Chandra Grating Observations of Cataclysmic Variables

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Kulinder Pal Singh, Tata Institute, Mumbai

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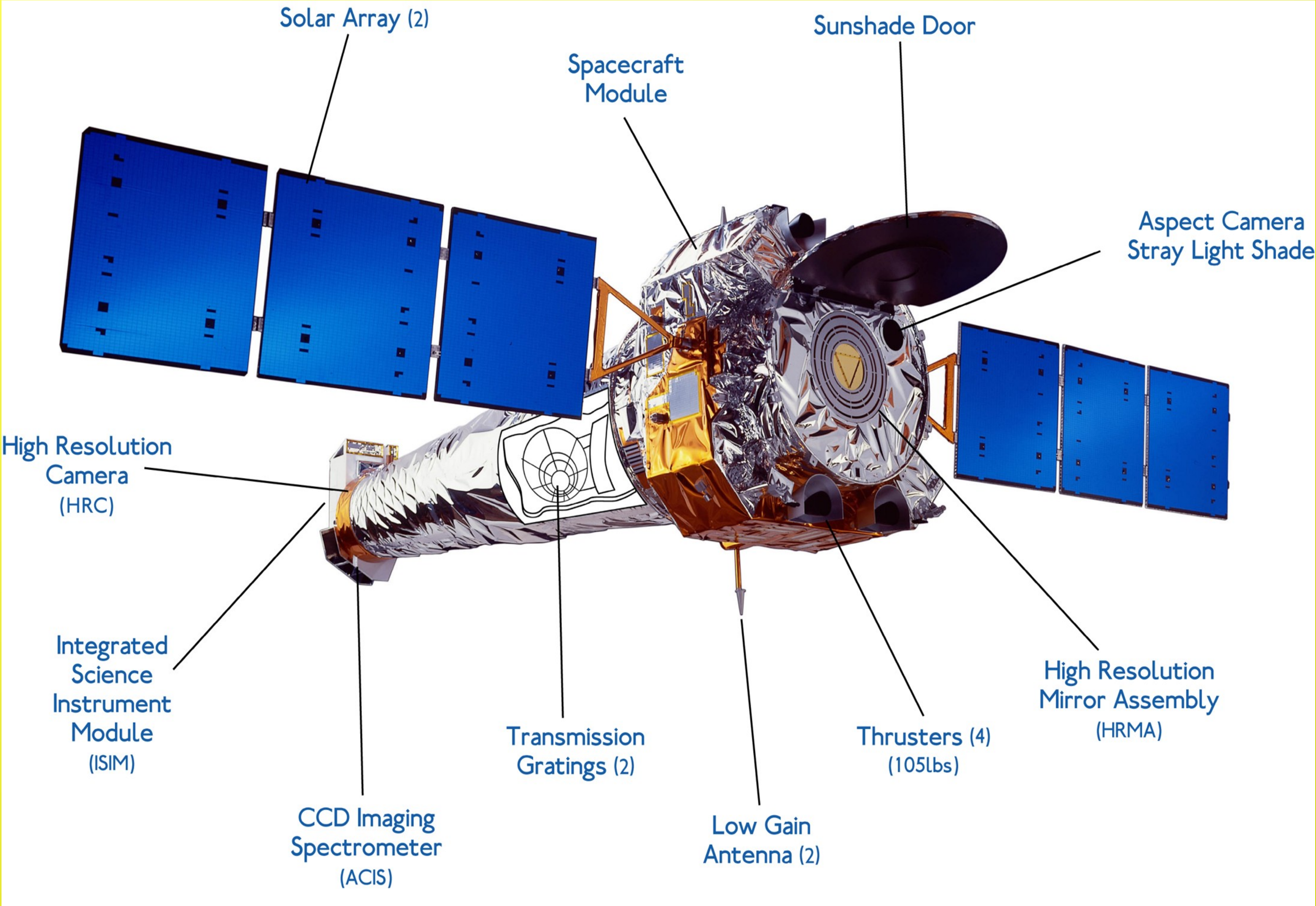
Chandra X-ray Observatory



