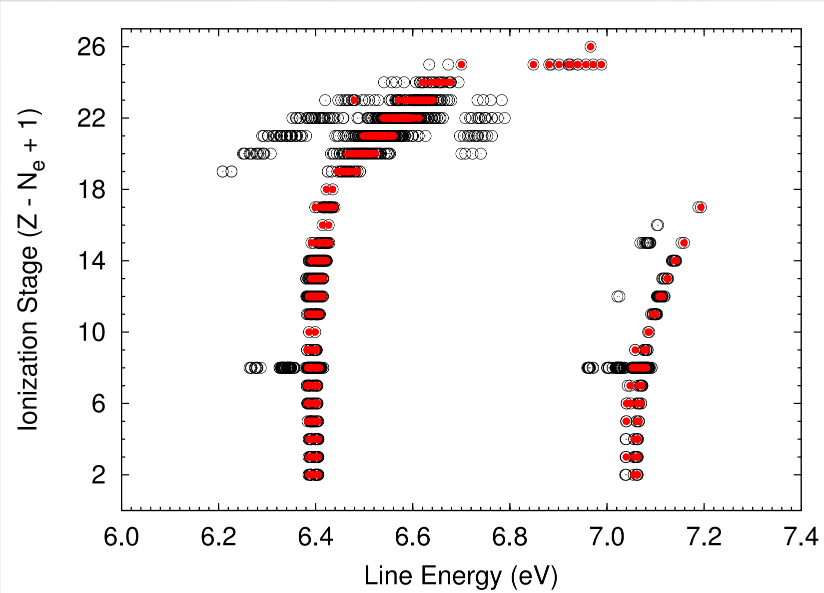
XILLVER: Changing the Iron Abundance

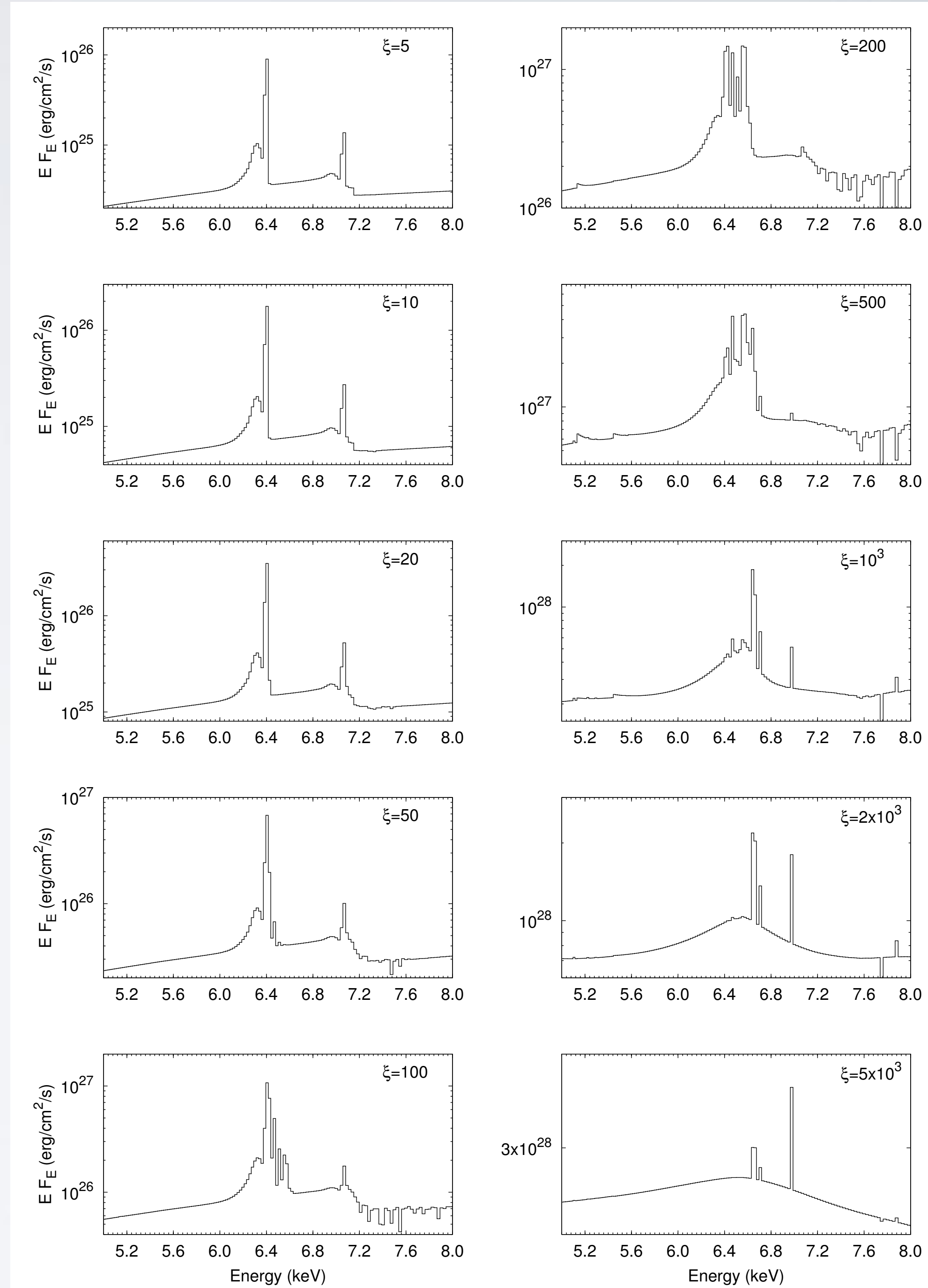


The amount of iron (or any other metals) affects both the state of the gas and the spectrum.

Higher Afe increases both the emission and absorption!

XILLVER: The Fe K Emission Complex

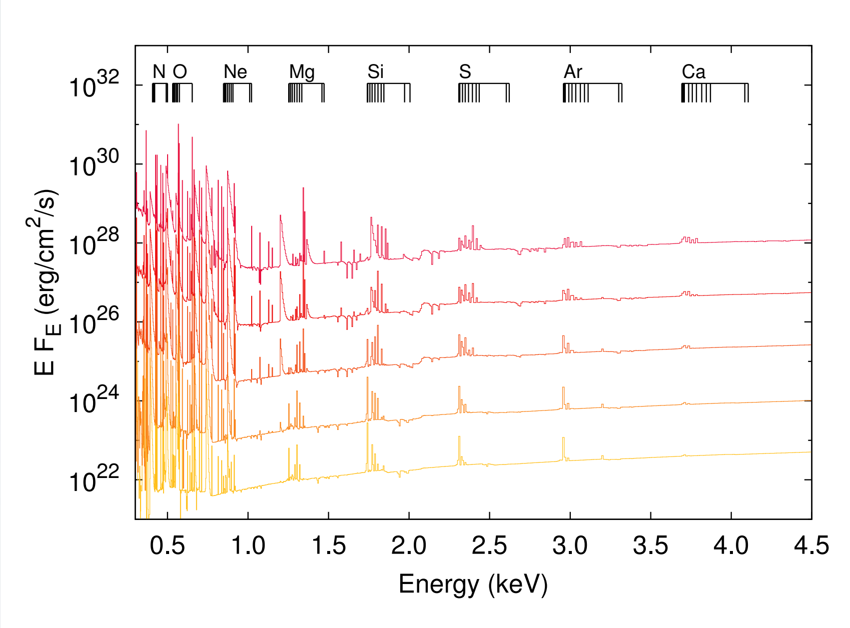




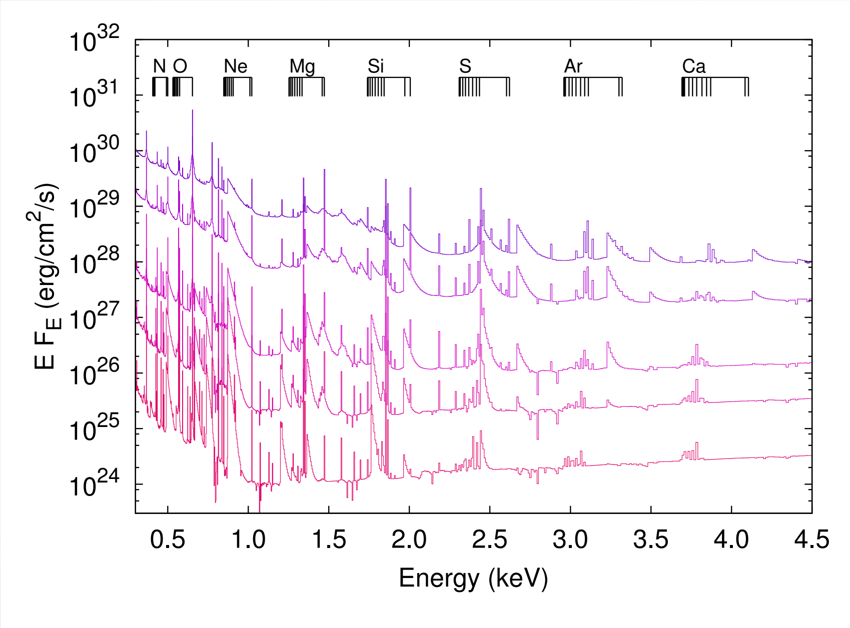
The emission of Fe in the 6-8 keV range is due to a large number of transitions

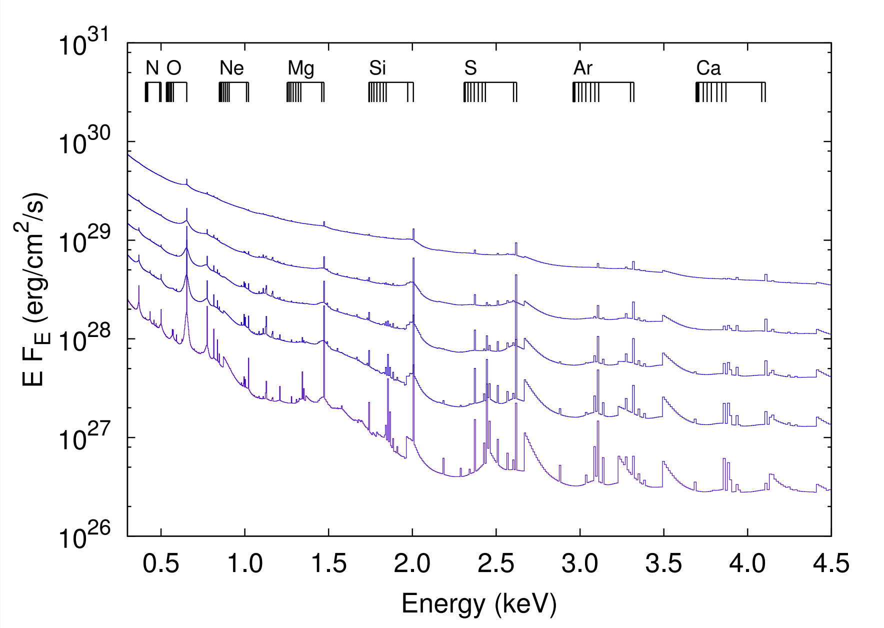
The line energy changes according with the ionization stage

XILLVER: More than Iron

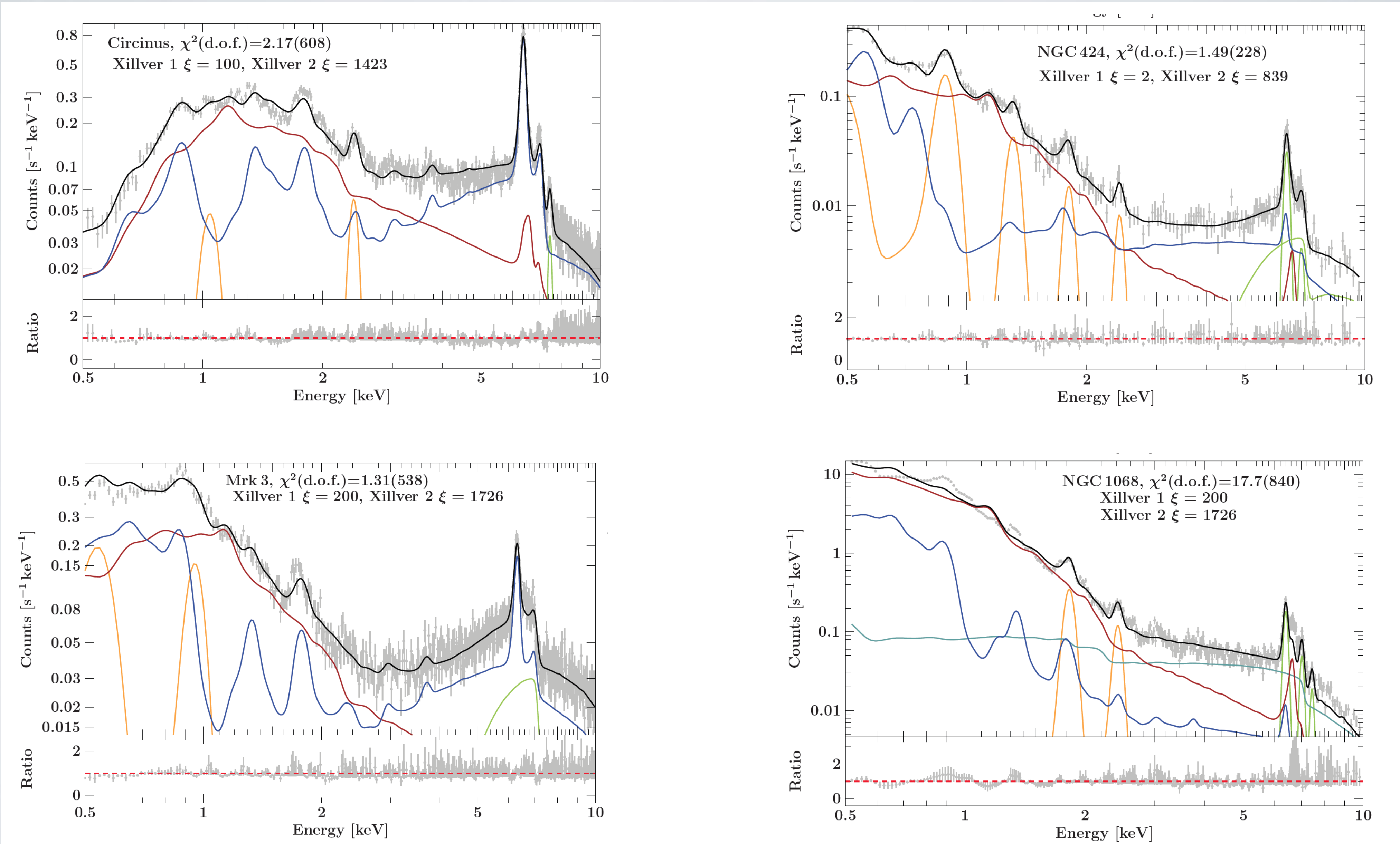


XILLVER includes all astrophysically relevant ions

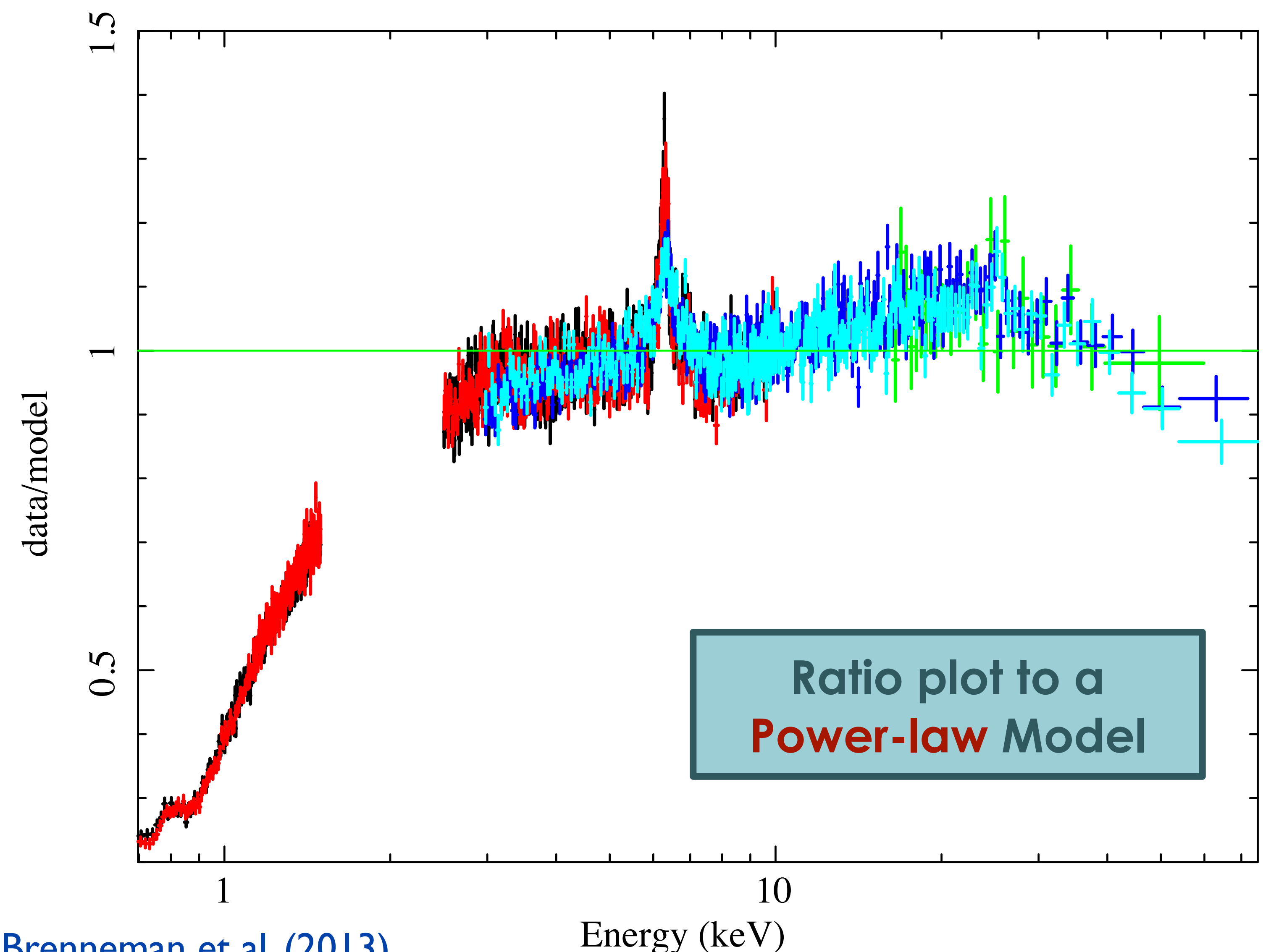




XILLVER: More than Iron

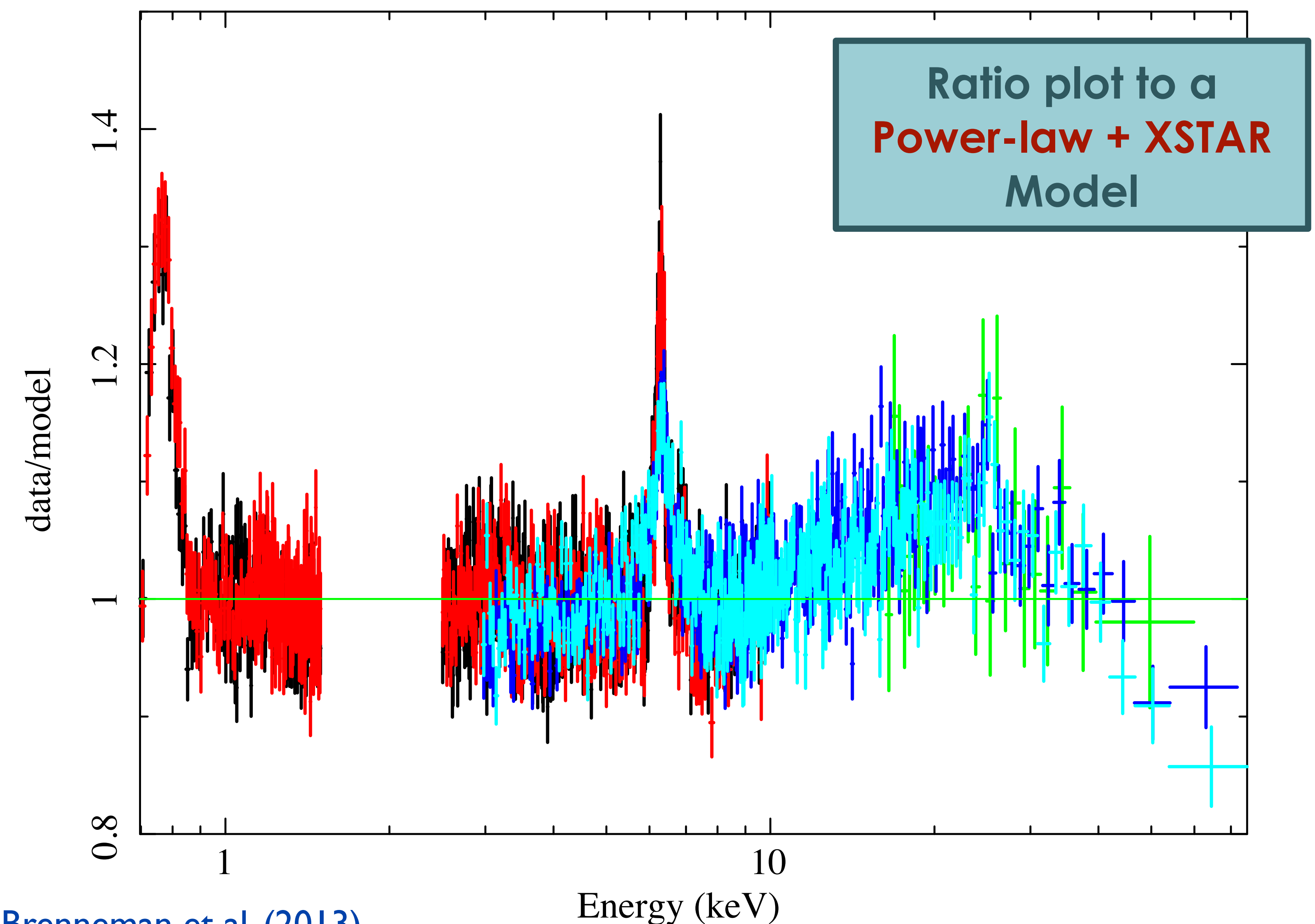


XILLVER: Cold Reflection in IC 4329A



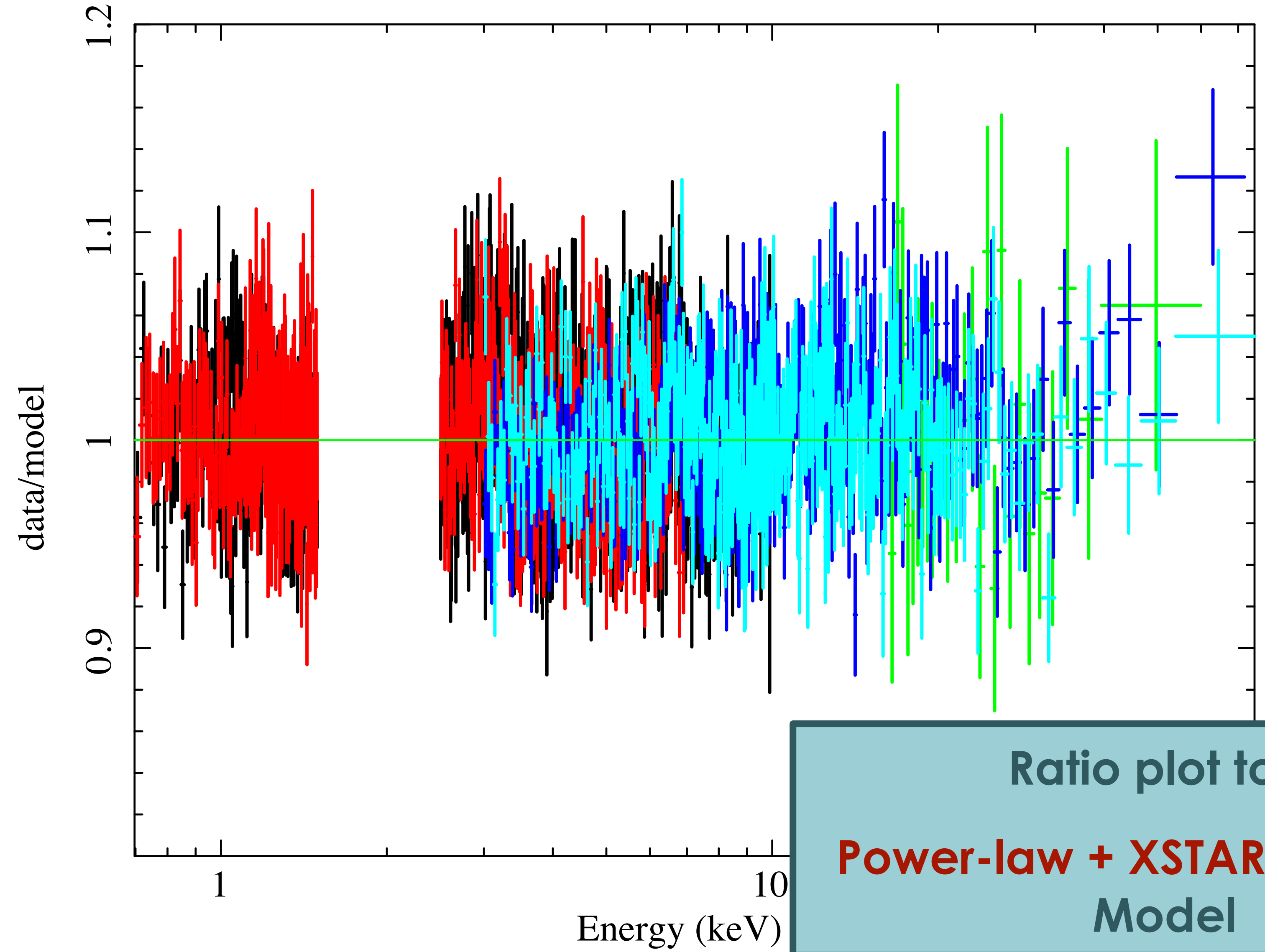
Brenneman et al. (2013)

XILLVER: Cold Reflection in IC 4329A



Brenneman et al. (2013)

XILLVER: Cold Reflection in IC 4329A



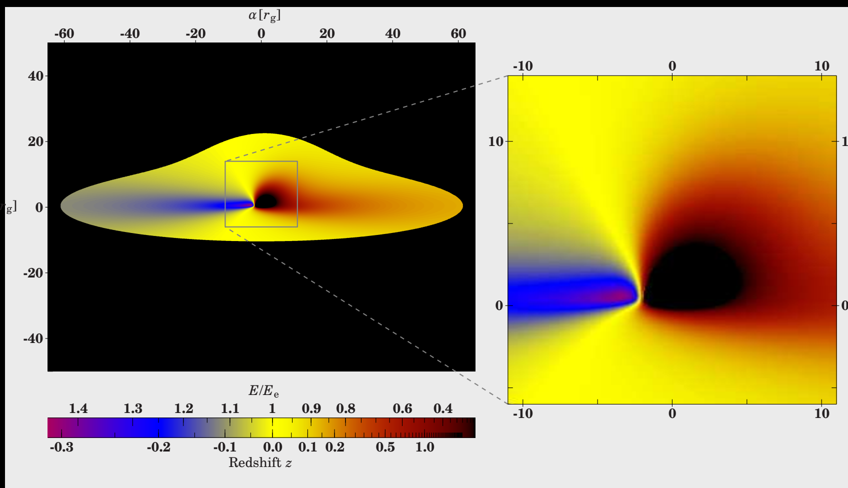
Brenneman et al. (2013)

Ratio plot to a

Power-law + XSTAR + XILLVER Model


Relativistic effects also need to be accounted for!