X-rays

Energy range: ~0.2-8 keV = 1.55 Å to 62 Å

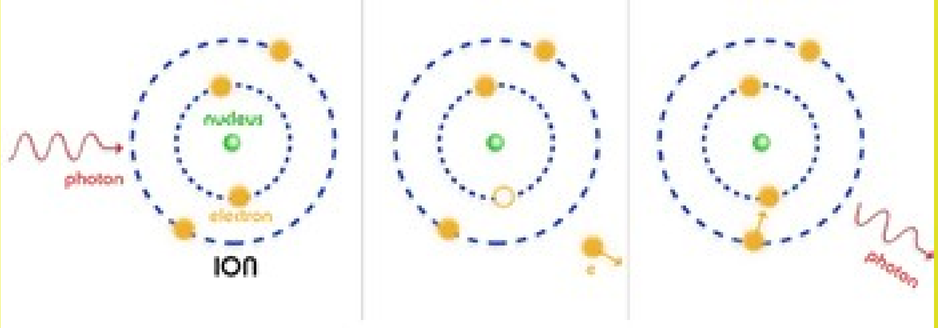
= 0.15 to 6.2 nm

Accepted terms: soft X-rays: $E < \sim 2$ keV

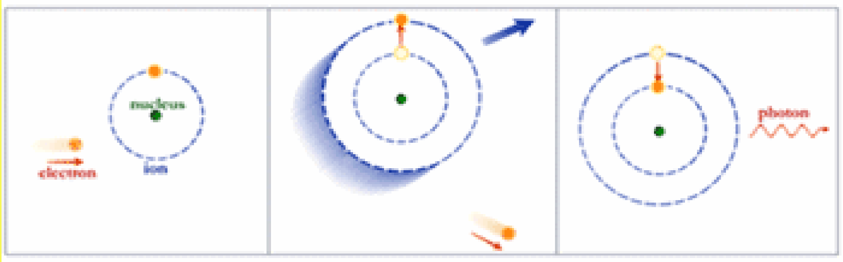
hard X-rays: $E > \sim 2$ keV

Typical equivalent temperature: 0.5-80 MK

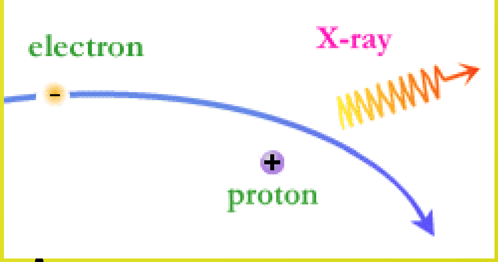
Processes



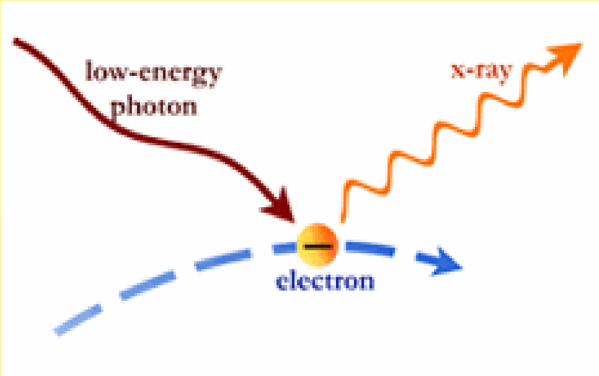
Atomic Emission



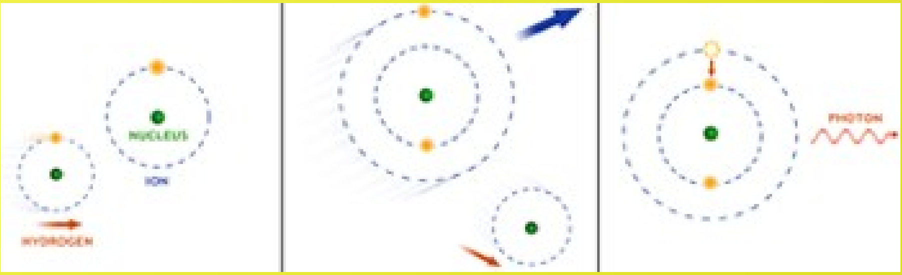
Fluorescence



Inverse Compton

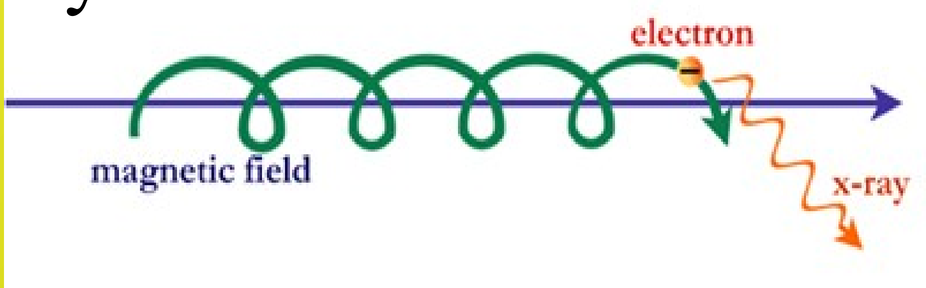


p-e collision (bremsstrahlung)