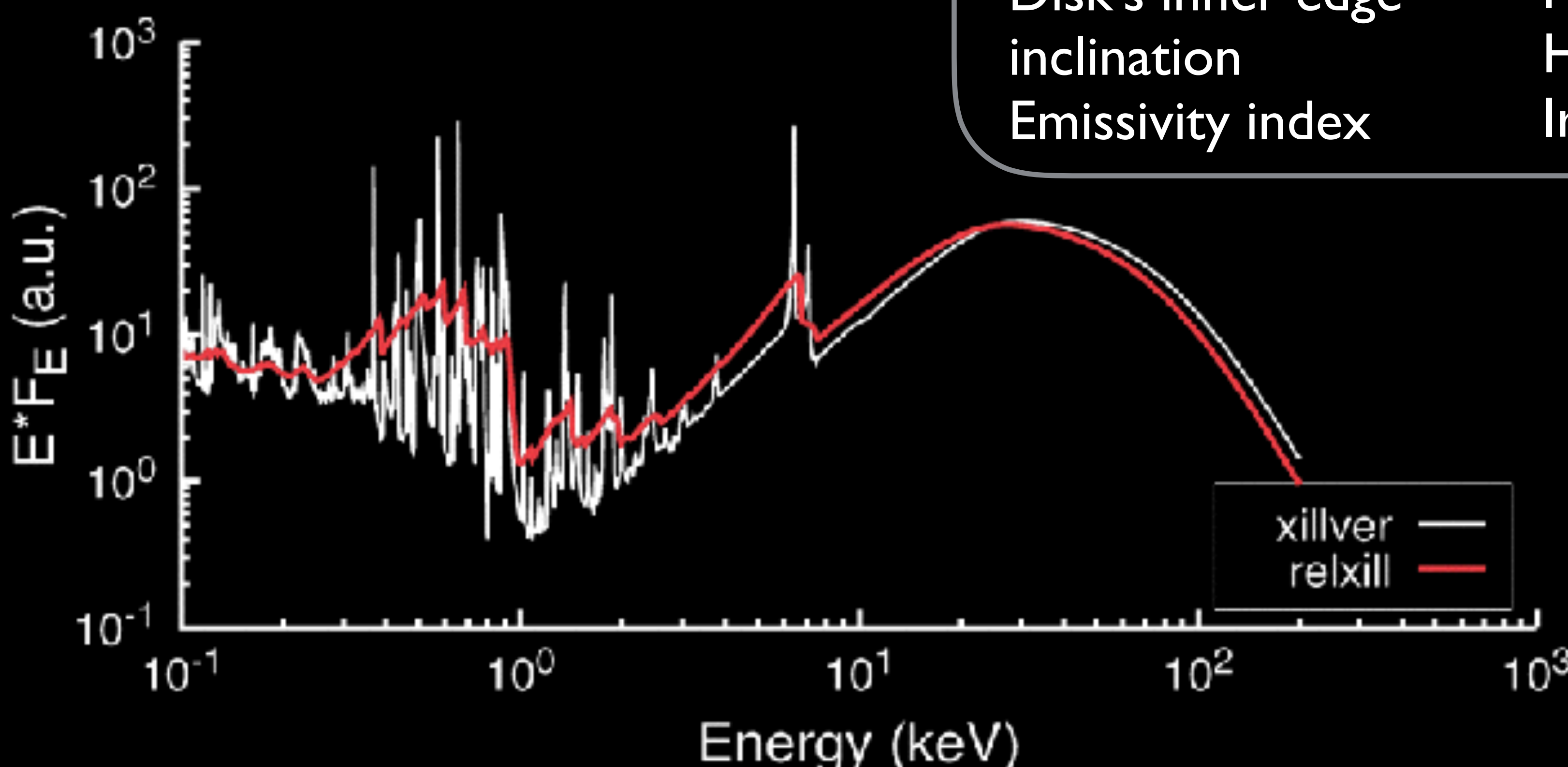
Modeling Relativistic Reflection



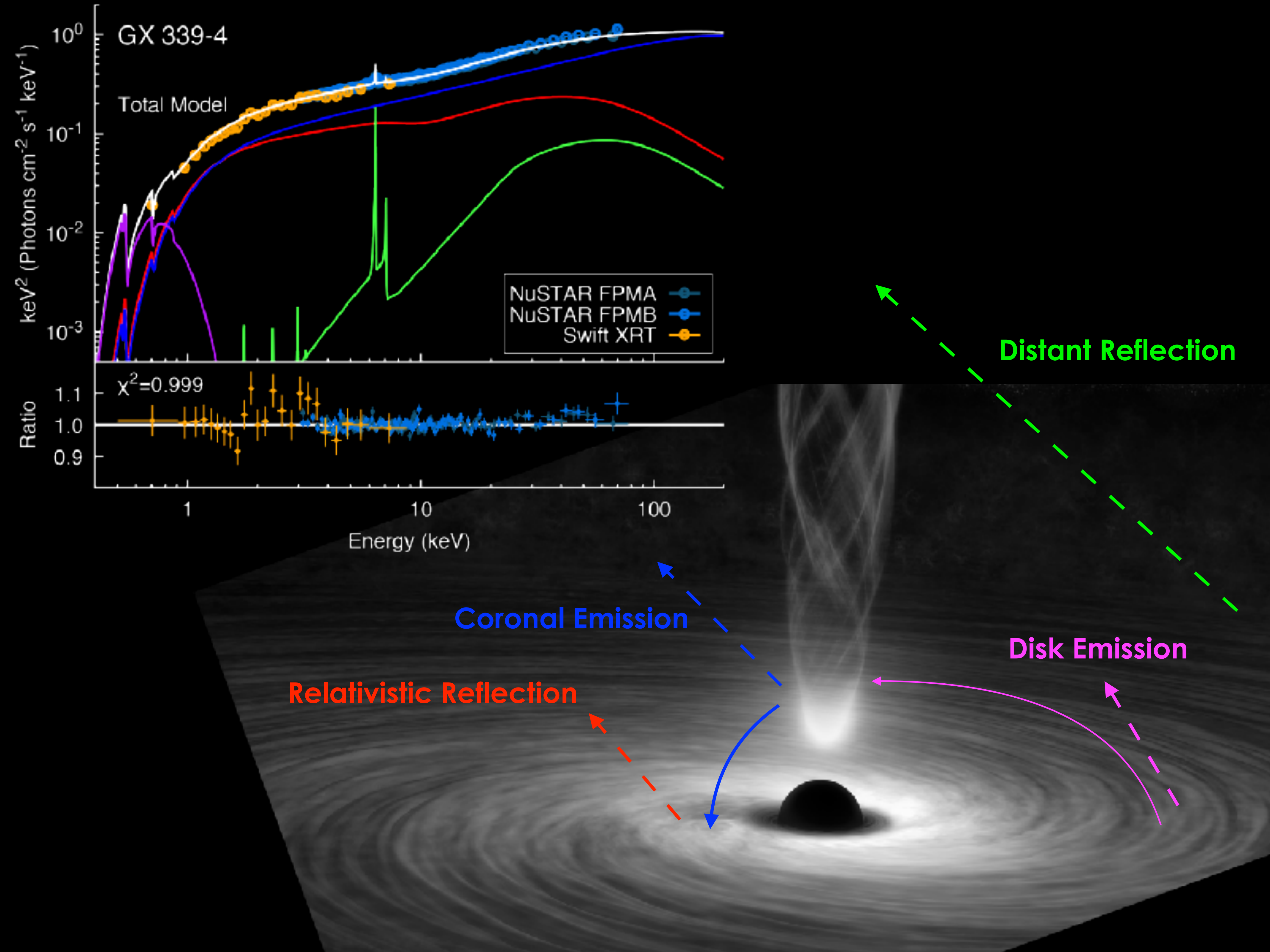
The relxill model: Combines ionized reflection spectra from xillver (Garcia & Kallman 2010), with the relativistic blurring code relline (Dauser et al. 2010)

Model parameters:

Black hole spin	Reflection fraction
Disk's inner edge	Photon index
inclination	High energy cutoff
Emissivity index	Iron abundance



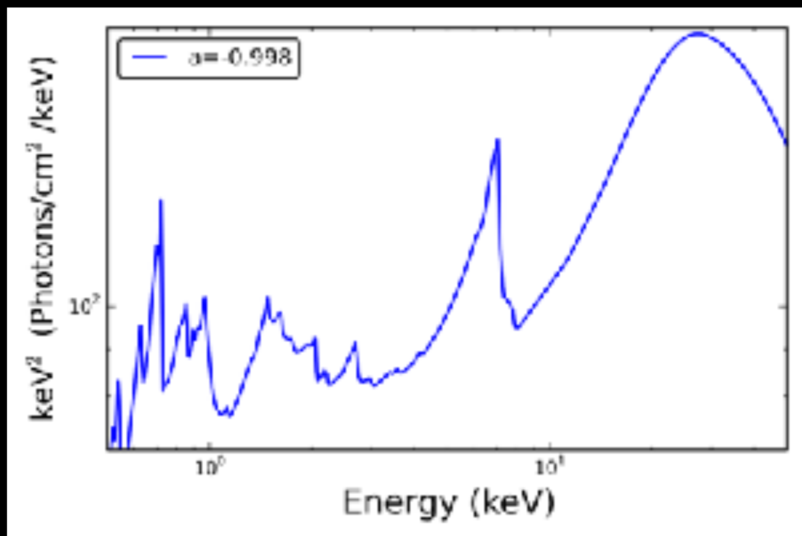
García et al. (2014)



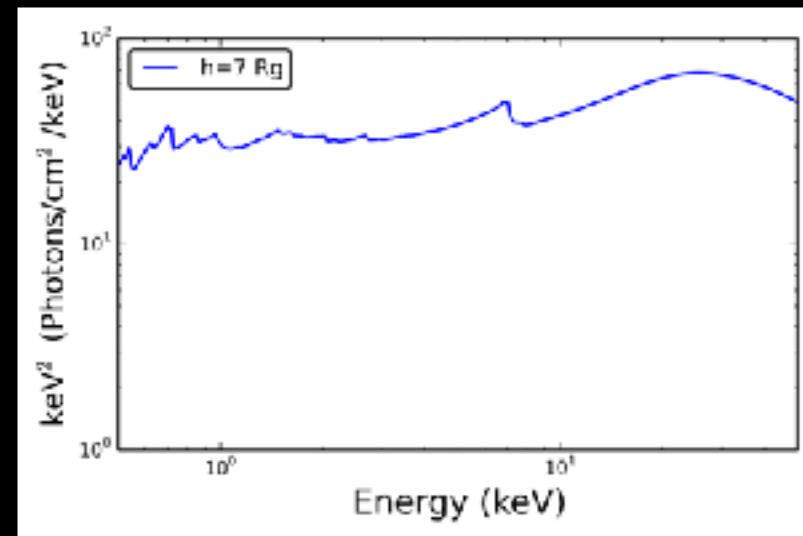
GX 339-4
Total Model
keV^2 (Photons cm^{-2} s^{-1} keV^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
NuSTAR FPMA
NuSTAR FPMB
Swift XRT
χ^2=0.999
Ratio
1.1
1.0
0.9
1
10
100
Energy (keV)
Distant Reflection
Coronal Emission
Disk Emission
Relativistic Reflection

Constraining Physical Quantities

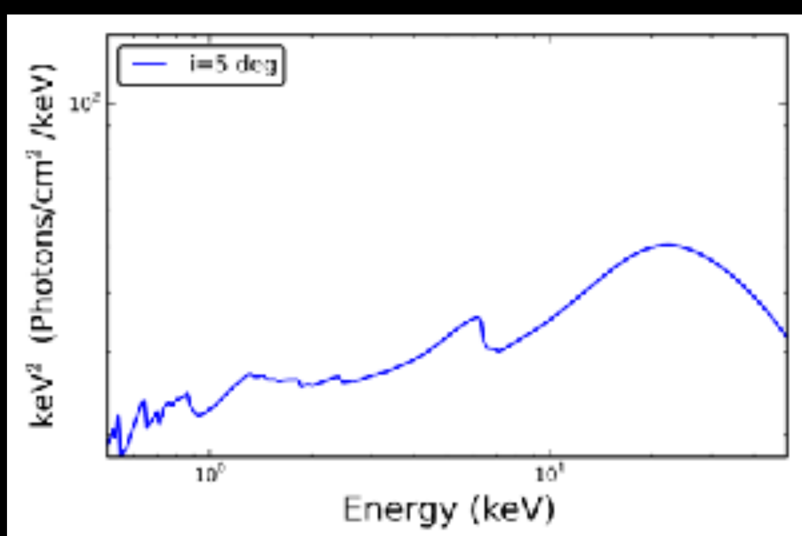
Black Hole Spin



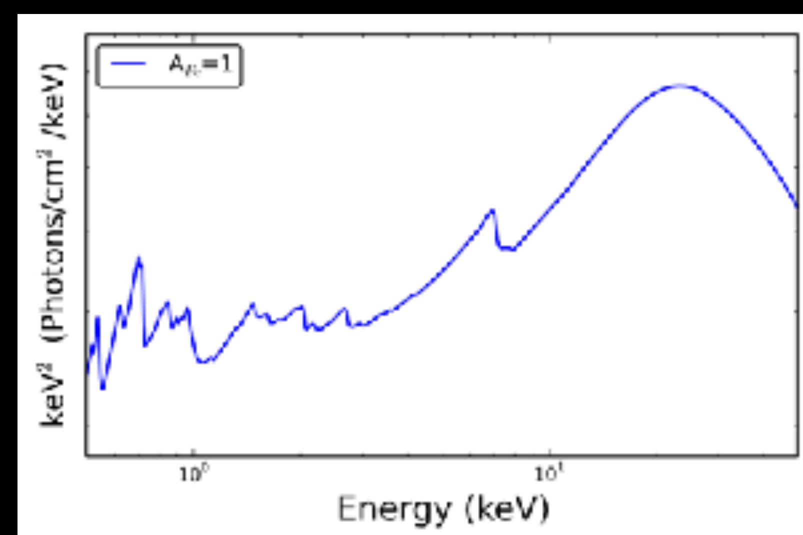
Coronal Height



Inclination



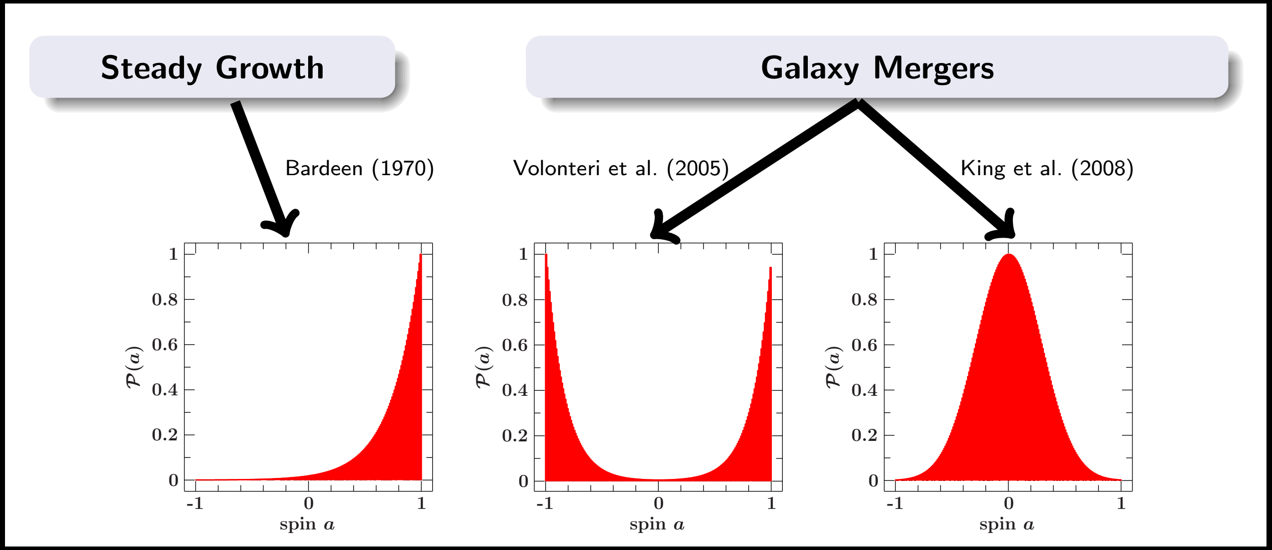
Iron Abundance

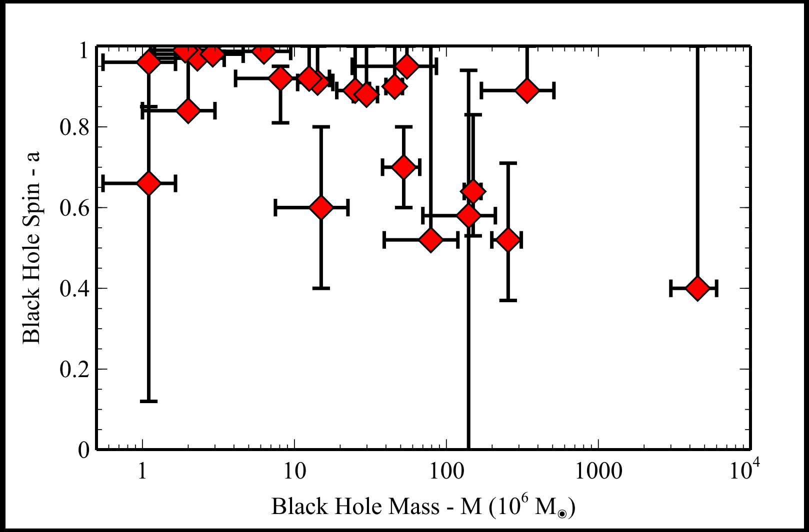


Measuring the Spin of Black Holes

Spin Distribution for SMBHs

The distribution of Spin vs Mass can constrain SMBH formation models (Steady Growth/Galaxy Mergers)





Reynolds (2014),Vasudevan et a. (2016)

Possible observational biases:

- Radiative efficiency scales as ~1/r, which favors high spin detections.
- Also, high spin and low coronae enhances the reflection fraction.

Measuring Spins in BHBs

- BH spins are not always easy to measure. BHBs provide better signal but there are still discrepancies.
- Results often depend on the quality of the data, but also on the quality of the observer ;)

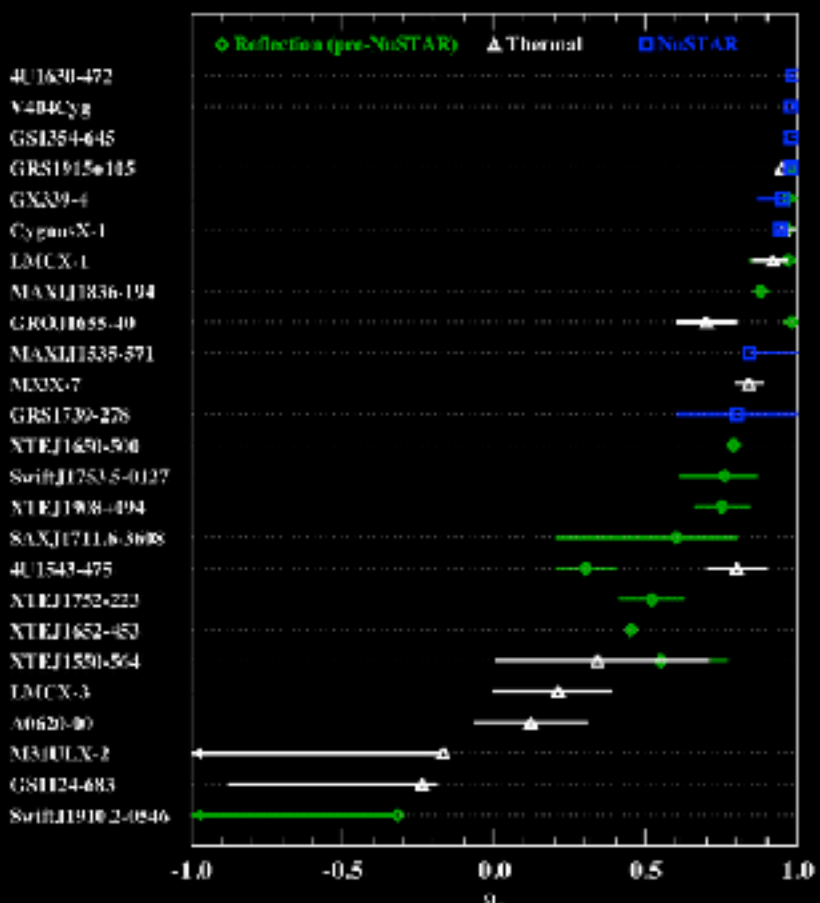
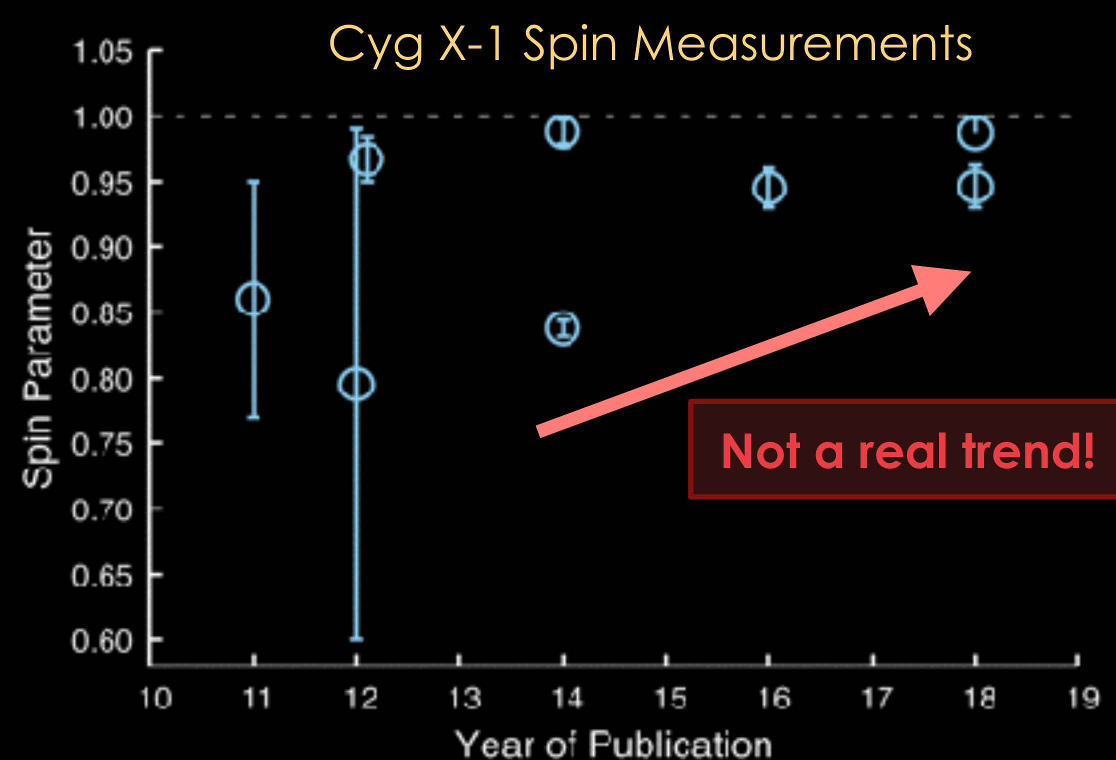


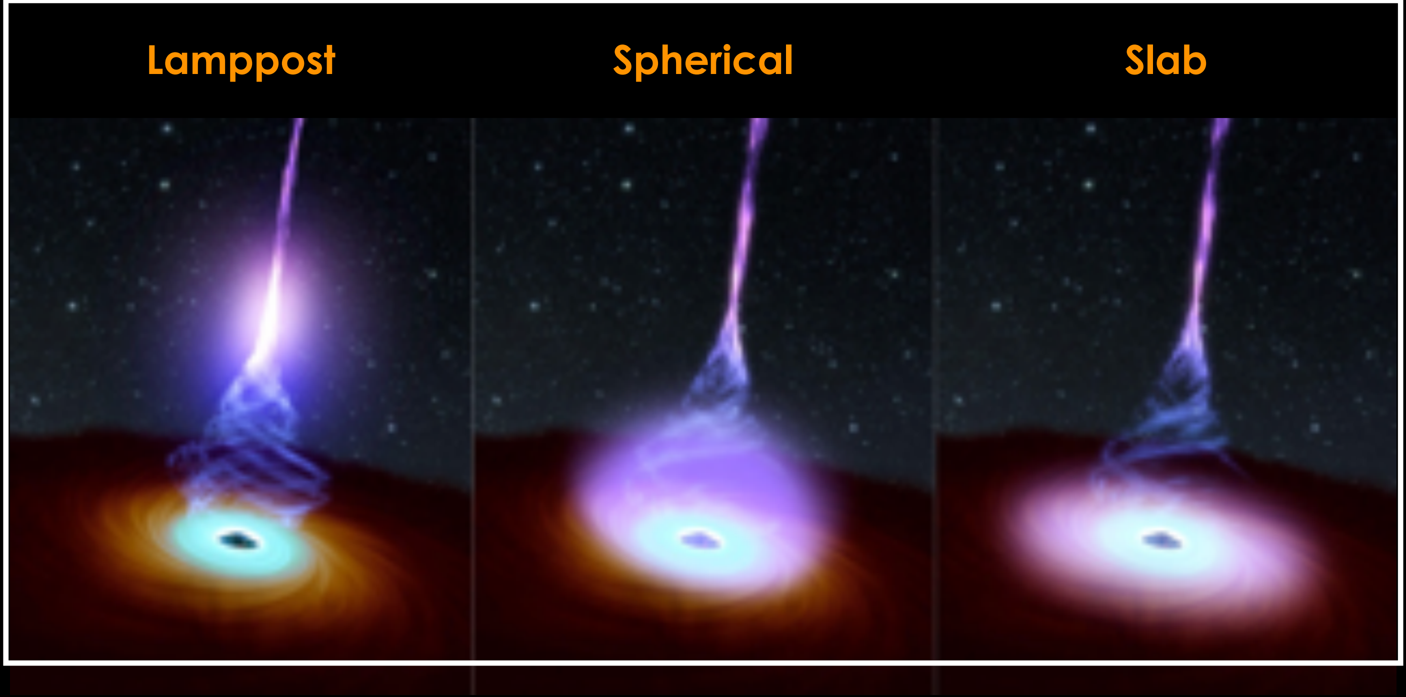
Figure courtesy of J. Tomsick



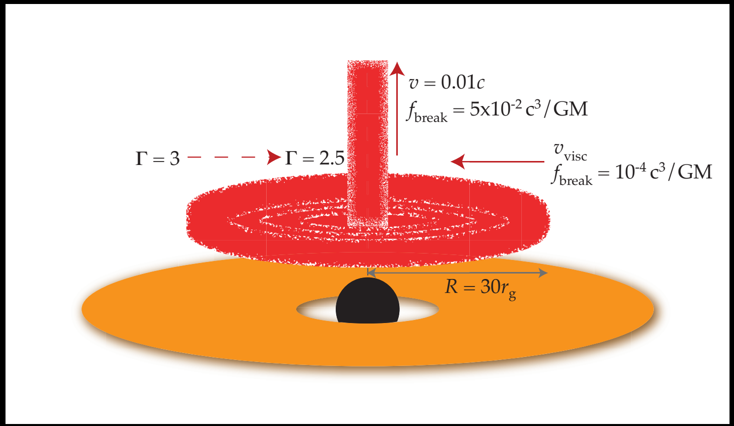
Compilation from Krawczynski (2018)

The Evolution of the Corona and the Accretion Disk

Coronal Geometry

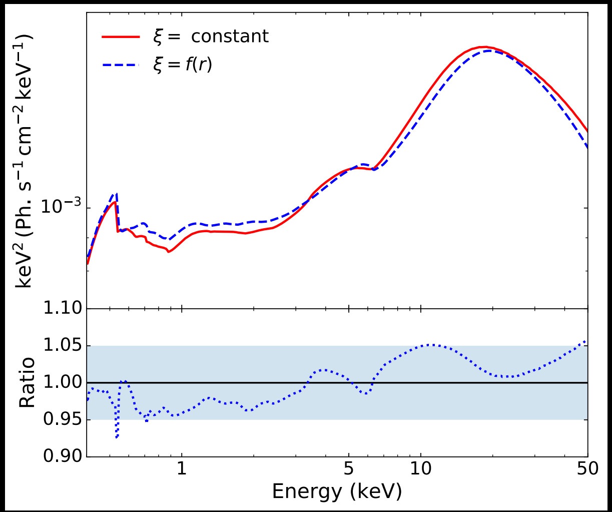


Non-Static and Extended Corona



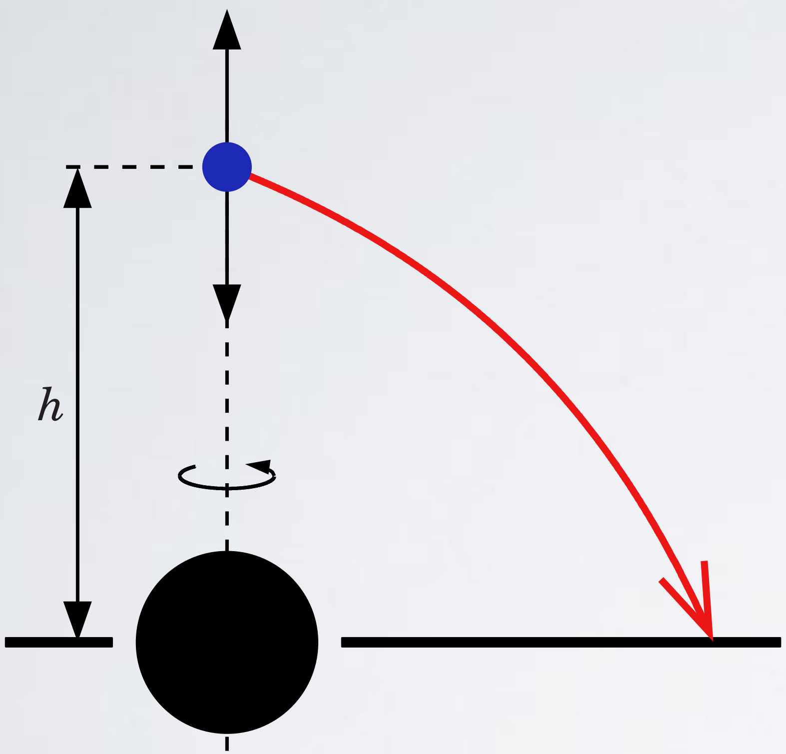
Wilkins et al. (2016)

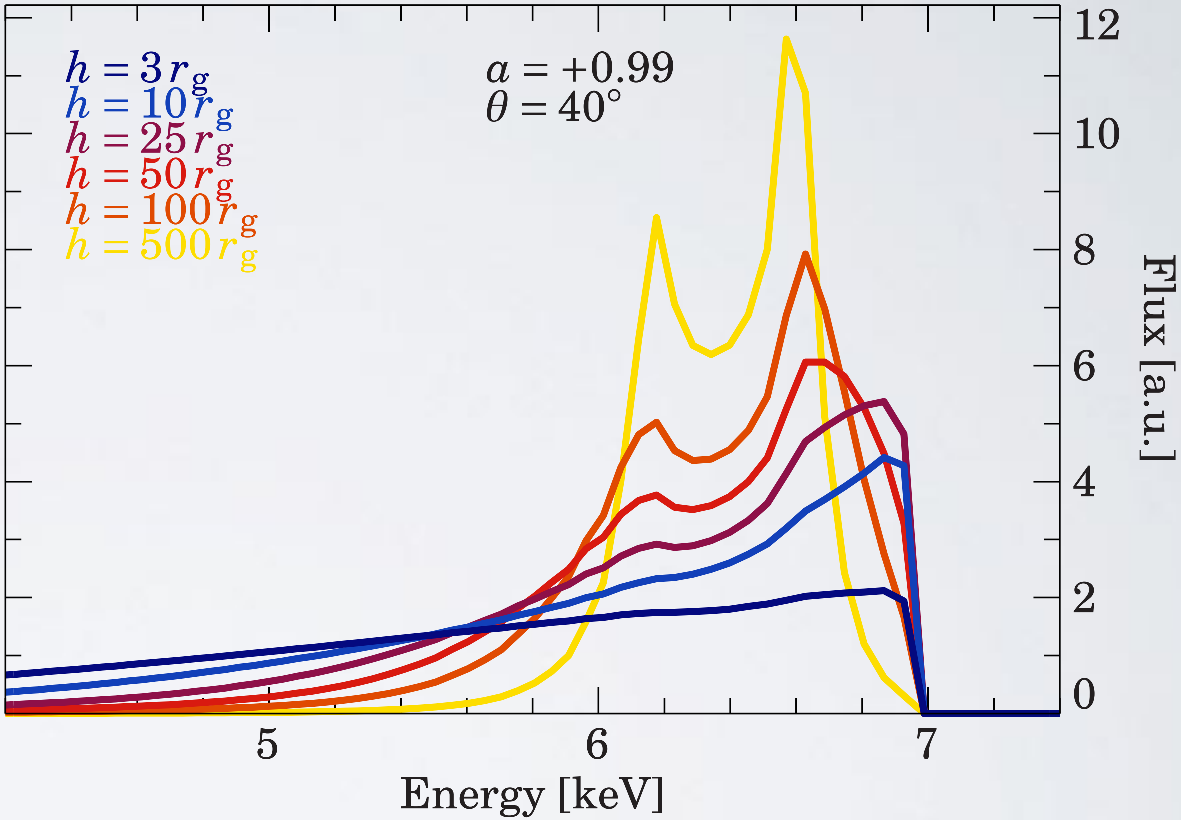
Ionization Gradients



Svoboda et al. (2012)
Kammoun et al. (2019)

Diagnostic Tool: Geometry





Probe geometry and location of the primary source

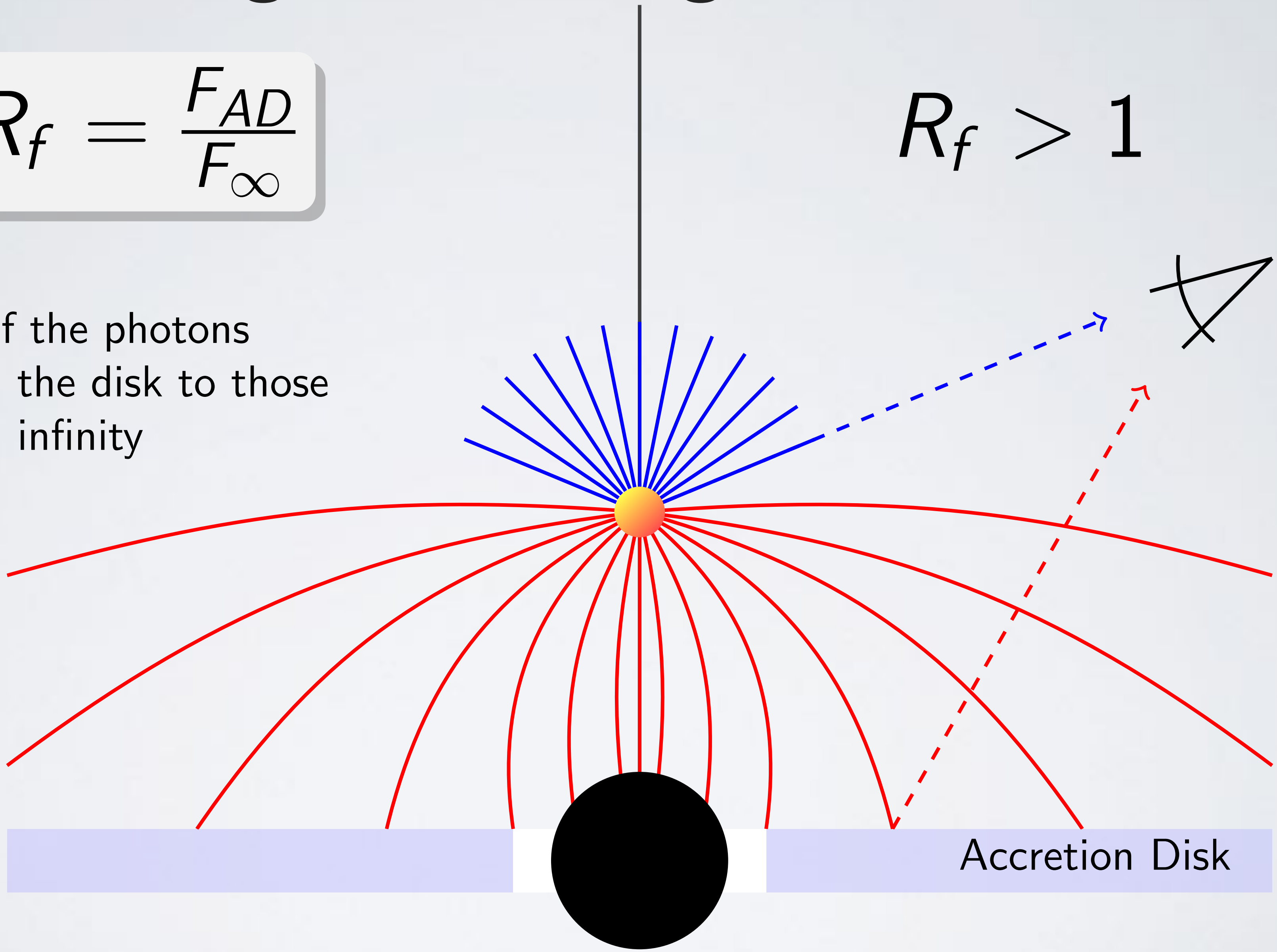
Low high implies enhanced irradiation of the inner regions

Light Bending Effects

$$R_f = \frac{F_{AD}}{F_\infty}$$

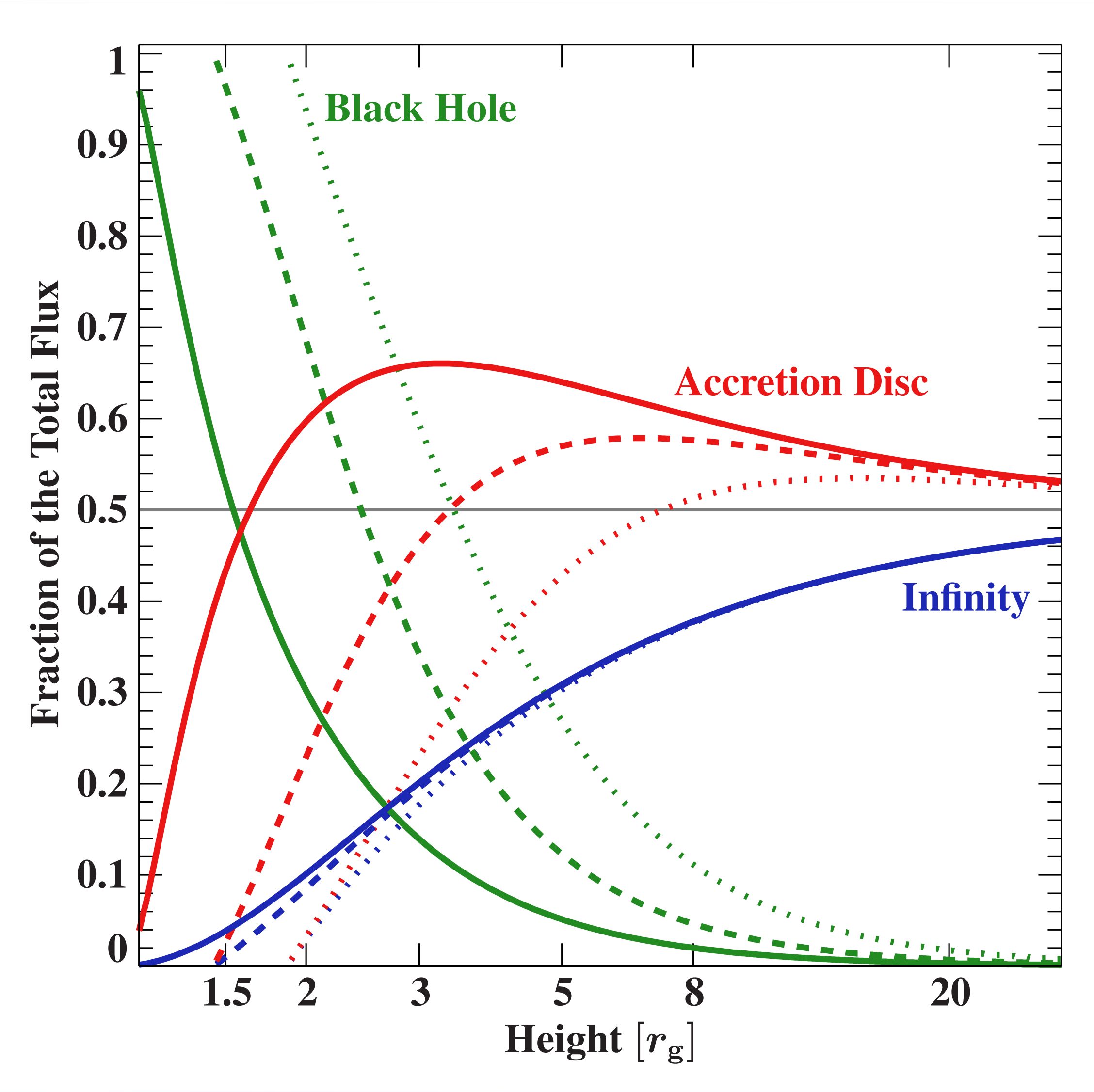
$$R_f > 1$$

Fraction of the photons that reach the disk to those that reach infinity



Dauser, Garcia et al. (2014)

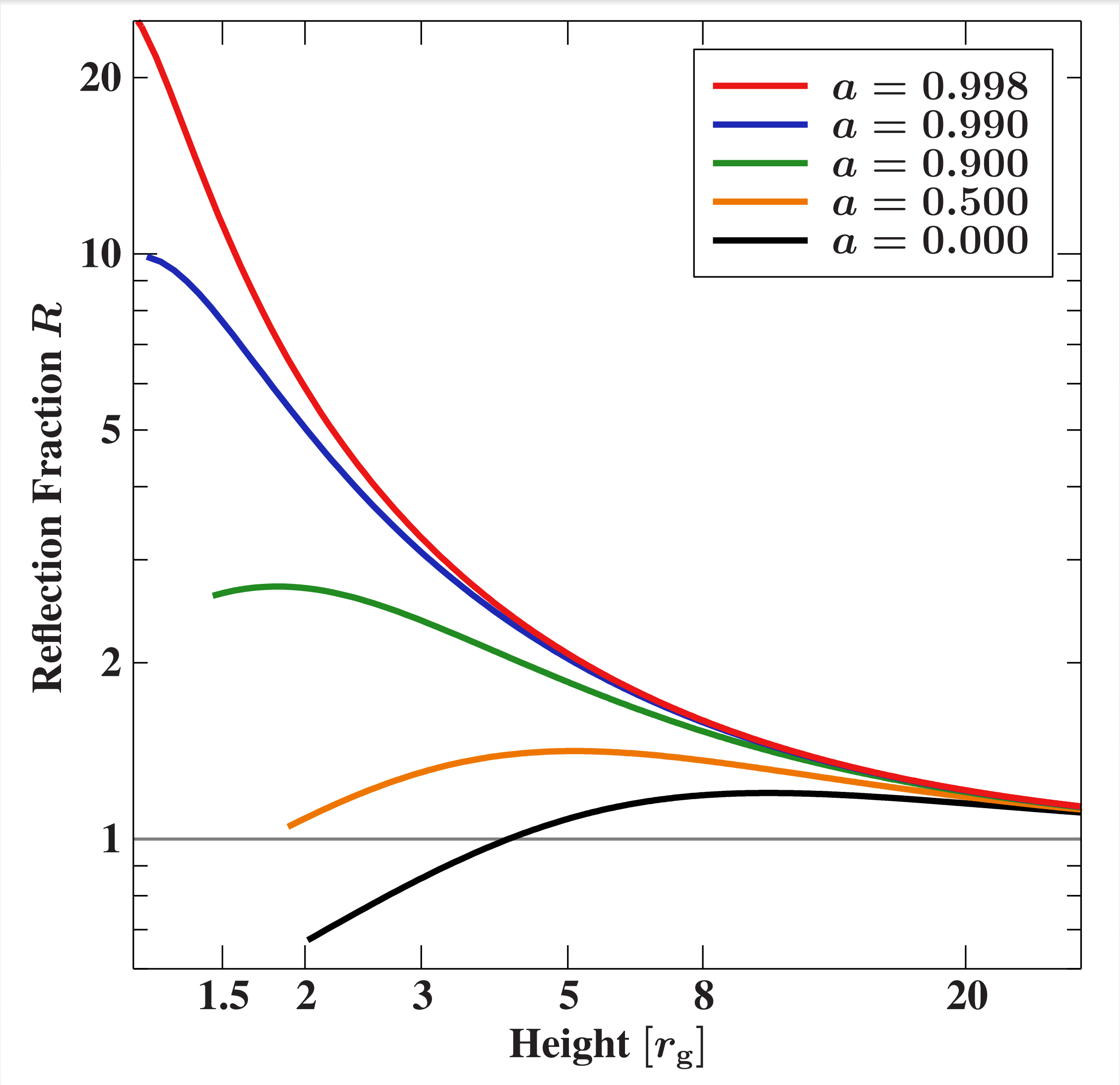
The Reflection Fraction



Photons from the corona can reach the observer, hit the accretion disk, or get lost in the black hole

Dauser, Garcia et al. (2014)

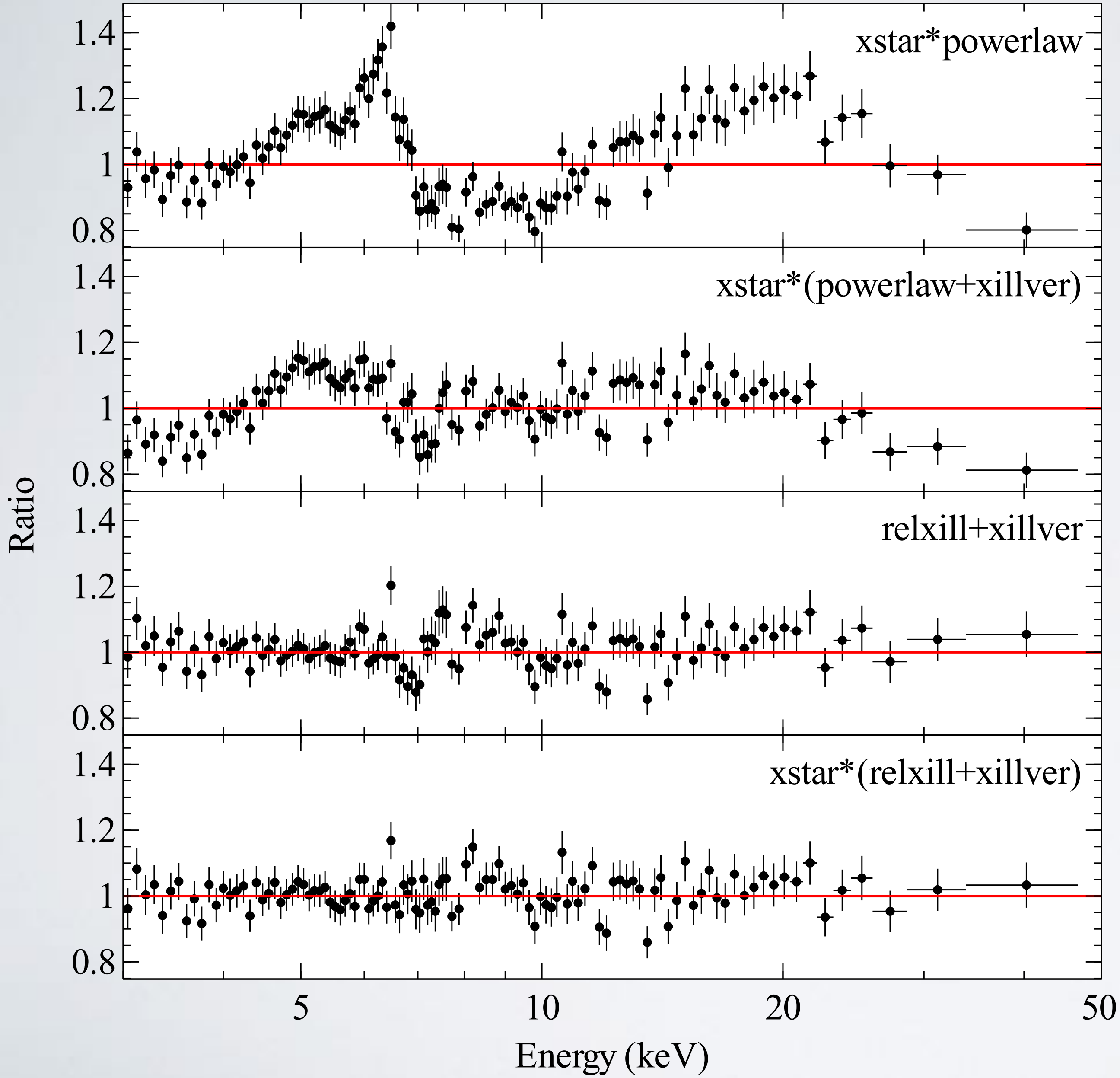
The Reflection Fraction



The reflection fraction is controlled by the spin, inner radius, and the height of the X-ray source

Dauser, Garcia et al. (2014)

Extreme Reflection in Mrk 335



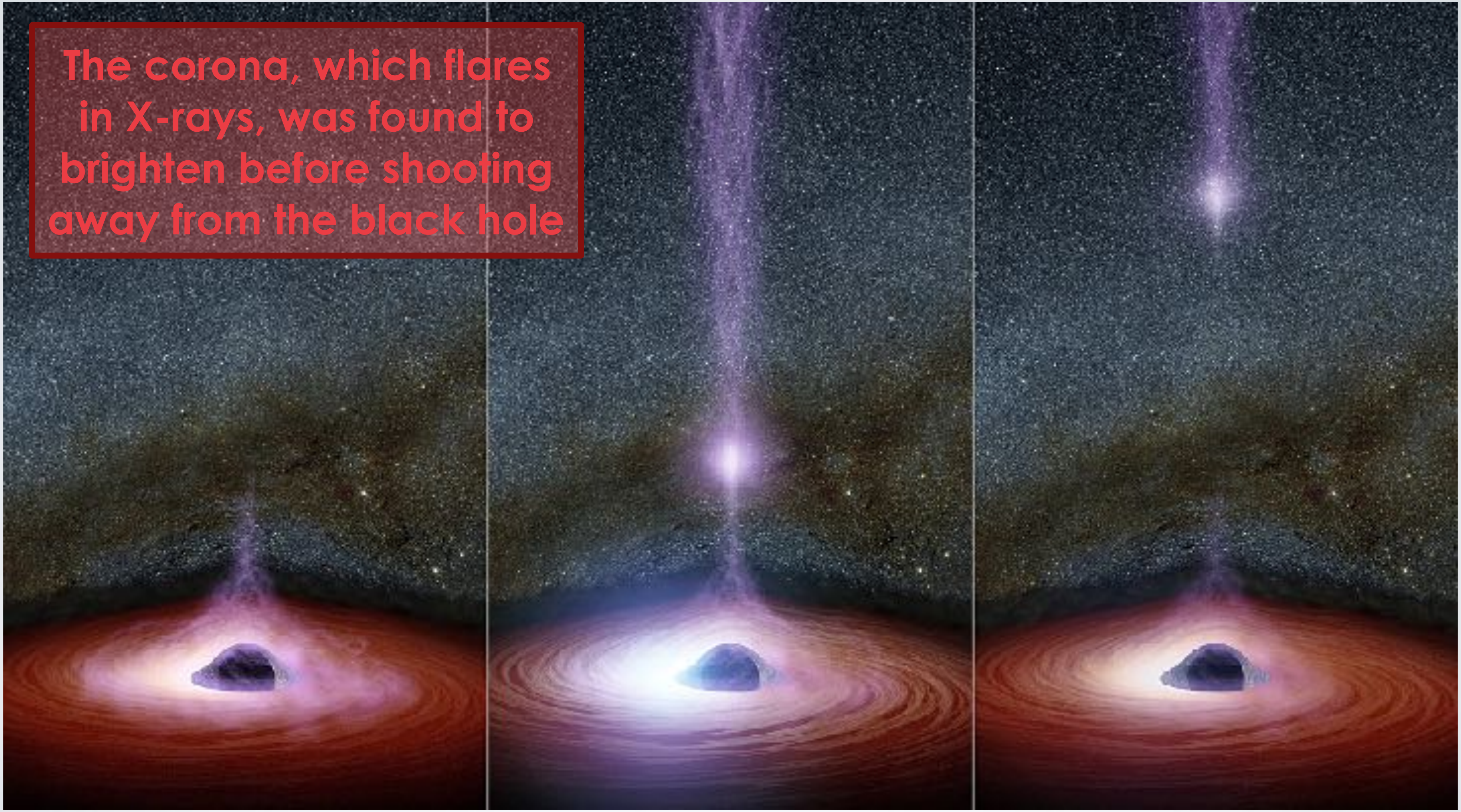
Relativistic effects are observed within just 2 gravitational radii of the event of horizon!
(Rg = GM/c^2)

Rapidly-spinning black hole
(a=0.9 at 3-sigma confidence)

Powerlaw: continuum Emission
XSTAR: warm absorber
XILLVER: distant reflection
RELXILL: relativistic reflection

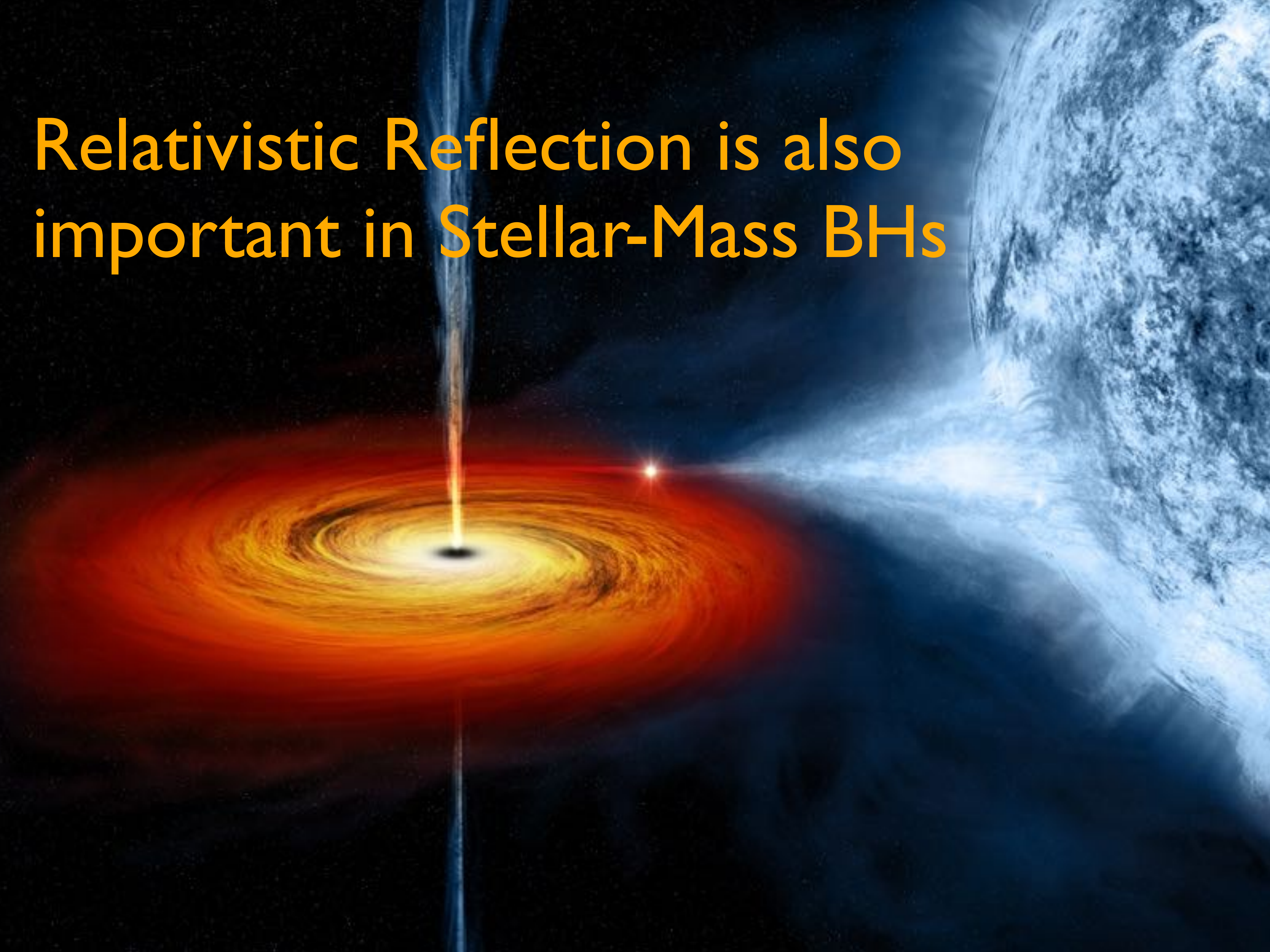
100 ks NuSTAR observation (Parker et al. 2014)

Extreme Reflection in Mrk 335

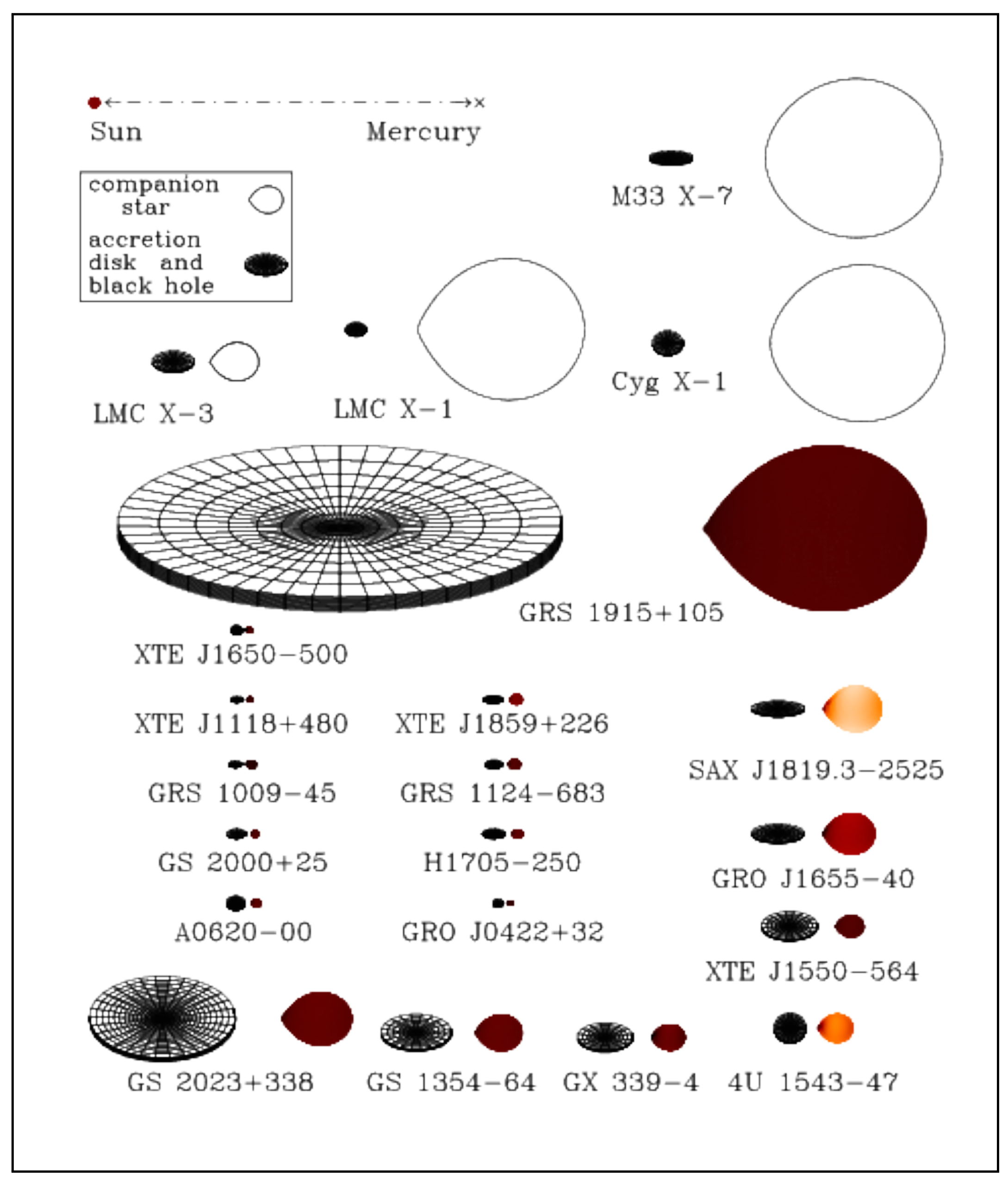


Wilkins et al. (2015)

Relativistic Reflection is also important in Stellar-Mass BHs



Black Hole Binaries (BHBs)



(Figure courtesy of Jerome Oroz)

- Stellar Masses (~5-30 Msun)
- Modest variability in human time-scales
- Many are transient in nature
- They flare in X-rays increasing their luminosity by a billion fold
- An outburst can last from weeks to months
- AU-scale persistent jets and parsec-scale ballistic jets
- X-ray Quasi-Periodic Oscillations (QPOs) (0.01-450 Hz)
- **Very distinct spectral states: hard/intermediate/soft**

RXTE: Rossi X-ray Timing Experiment

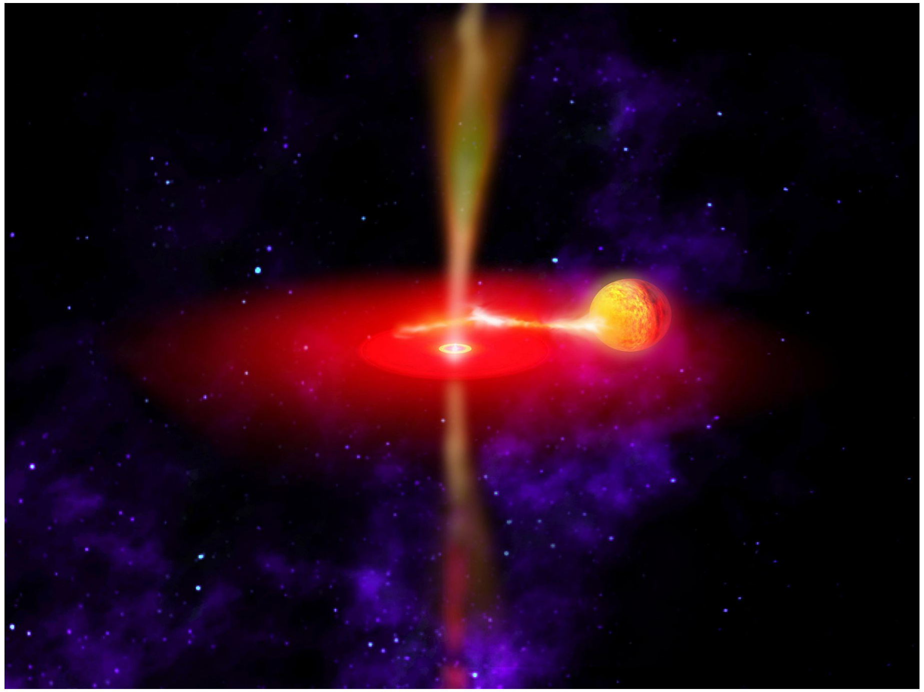
Observed hundreds of X-ray sources between December 1995 and January 2012

Proportional Counter Array (PCA)

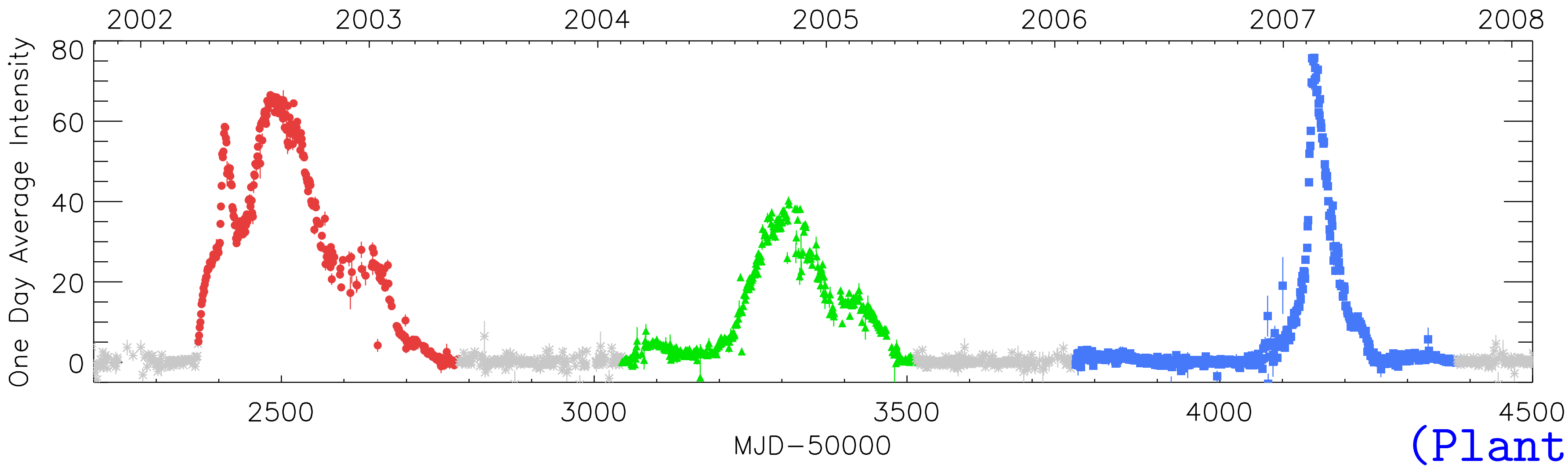
- Energy range: 2 - 60 keV
- Energy resolution: $<$ 18% at 6 keV
- Time resolution: 1 microsec
- Detectors: 5 proportional counters
- Collecting area: 6500 square cm
- Layers: 1 Propane veto; 3 Xenon, each split into two; 1 Xenon veto layer
- Sensitivity: 0.1 mCrab

PCA made ~110,000 pointed observations collecting ~295 Msec of data

The Prototypical BHB GX 339-4

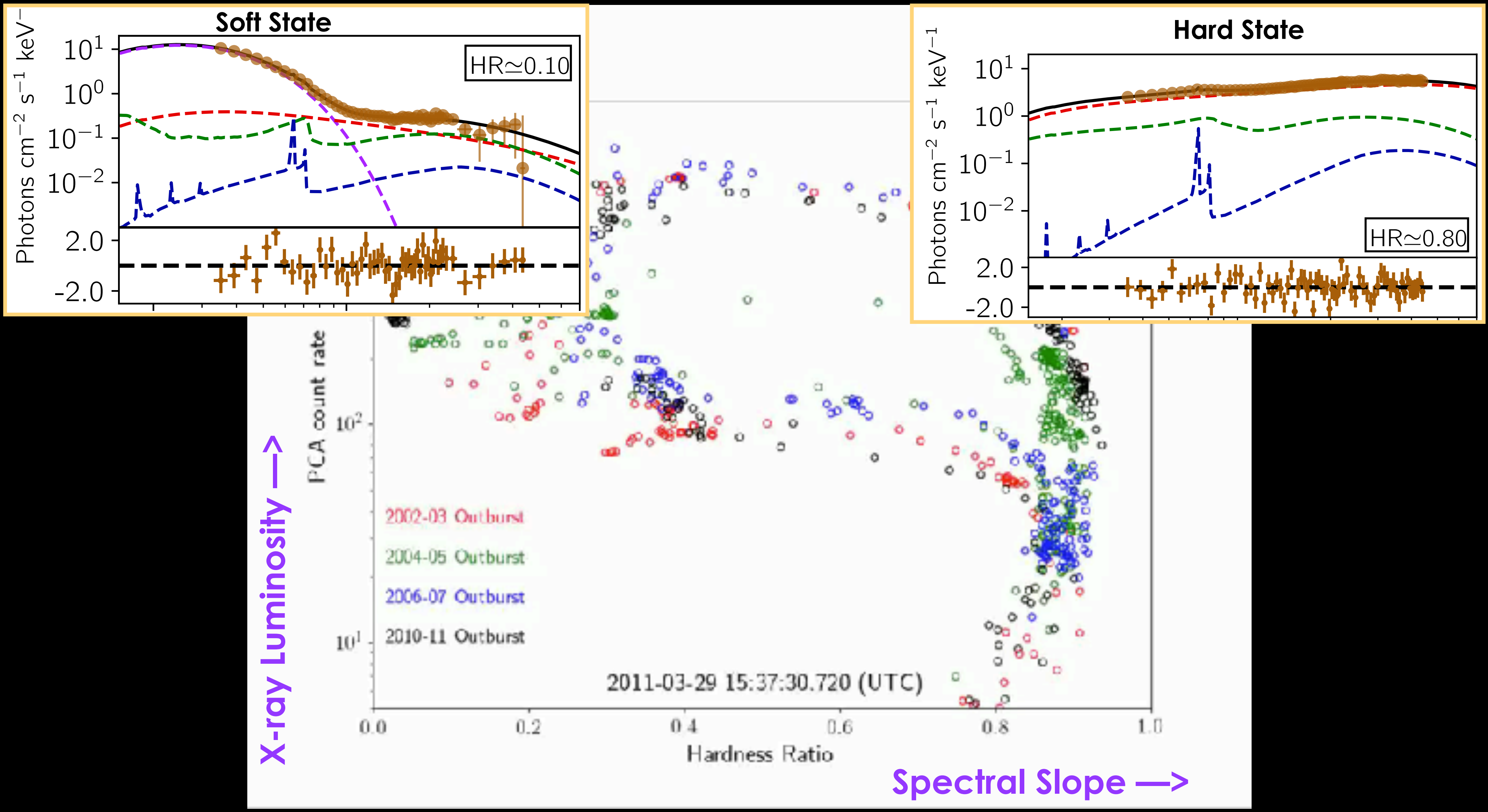


Hynes+03:
$f(M) = 5.8 \pm 0.5 M_\odot$
Kolehmainen+Done10:
$D = 6 - 15$ kpc
$M = 6.2 - 15 M_\odot$
$20^\circ < i < 70^\circ$



(Plant+14)

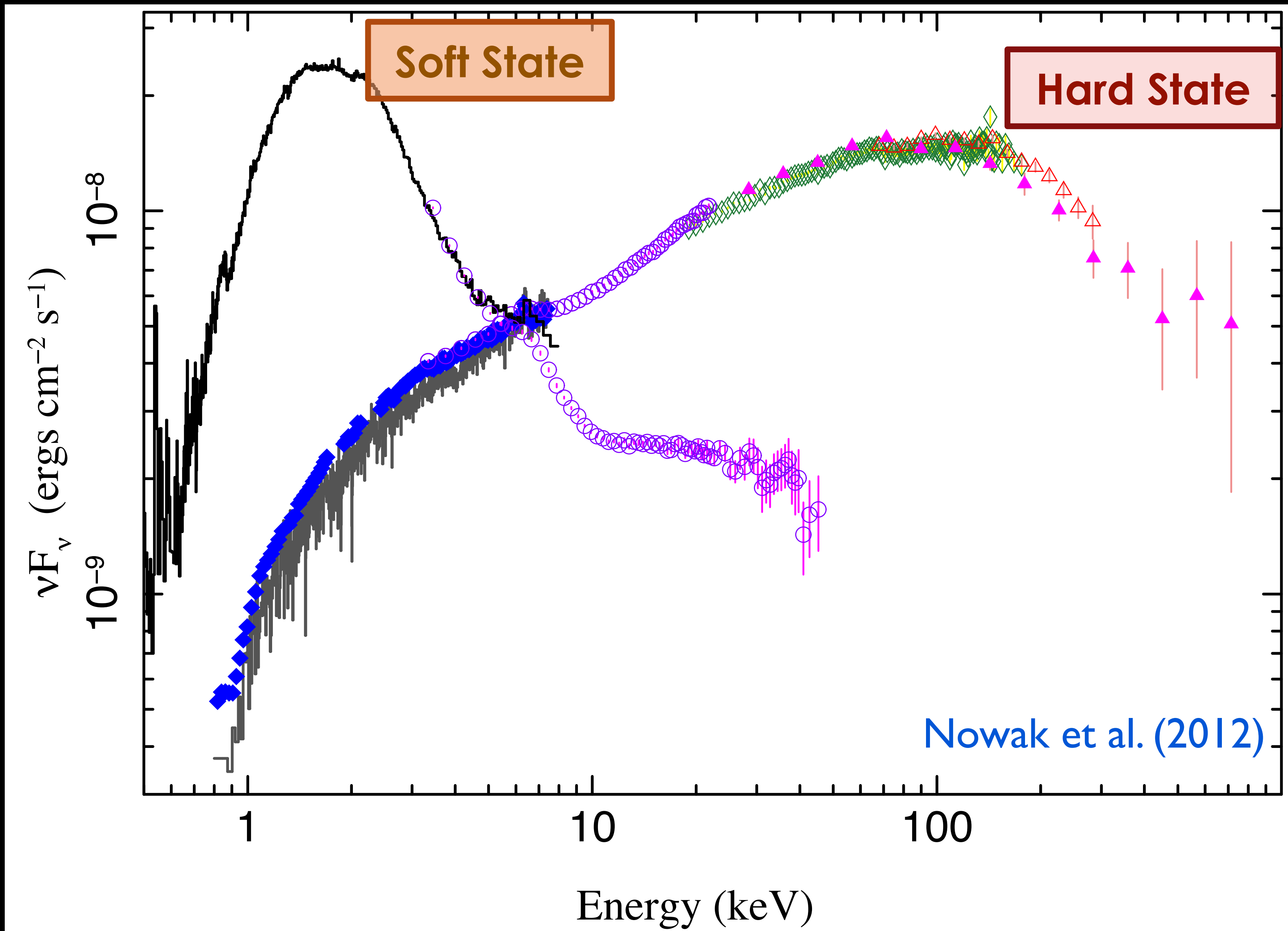
BHBs in Outburst— GX 339-4



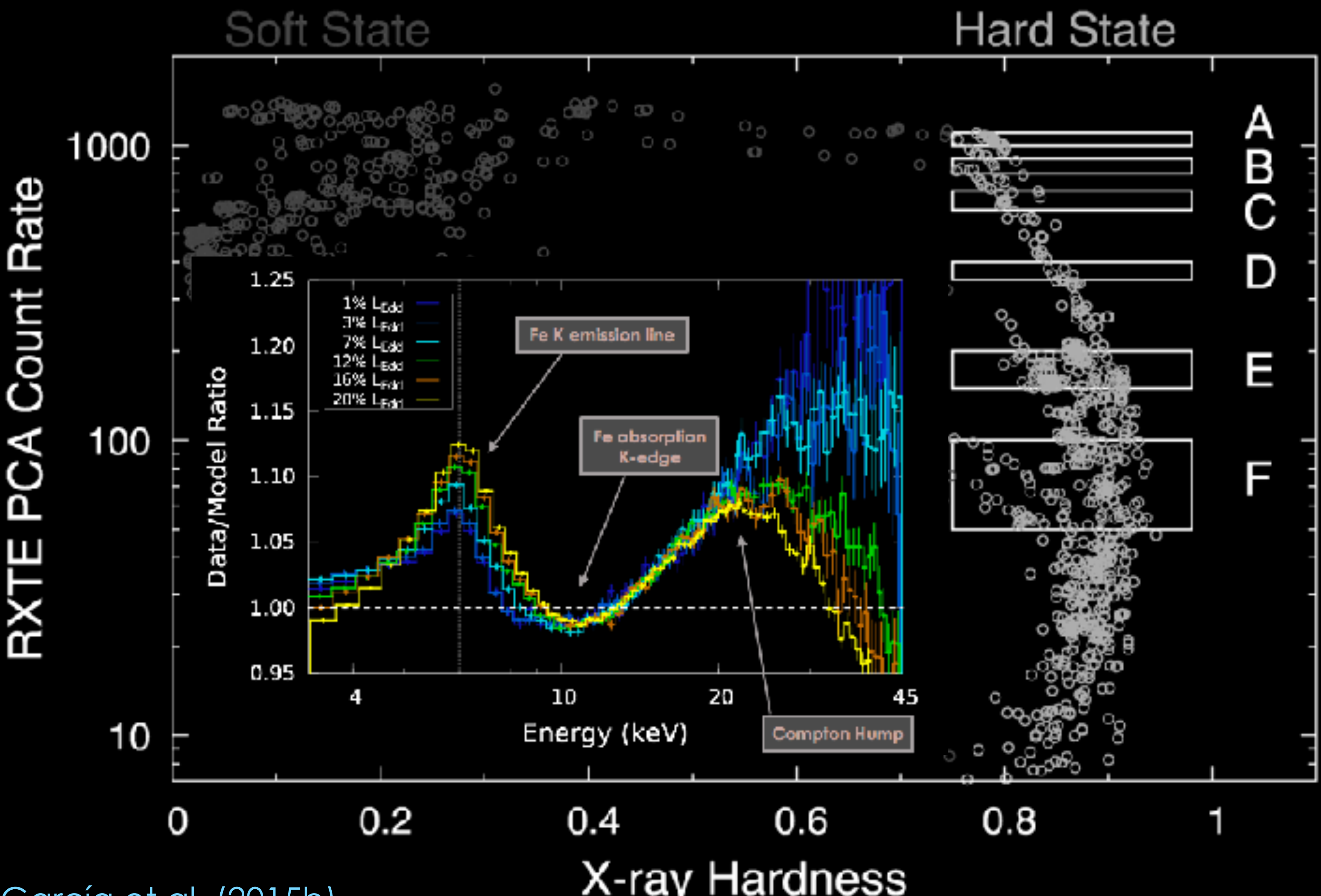
Archival data from the *Rossi X-ray Timing Explorer (RXTE)*

(Animation courtesy of Navin Sridhar)

BHBs in Outburst— Cyg X-1



The Hard State of GX 339-4



García et al. (2015b)

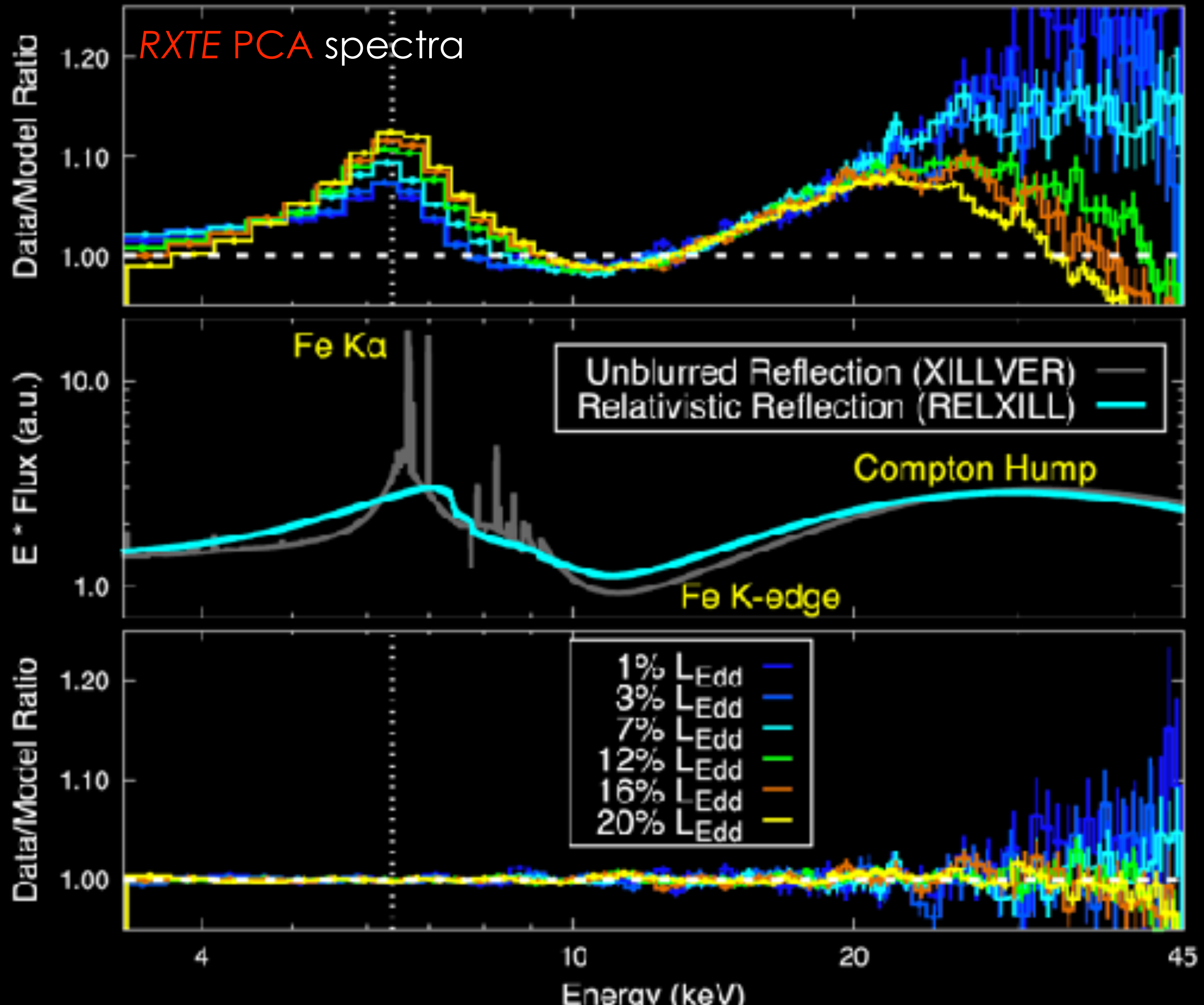
Disk and Corona Evolution

Relativistic reflection fits of the black hole binary system GX 339—4

a = 0.95 +/- 0.04
i = 48 +/- 1 deg
Fe abundance 5x Solar

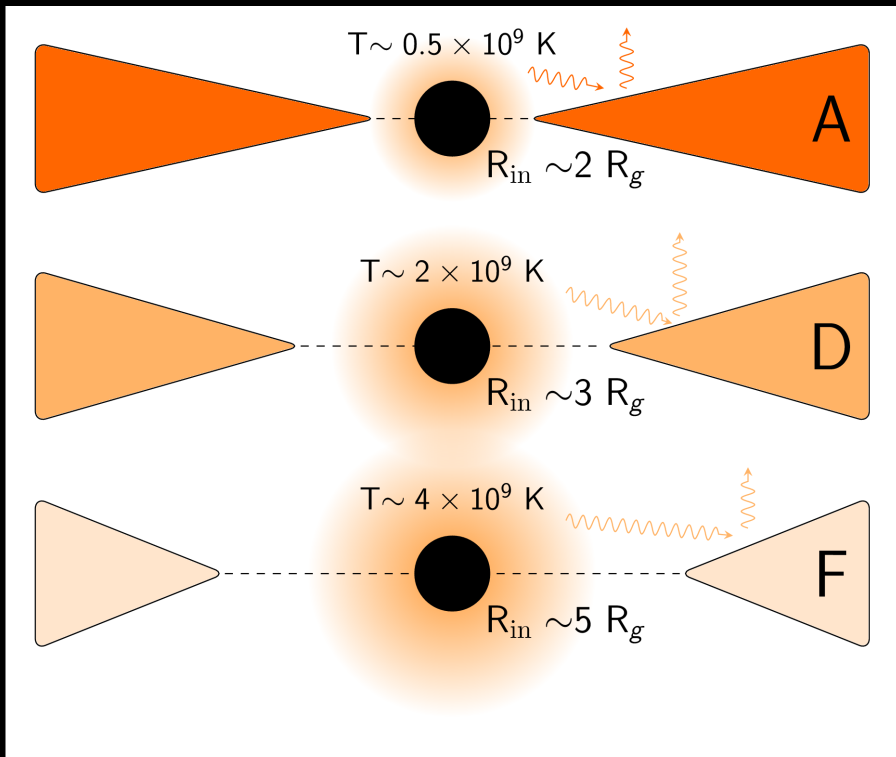
García et al. (2015b)

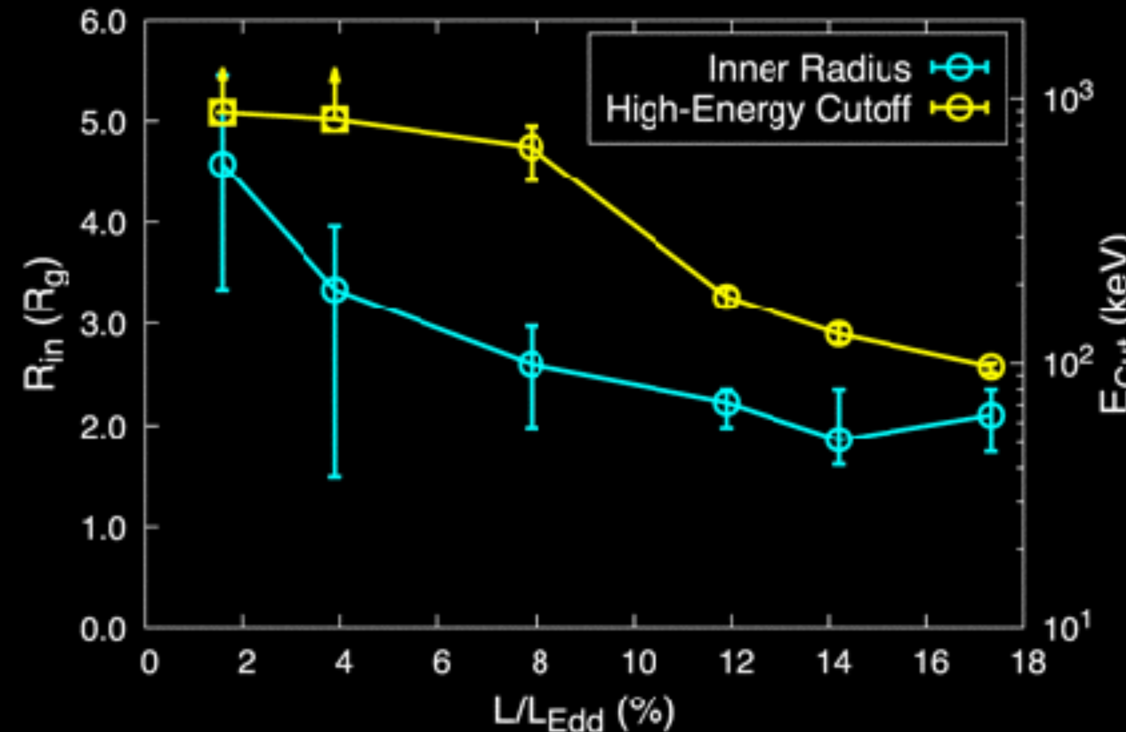
Total of 77 million counts in six *RXTE* PCA spectra (3–45 keV)



García et al. (2015b)

Disk and Corona Evolution



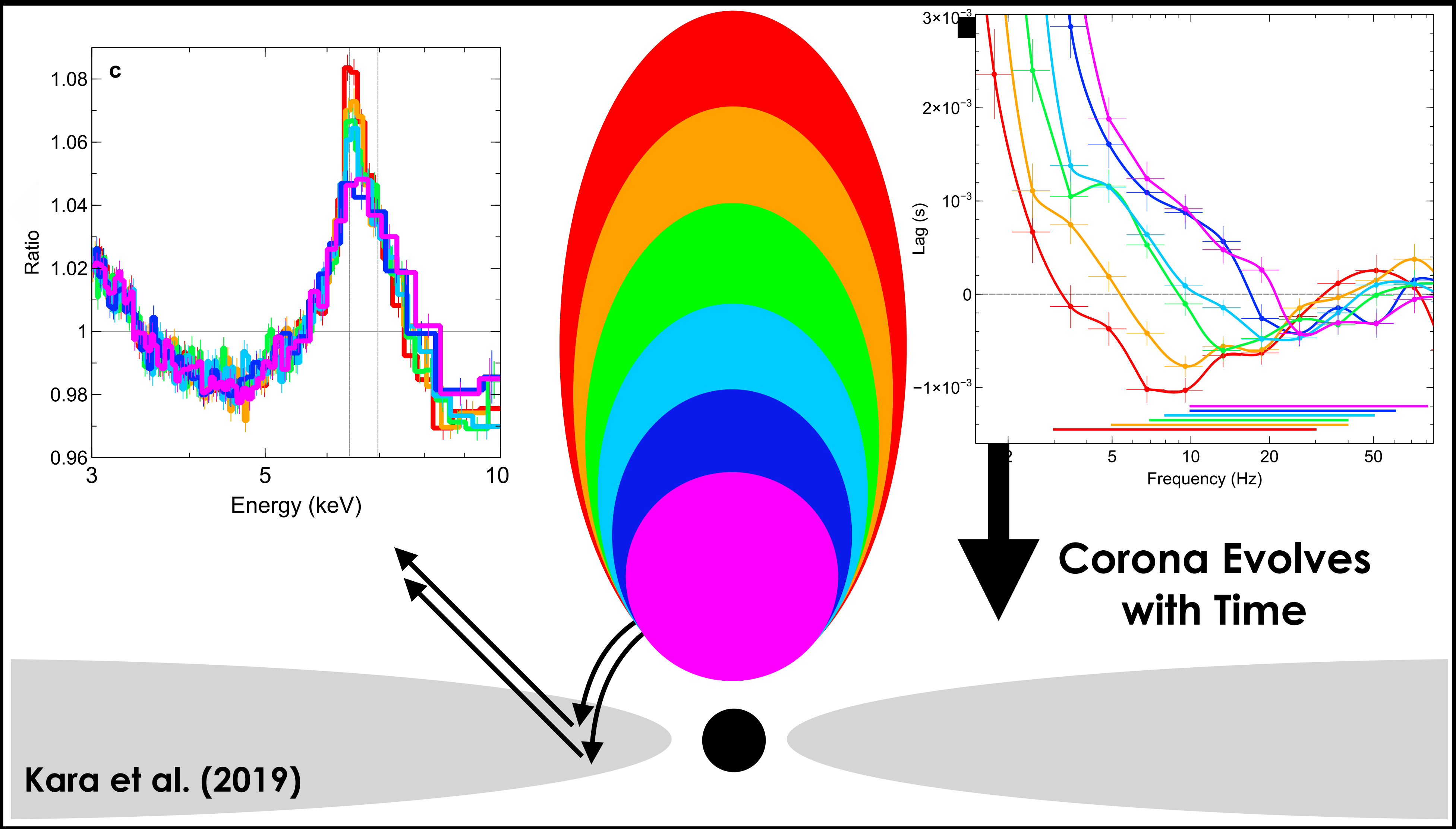


For a 10 Solar-mass BH:
Delta Rin ~45 km

- Luminosity increases by ~20x
- Rin decreases from a few to ISCO
- Coronal Temp decreases by 10x
- Yet, continuum slope remains the same (Γ~1.6)… why?

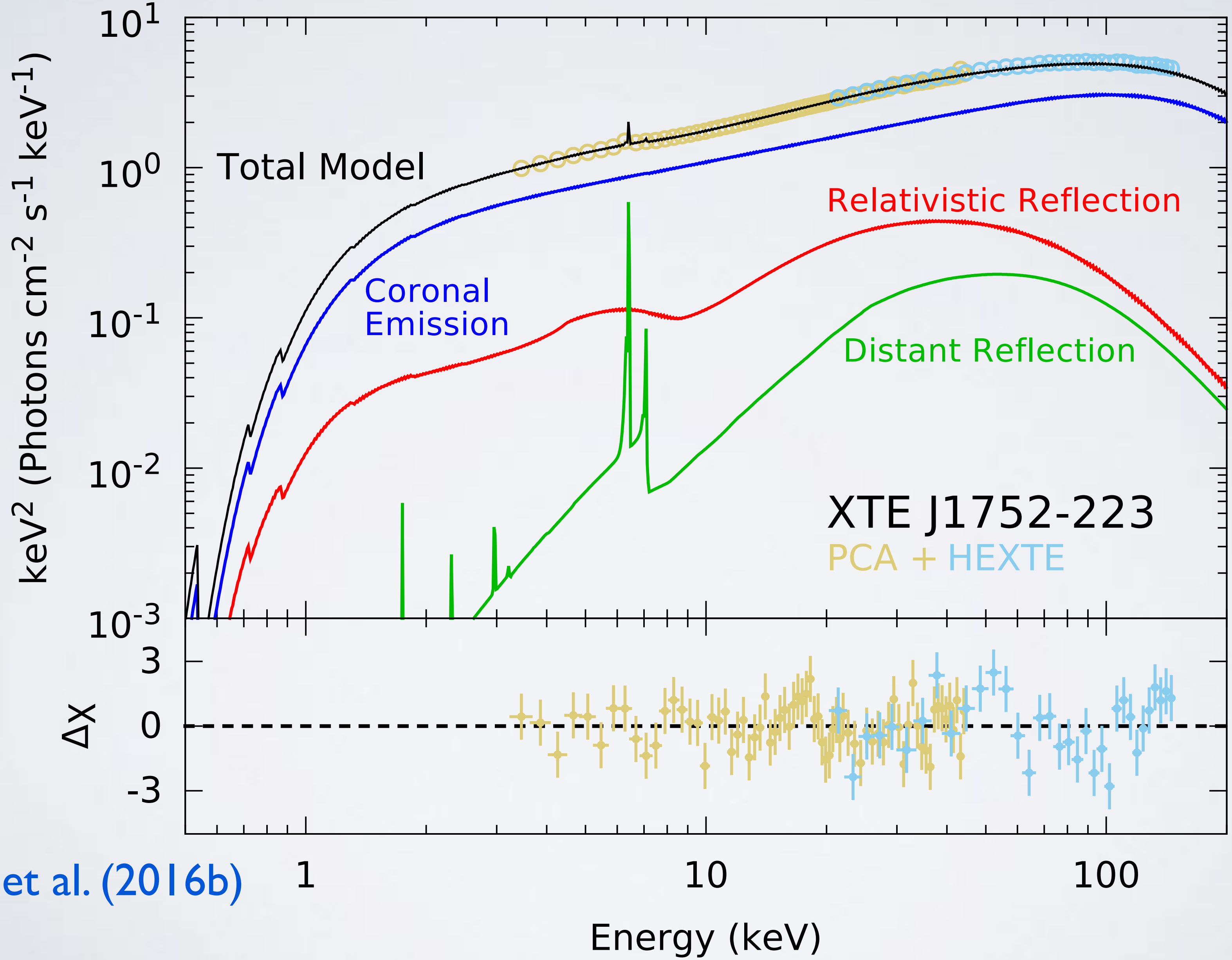
Disk and Corona Evolution

New Black Hole Binary **MAXI J1820+70** as seen by ***NICER***



Fits to XTE J1752-223

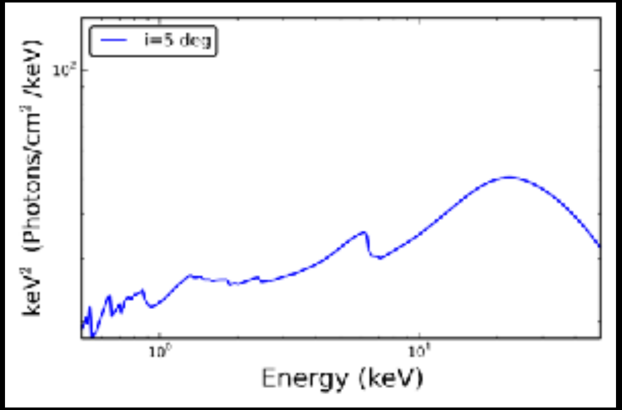
Similarly to GX 339-4, we find a rapidly spinning black hole (a*~0.992), also with super-solar iron abundance (Afe~4)



García et al. (2016b)

Illumination Geometry

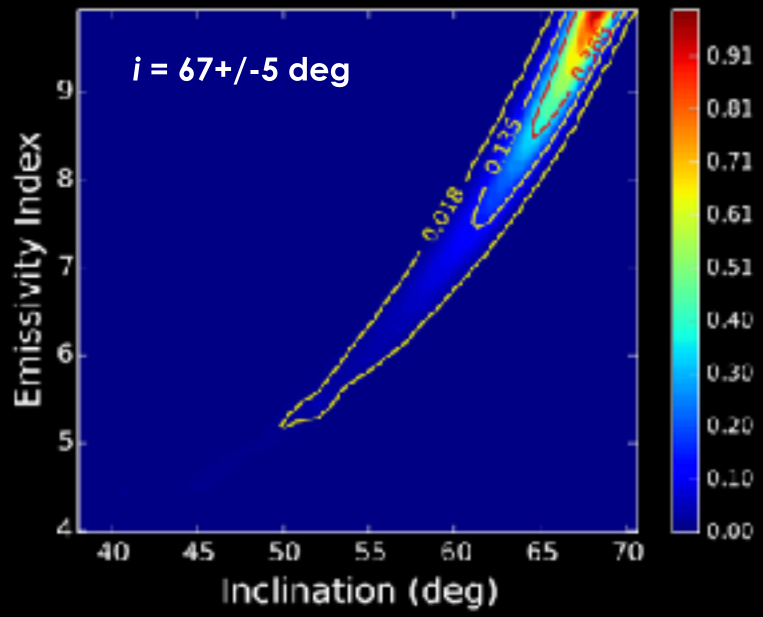
Inner-Disk Inclination



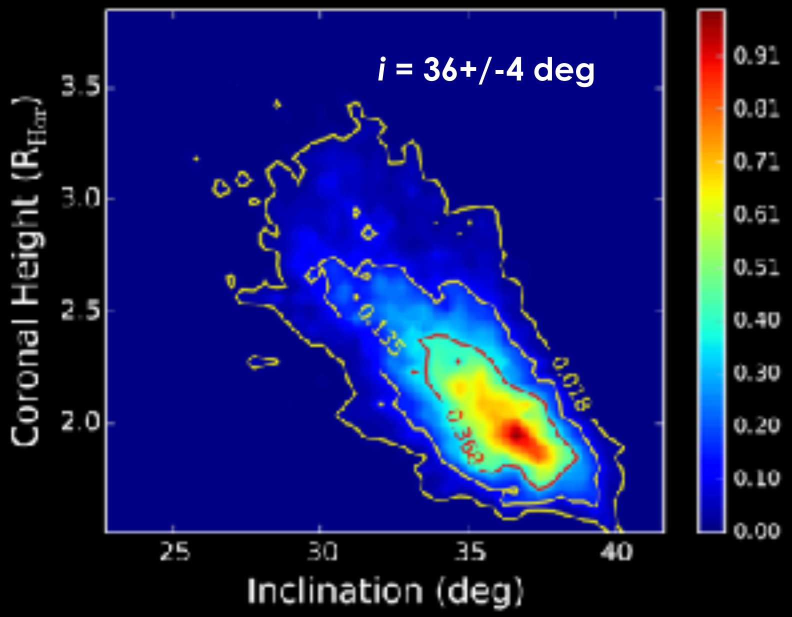
Reflection Spectroscopy of XTE J1752—223:

Highest signal-to-noise reflection spectrum to date (S/N ~ 3000) *** **Update: MAXI J1820+70!**

Power-law Emissivity



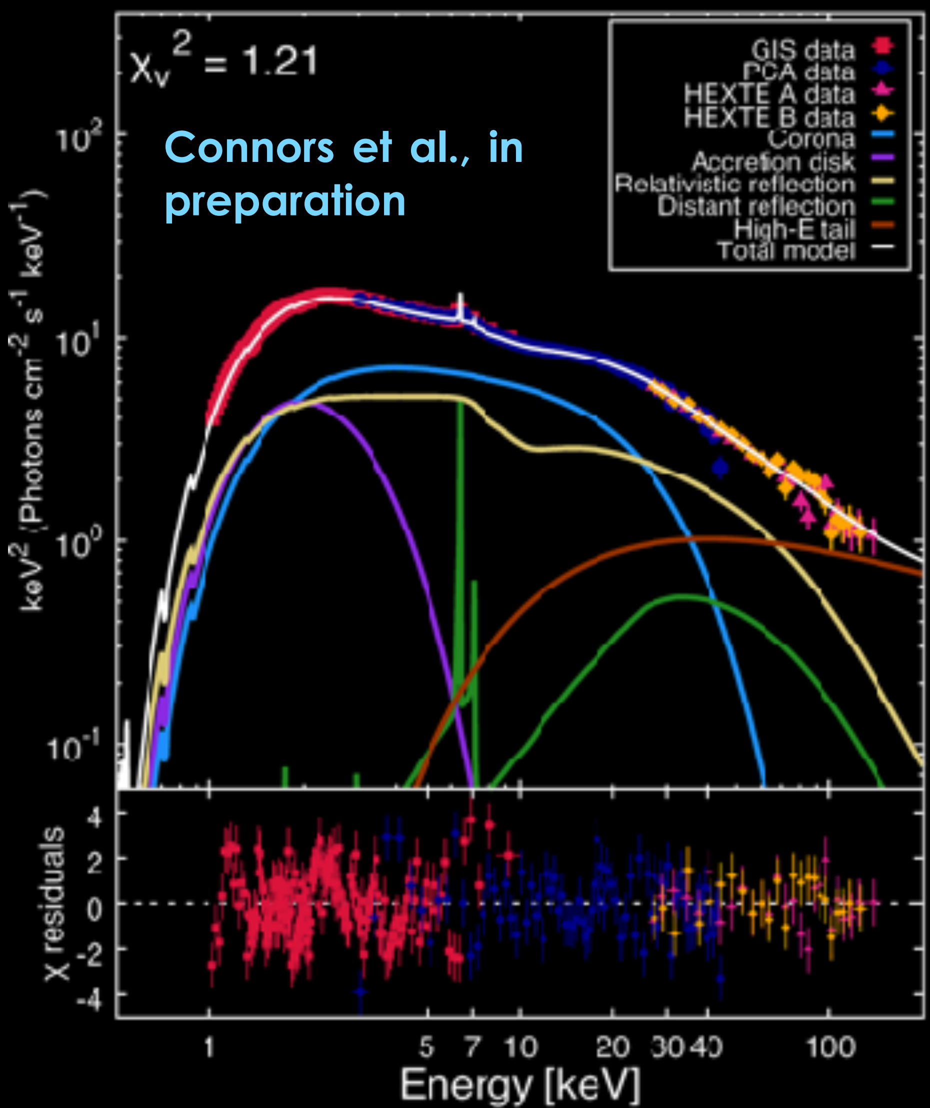
Lamppost Geometry



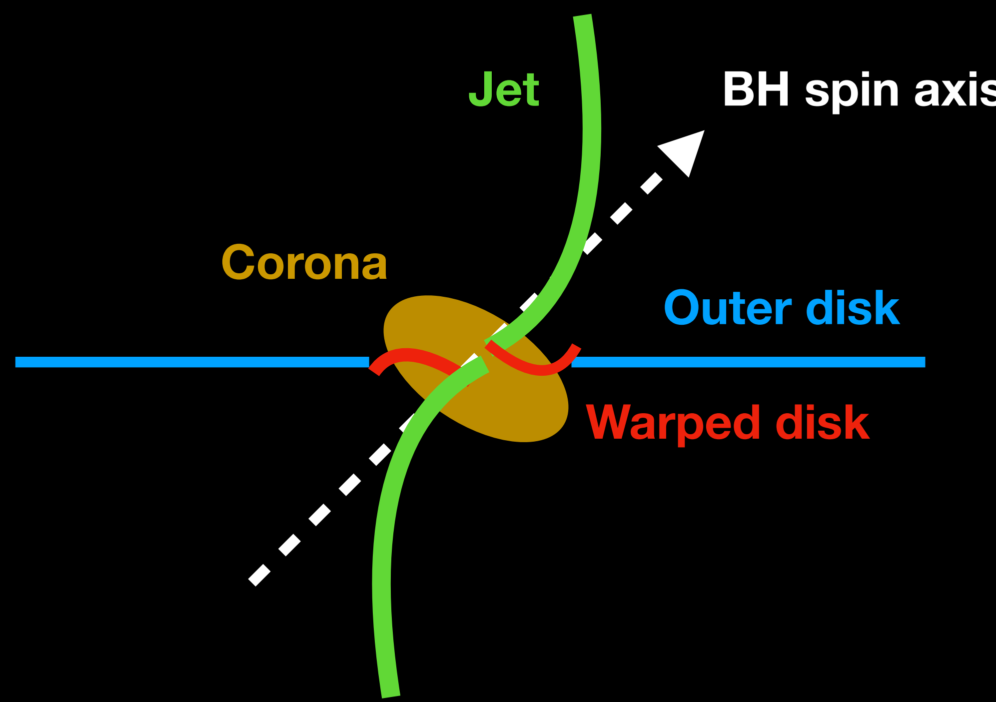
Inclination from the lamppost model consistent with radio jet determinations of ***i* < 49 deg** (Miller-Jones et al. 2011).

García et al. (2018b)

XTE J1550-564 - LOW INCLINATION DISK?

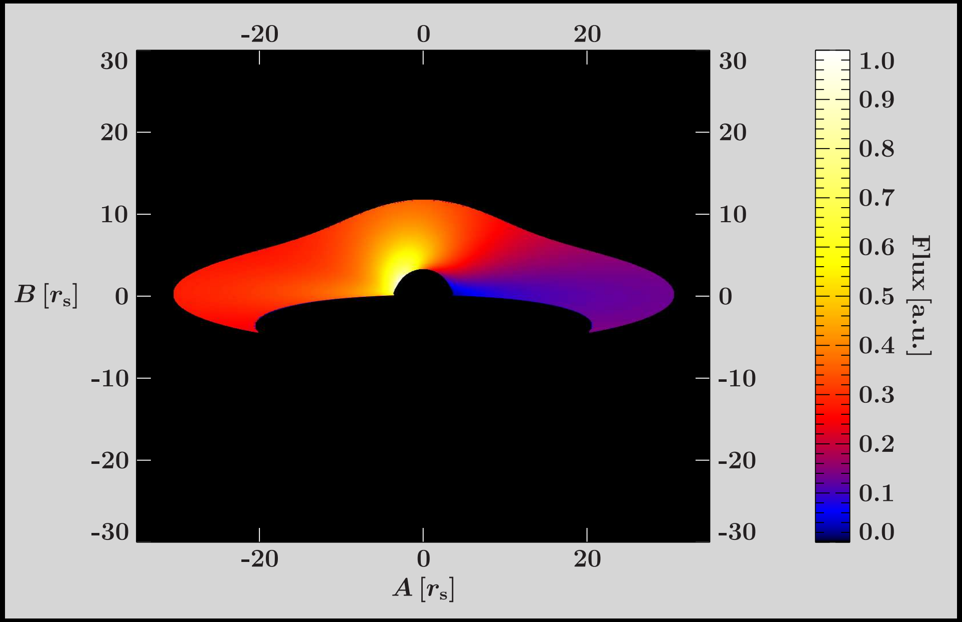


Inclination from reflection modeling inconsistent with radio jet and optical monitoring determinations of the orbital inclination, ***i* ~ 40 deg, as opposed to *i* ~ 75 deg** (Orosz et al. 2011, Steiner et al. 2012).



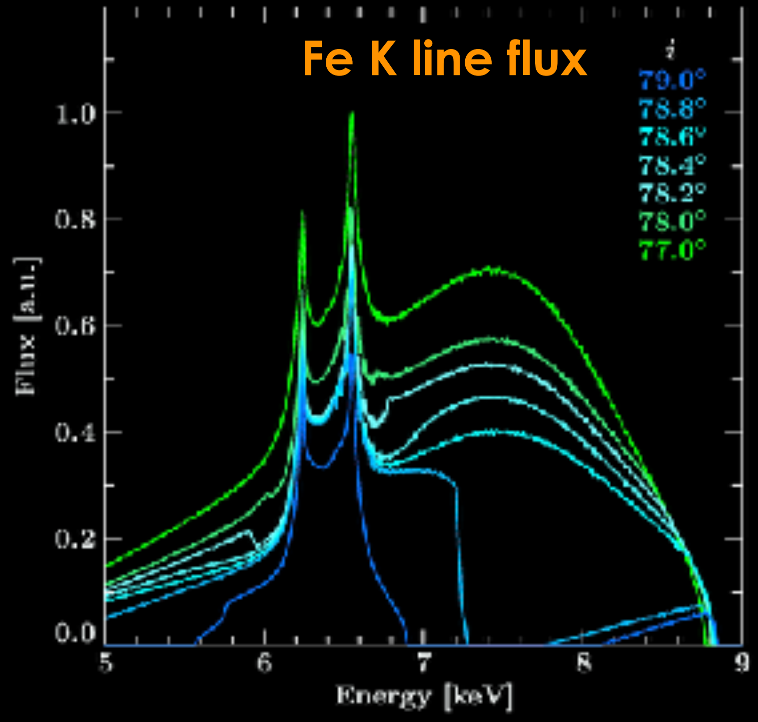
Possible misaligned inner accretion region?

Irradiation of Flared Disks



Obscuration effects:

Under an inclination of **78.5°**, part of the disk is covered, affecting both the line profiles and the time lags

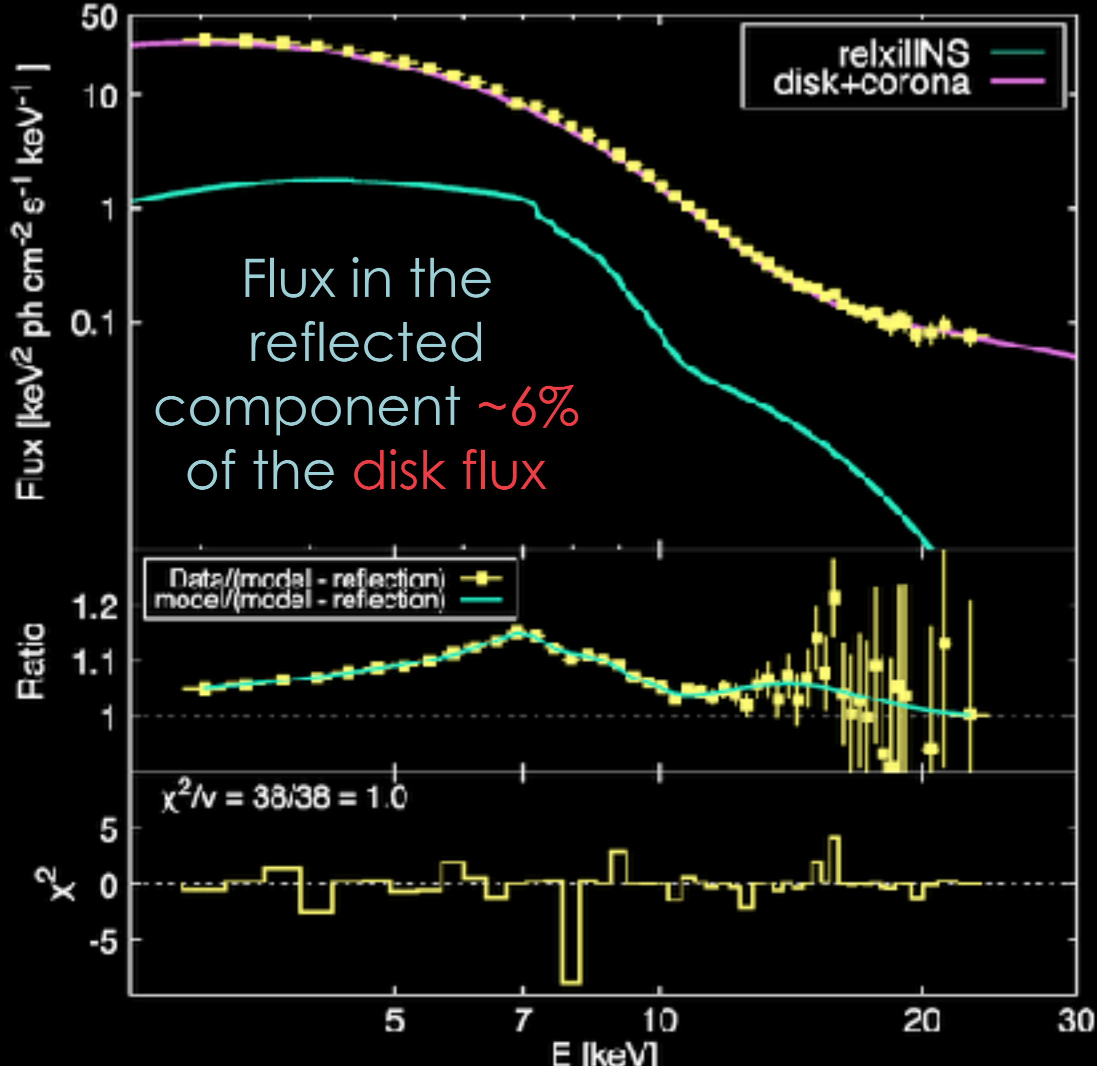


Disk obscuration reduces the blue-wing of the Fe K emission

—> Resembles lower inclination!

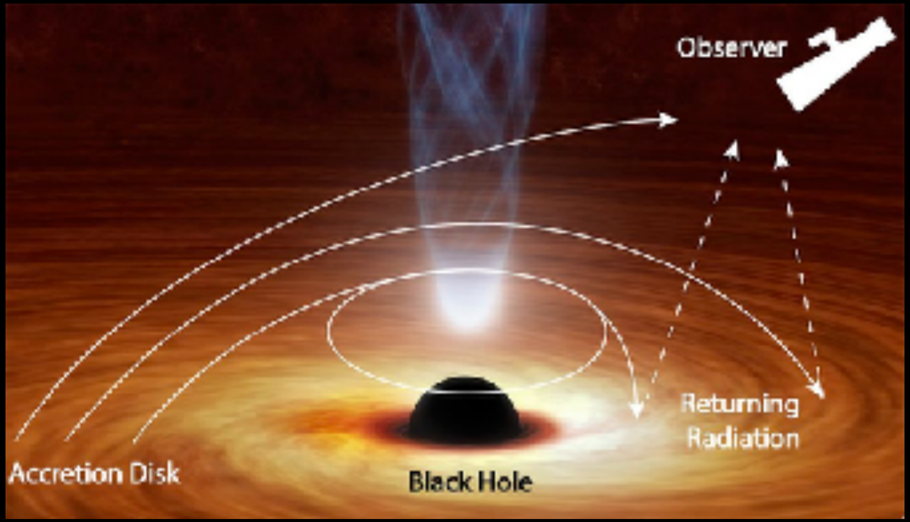
See Taylor & Reynolds (2018)

Disk Self Irradiation



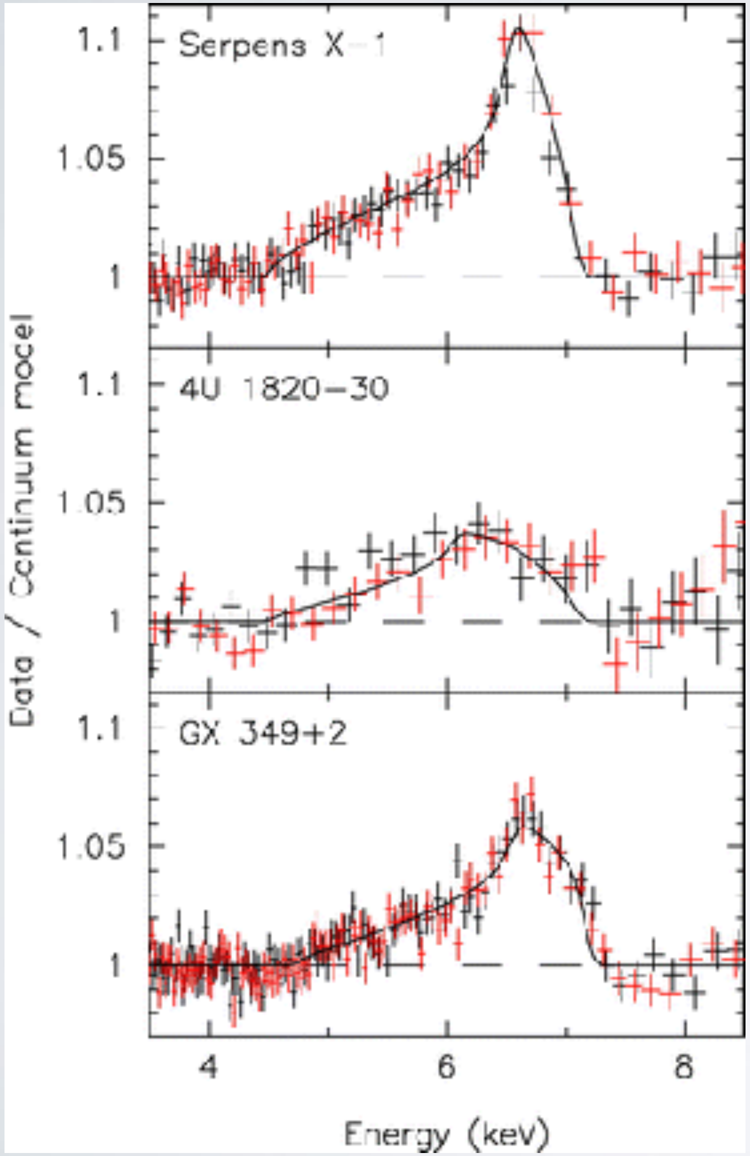
Connors, JG,+20

Radiation Returning to the Disk due to GR light bending



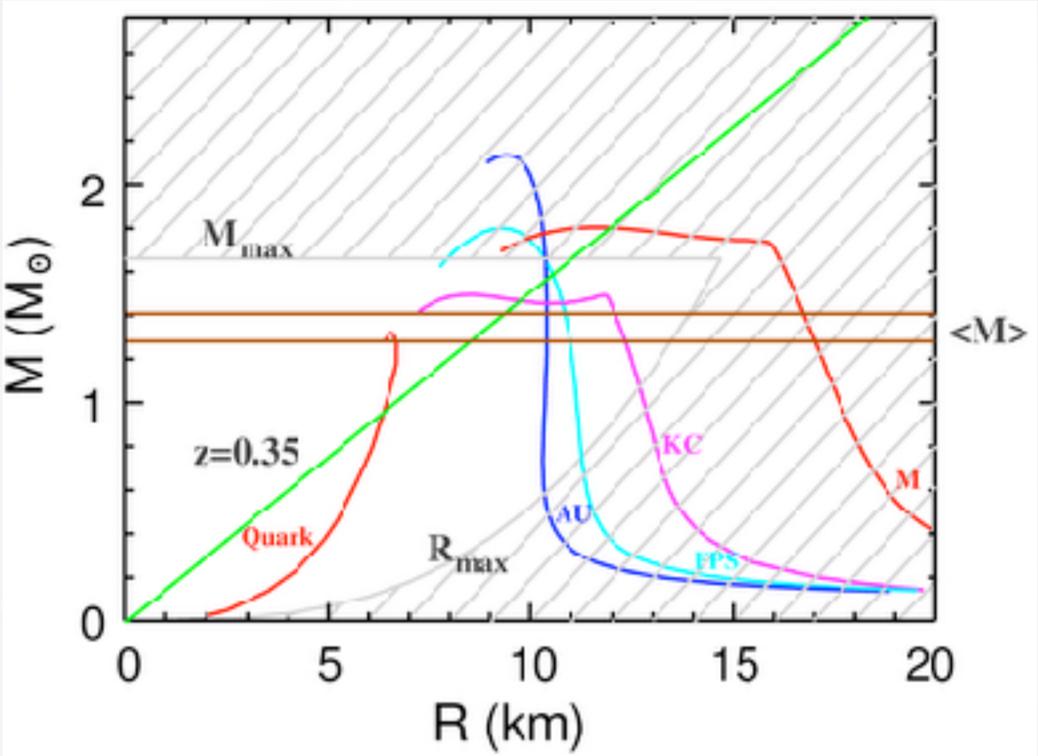
Flux fraction of returned radiation consistent with ray tracing calculations

Fe K Reflection in Neutron Stars



Iron K lines in three Neutron Stars observed with Suzaku (Cackett et al. 2008)

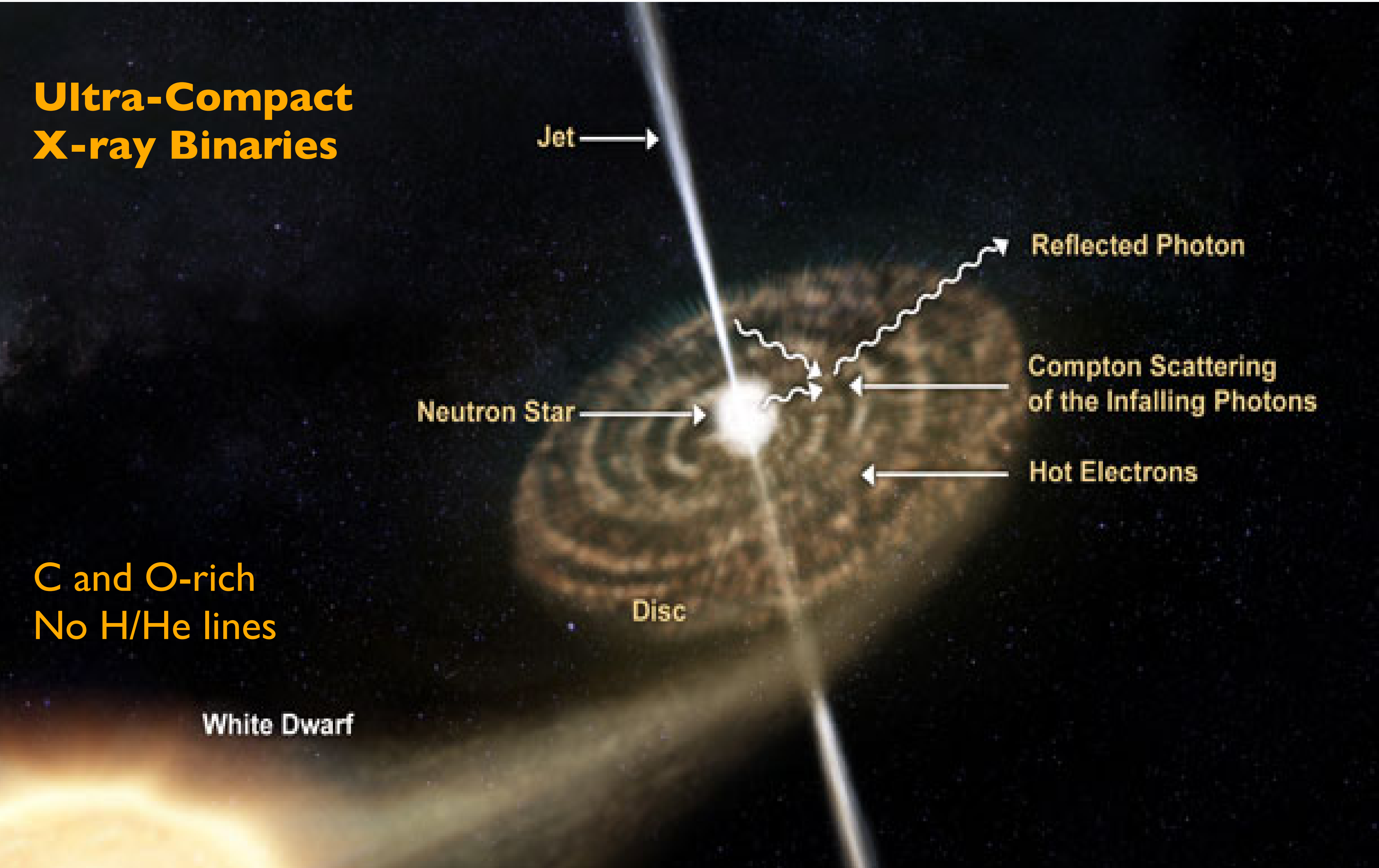
In this case, the Fe K-line provides an estimation of the NS radius, which together with the mass constraints the eq. of state.



Relativistically Blurred Oxygen?

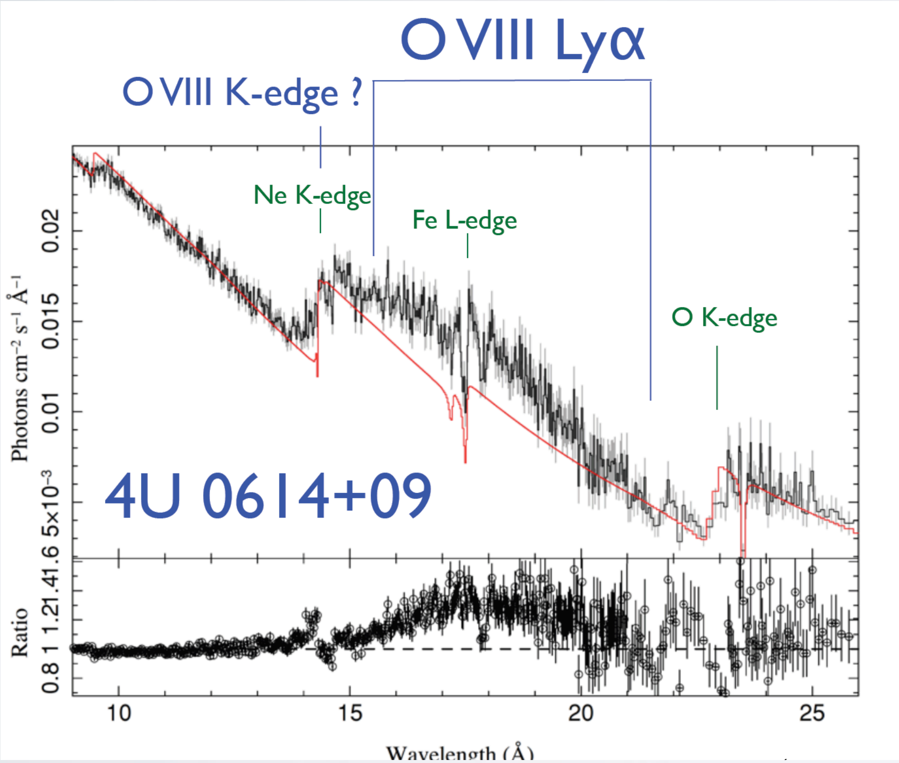
Ultra-Compact X-ray Binaries

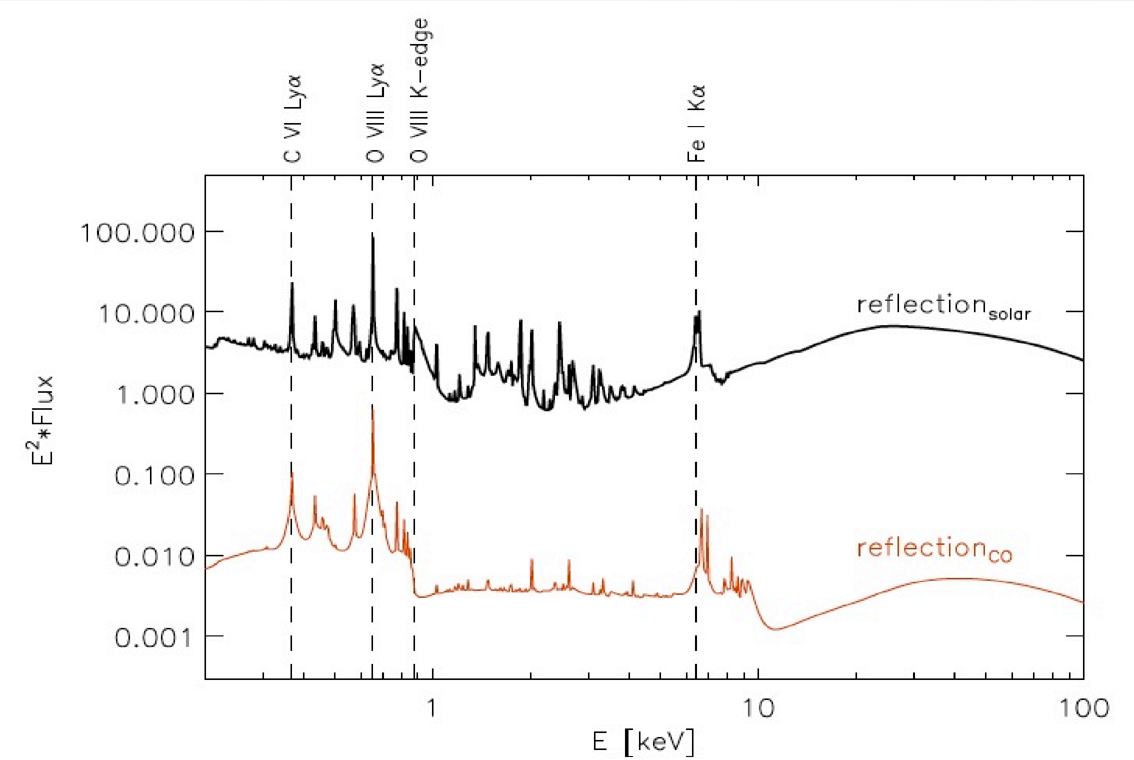
C and O-rich
No H/He lines



Relativistically Blurred Oxygen?

4U 0614+09: Neutron star with a Carbon and Oxygen rich White Dwarf donor.



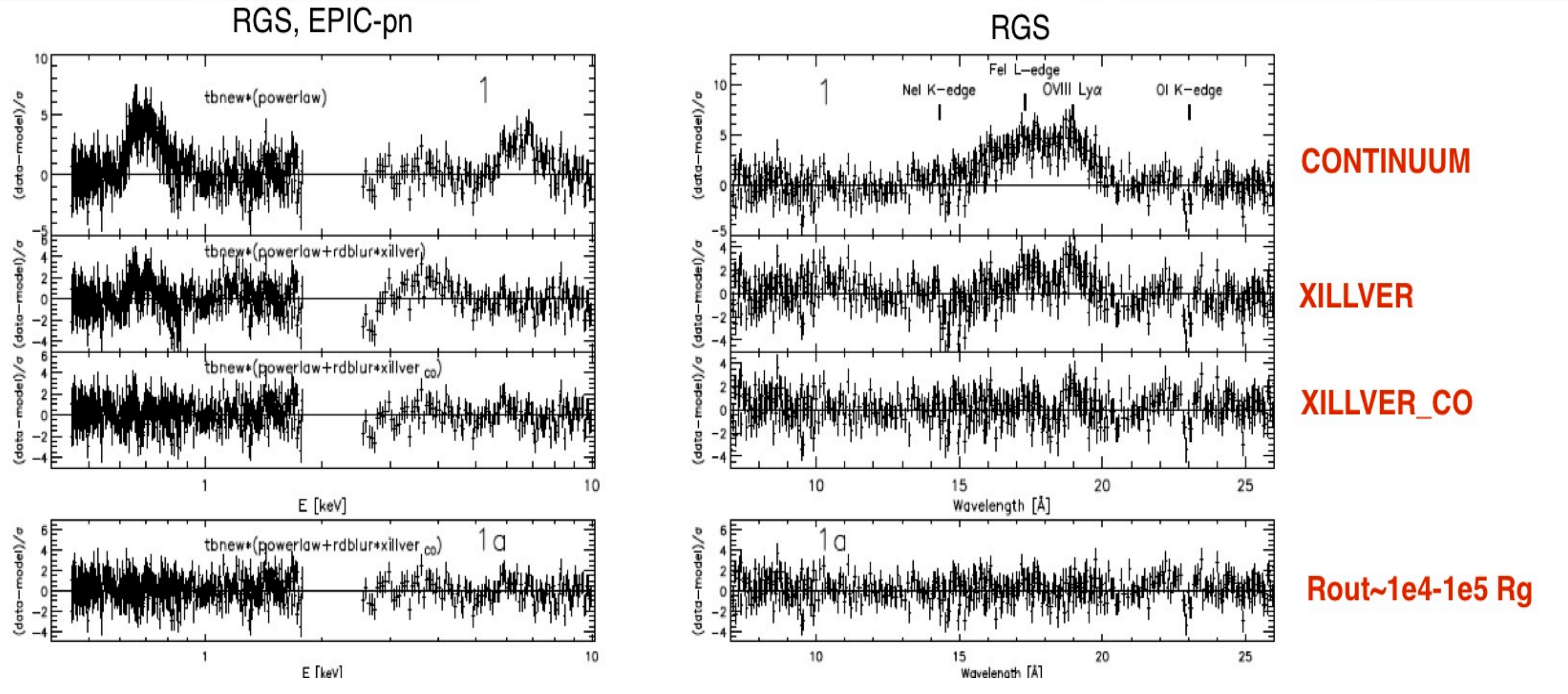


Chandra spectra shows strong O VIII Ly-alpha emission.
Custom-made XILLVER model with low H & He abundances (1% solar)
C & O abundances are free parameters

Fits to 4U 0614+091 XMM Data

C & O Abundance: 140 +/- 50 x Solar value

Strong Ne K-edge or O VIII K-edge? No neon emission in optical spectra



Madej, Garcia et al. (2014)

Summary

X-ray Reflection Spectroscopy provides one of the most powerful tools to study accreting black holes, with which one can study:

* **The Evolution of Disk and Corona**: changes in the corona and accretion disk appear to be correlated. This indicates a connection in the physics that governs the evolution of both structures.

* **The Spins of Black Holes**: Estimates of BH spins for both AGN and BHB are important to understand their formation and evolution history.

* **The Physics of the accreting flow:** Large iron abundances in reflection measurements are indicative of high-density plasma effects, likely affecting the atomic structure properties.

Escuela Latinoamericana de Relatividad y Astrofísica (ELRA)

Diciembre 1-3, Online

Esta pequeña escuela tiene como objetivo ofrecer cursos introductorios a estudiantes de habla hispana. Los cursos proporcionarán las herramientas más básicas necesarias para iniciarse en la investigación de algunos temas actuales en astrofísica relativista.

La inscripción será gratuita y abierta a toda la región.

Cursos (Sesiones de 45+15)

* **Física de Objetos Compactos (Jorge Rueda (ICRANet))**
* **Técnicas estadísticas para el análisis de datos astrofísicos (Cecilia Garraffo (Harvard))**
* **Técnicas de análisis espectral en rayos X de objetos compactos (Mariano Mendez (Groningen))**

Comité organizador:

Alejandro Cárdenas-Avendaño (Fundación Universitaria Konrad Lorenz/ Princeton University)
Javier García (California Institute of Technology)
Luis Nuñez (Chair, Universidad Industrial de Santander)
Jorge Rueda (International Center for Relativistic Astrophysics)

Adicionales

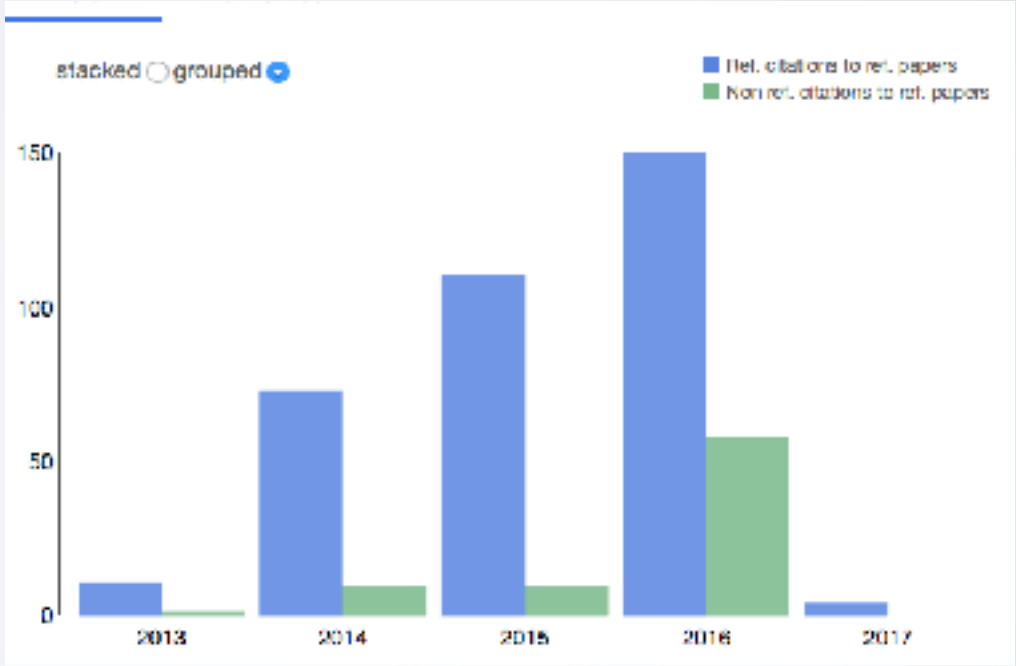
Some Reflections

- Reflection spectroscopy has proven to be a fantastic tool to study the inner-most regions of accreting sources.

- The state-of-the-art atomic data and modeling tools are allowing us to impose tight constraints on important parameters such as spin, inclination, and Fe abundance.

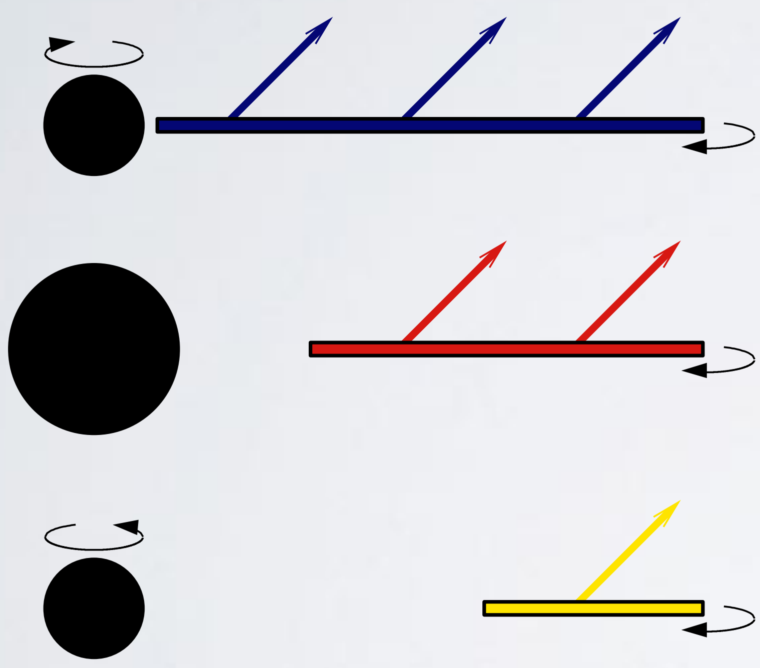
- The community has played an important role in the improvement of our models:

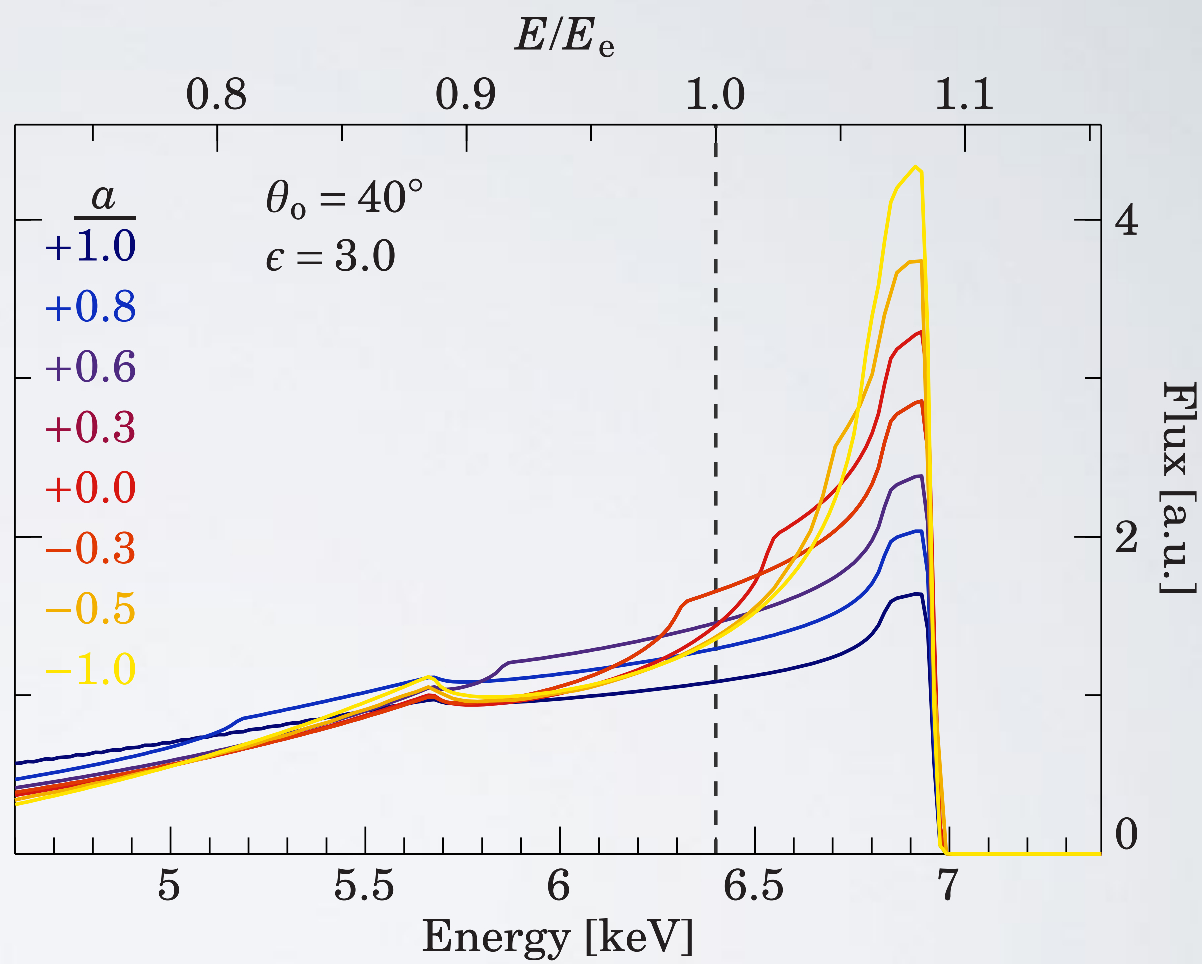
- 180 Citing papers
- ~120-140 fits to a single source
- Most of these (~80) are NuSTAR observations!



All of physics is either impossible or trivial. It is impossible until you understand it, and then it becomes trivial. —*Ernest Rutherford*

Diagnostic Tool: Black Hole Spin

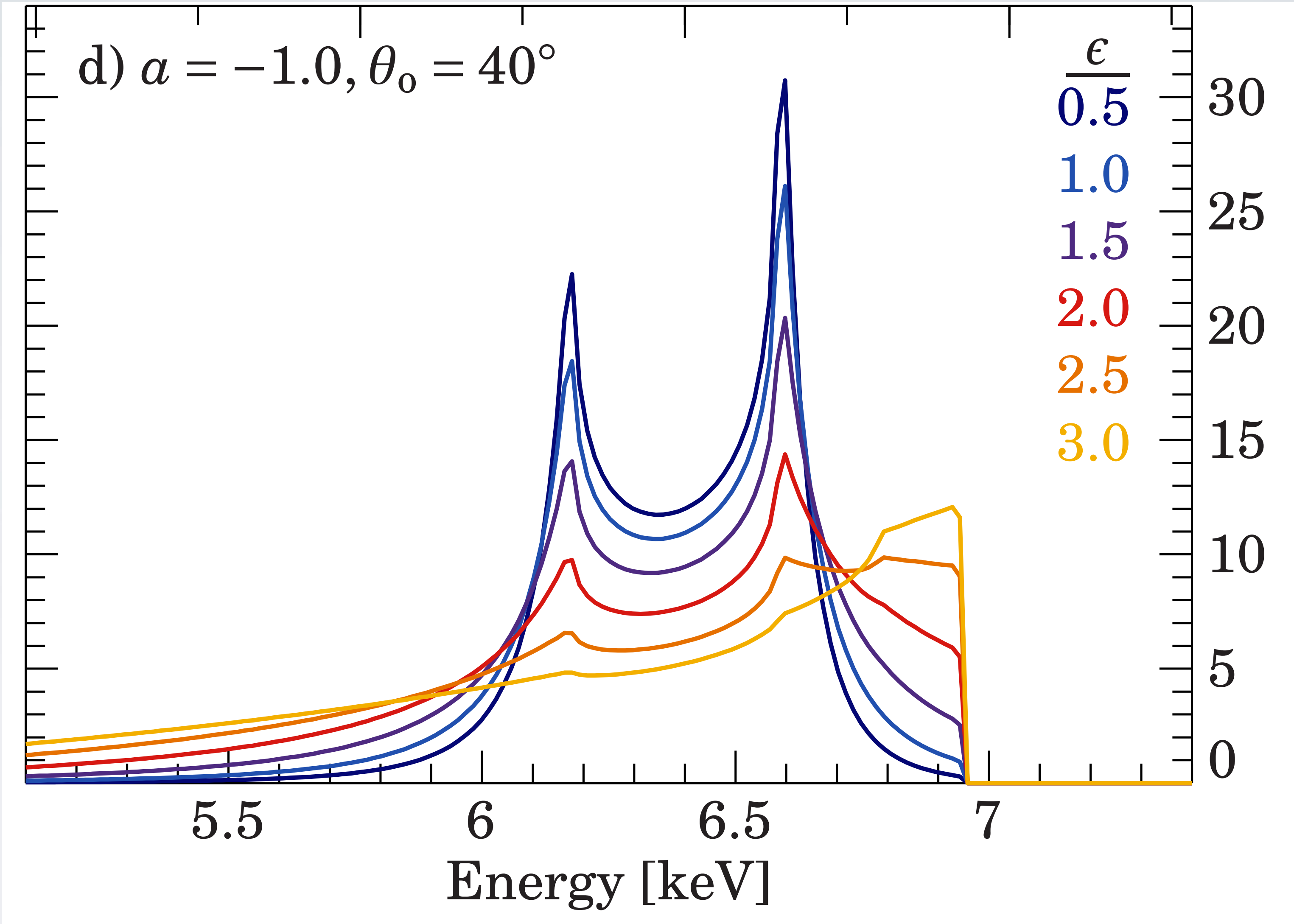




possible **Spin** values: $\mathbf{a} = -1 \ldots 1$

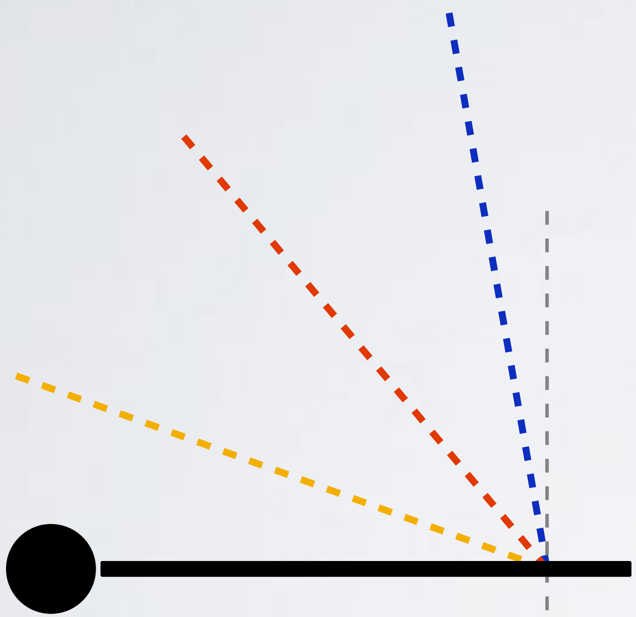
a = cJ/GM² (Dimensionless Spin Parameter)

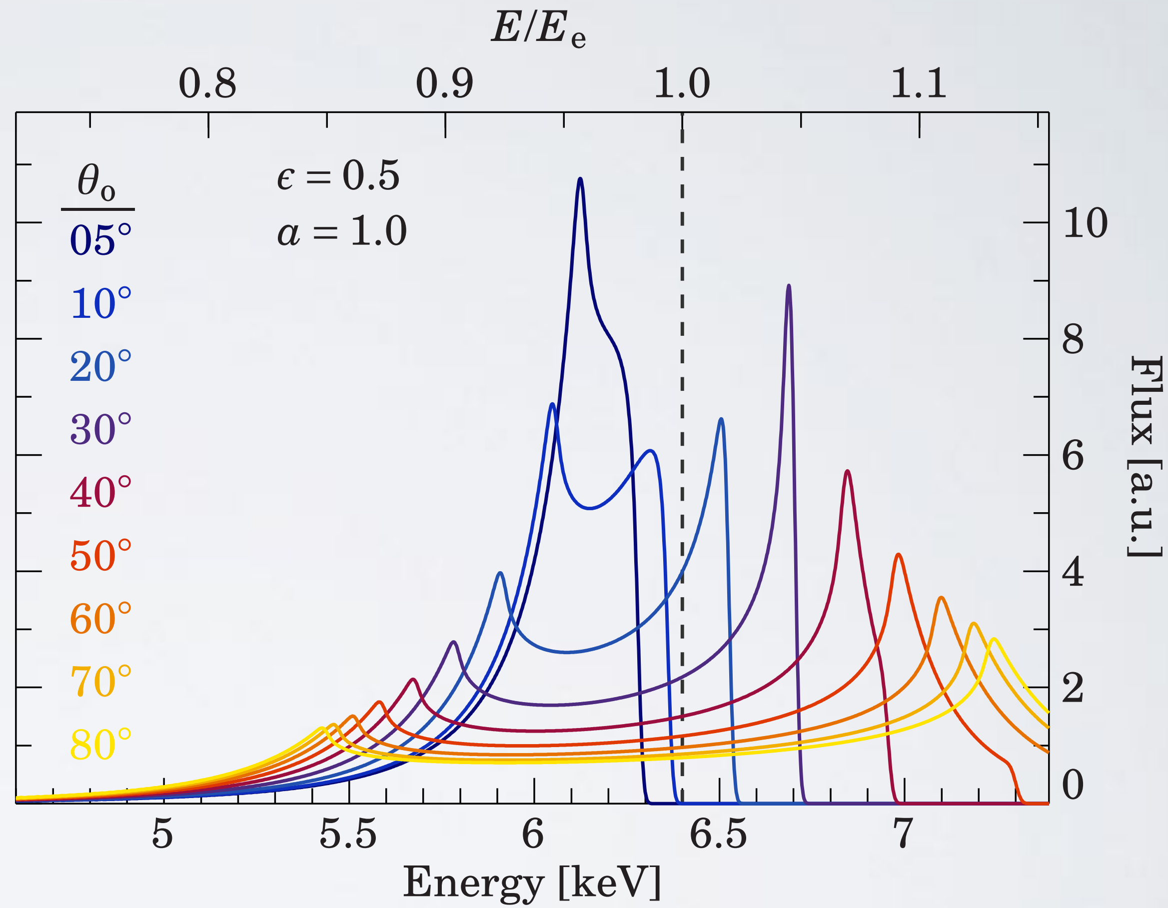
Diagnostic Tool: Emissivity Index



Assumes illumination (and thus emission) follows F~r^e

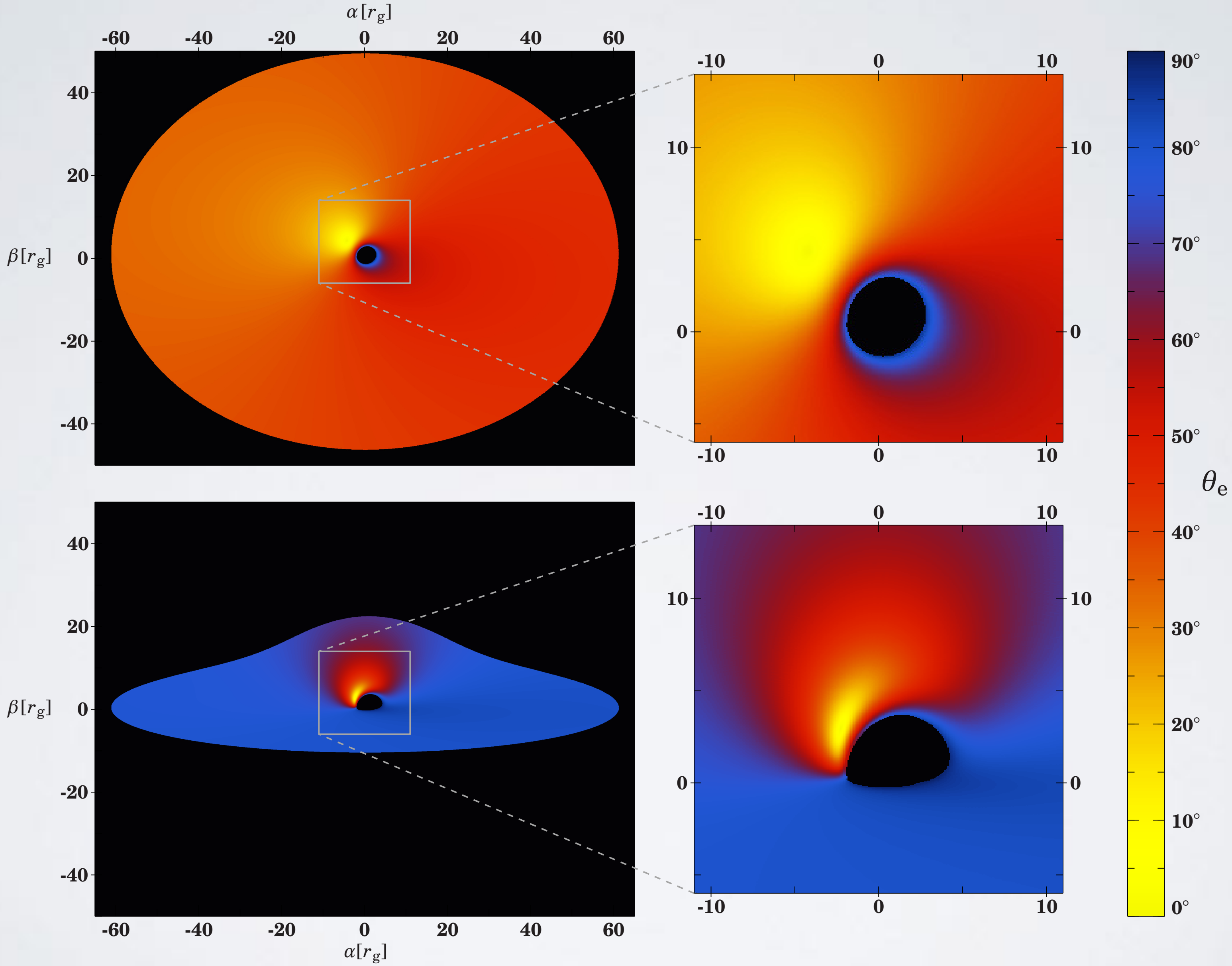
Diagnostic Tool: Inclination





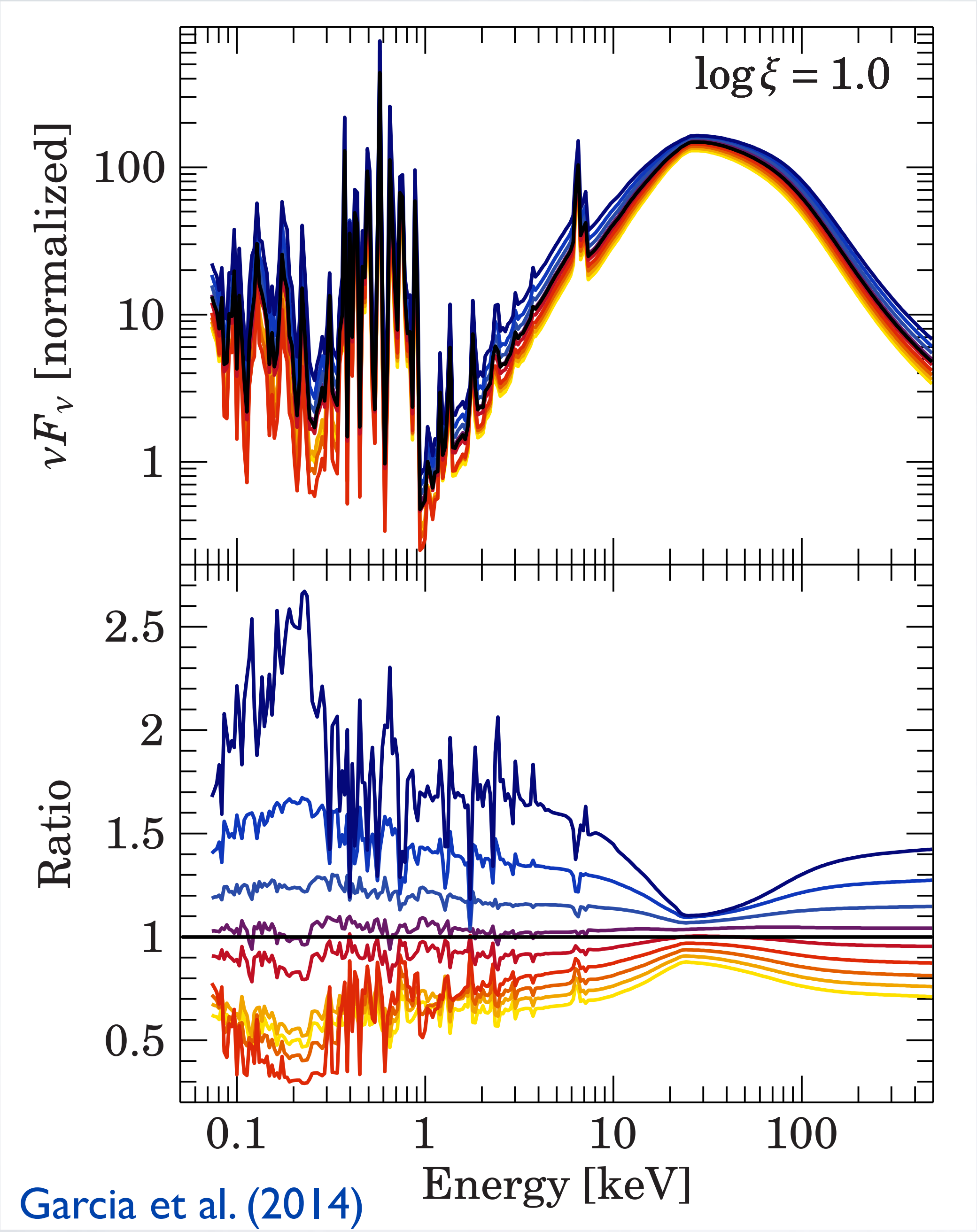
Inclination mostly affects the blue side of the line

Diagnostic Tool: Emission Angle



Garcia et al. (2014)

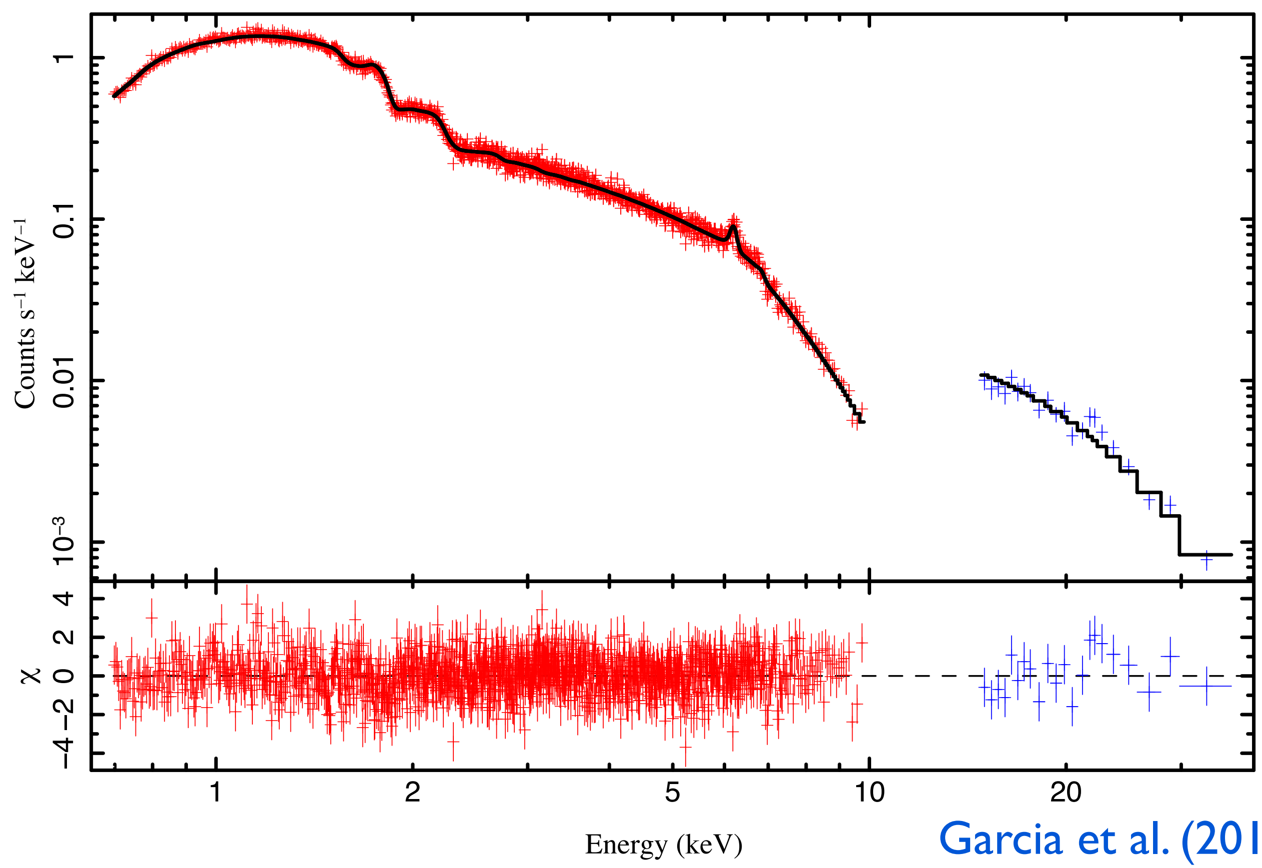
RELXILL: The Emission Angle



The reflection spectra differ depending on the Emission Angle

Previous convolution models use Angle Average Spectra

RELXILL: Fits to Ark 120

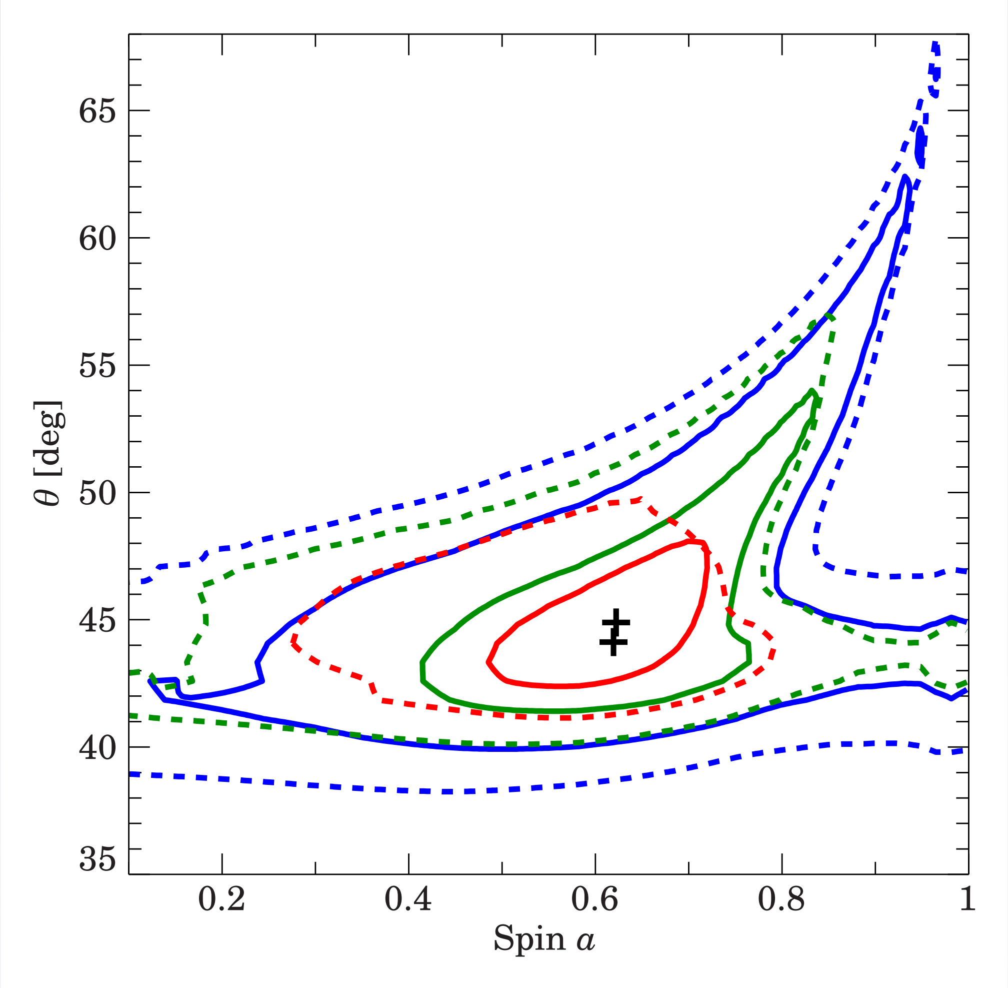


Garcia et al. (2014)

Par	Value
$q_{in} = q_{out}$	$4.8^{+1.8}_{1.1}$
a	$0.655^{+0.122}_{-0.126}$
i (deg)	$45.3^{+4.8}_{-2.4}$
R_{in} (ISCO)	1
R_{out} (ISCO)	400
z	0.0327
Γ	$2.17^{+0.02}_{-0.01}$
$\log \xi$	$0.84^{+0.24}_{-0.10}$
A_{Fe}	$1.78^{+0.39}_{-0.40}$
angle_on	1
$N(10^{-4})$	$2.07_{-0.2}$
$N(10^{-4})$	$0.14^{+0.07}_{-0.04}$

Suzaku spectrum of the Seyfert 1 galaxy Ark 120. Solid line is the best fit model with RELXILL.

RELXILL: Fits to Ark 120

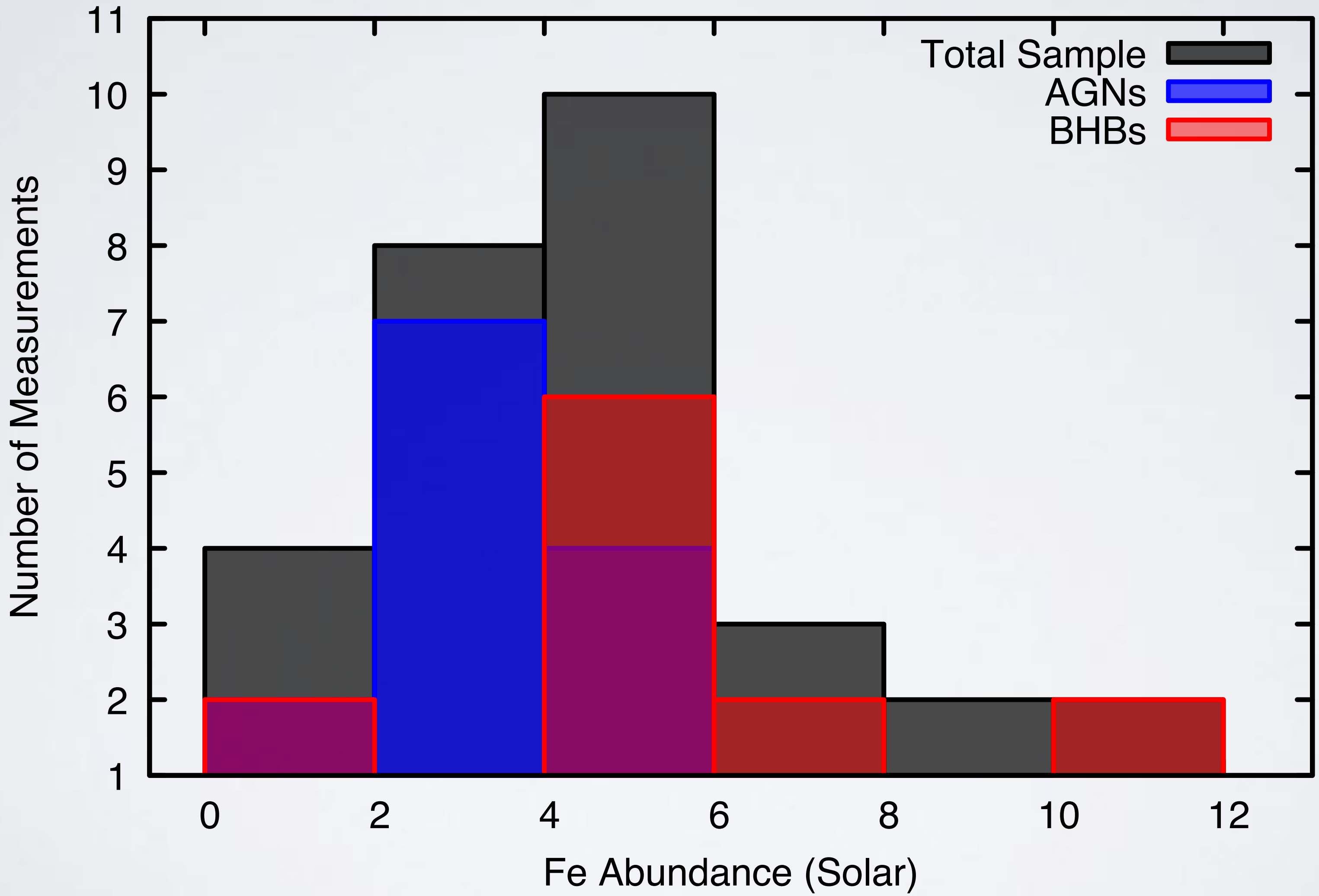


Contours plots of inclination and spin for 69%, 90% and 99% confidence

The uncertainties are dramatically reduced when the angle-resolved model (solid lines) is implemented.

The Problem of the Iron Abundance

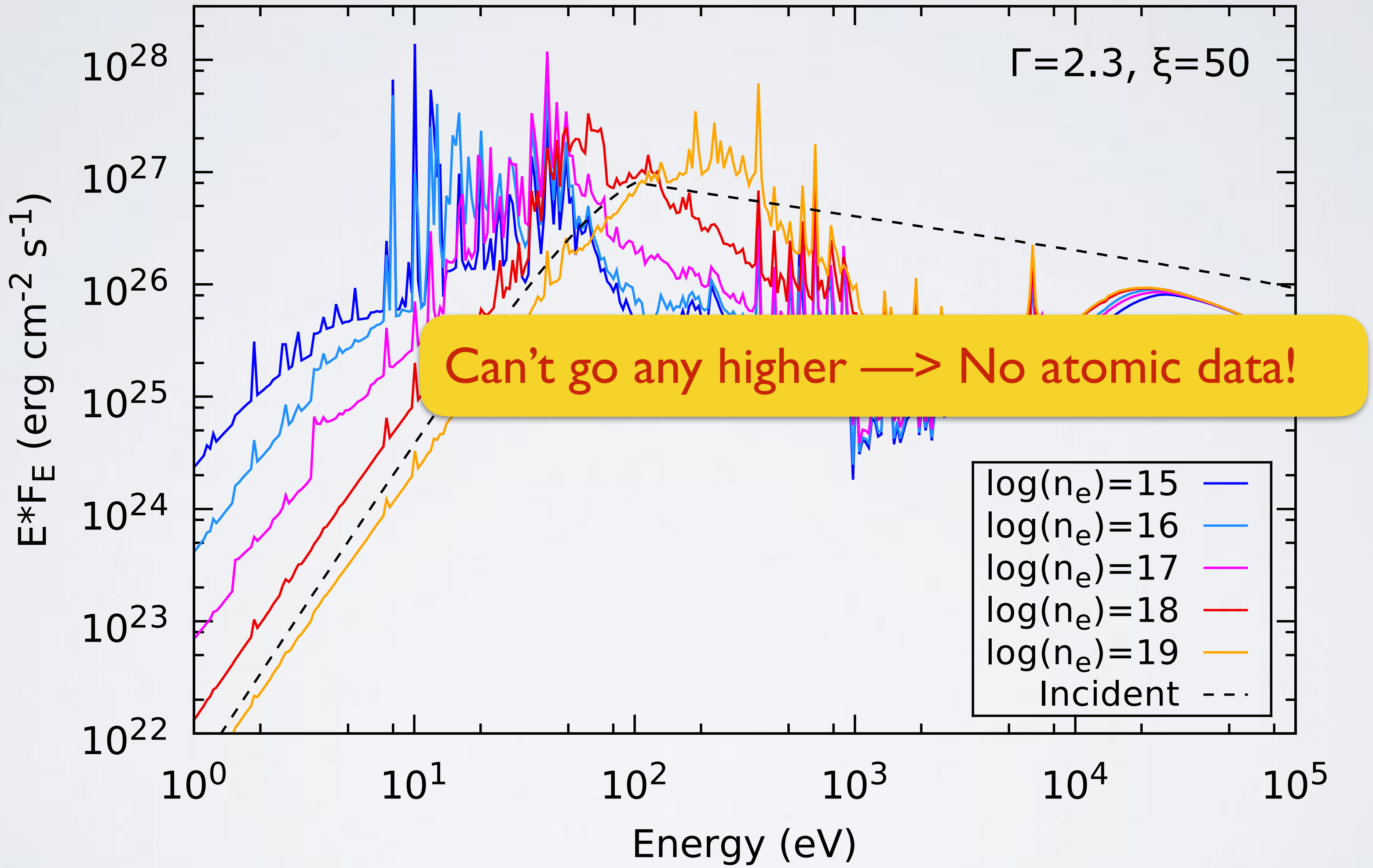
Iron abundance determinations using reflection spectroscopy from publications since 2014 tend to find a few times the Solar value!



13 AGNs
9 BHBs

High-Density Effects

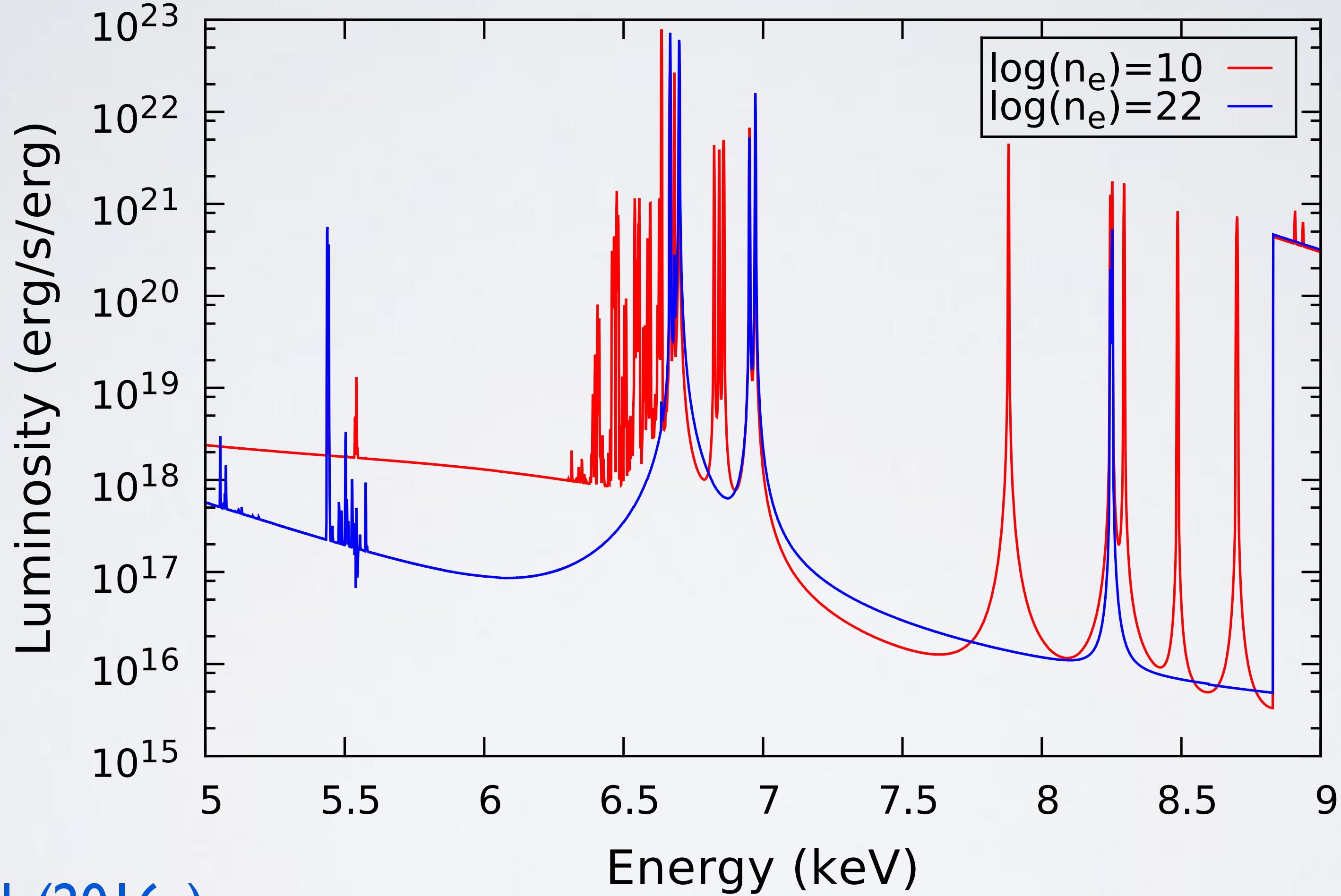
Models with high gas density ($n_e >> 10^{15}$ cm^{-3}) produce a remarkable flux excess at soft energies as free-free emission becomes important.



García et al. (2016a)

High-Density Effects

High-density effects such as continuum lowering could have an impact in the Fe abundance. However, new atomic data for high density plasmas is required!



García et al. (2016a)

The Hardeness-Intensity Diagram

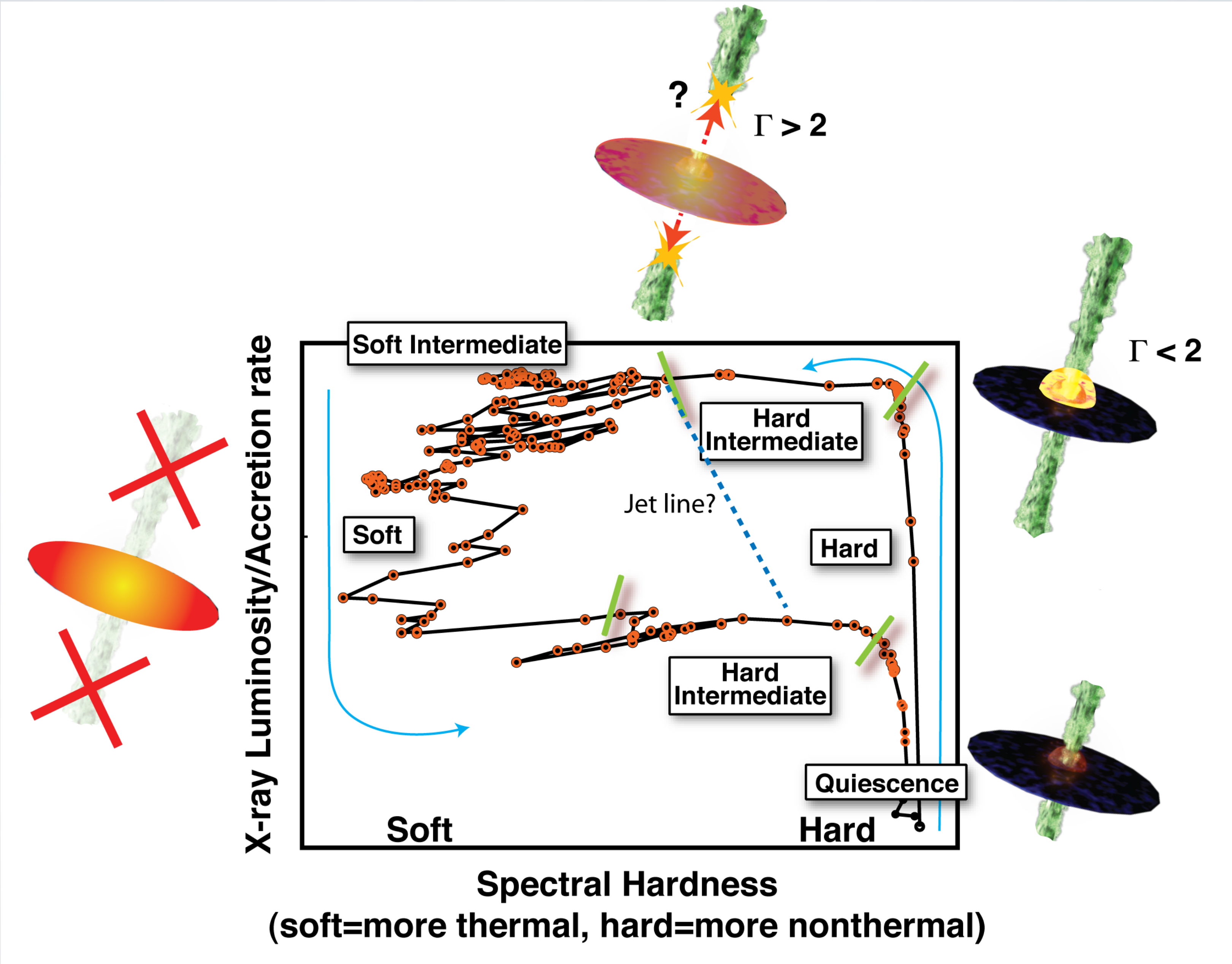


Figure courtesy of Sera Markoff