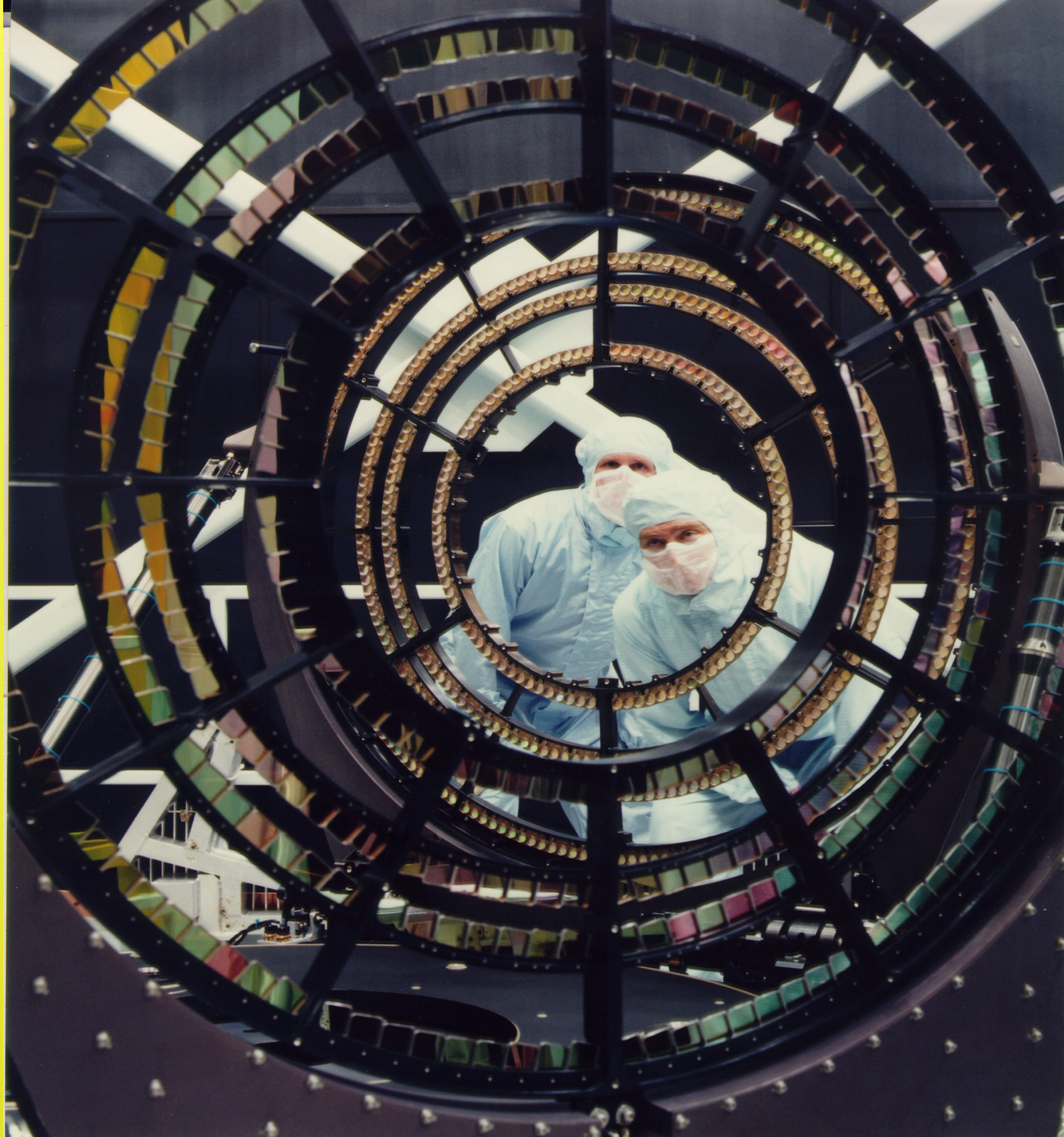


Charge exchange

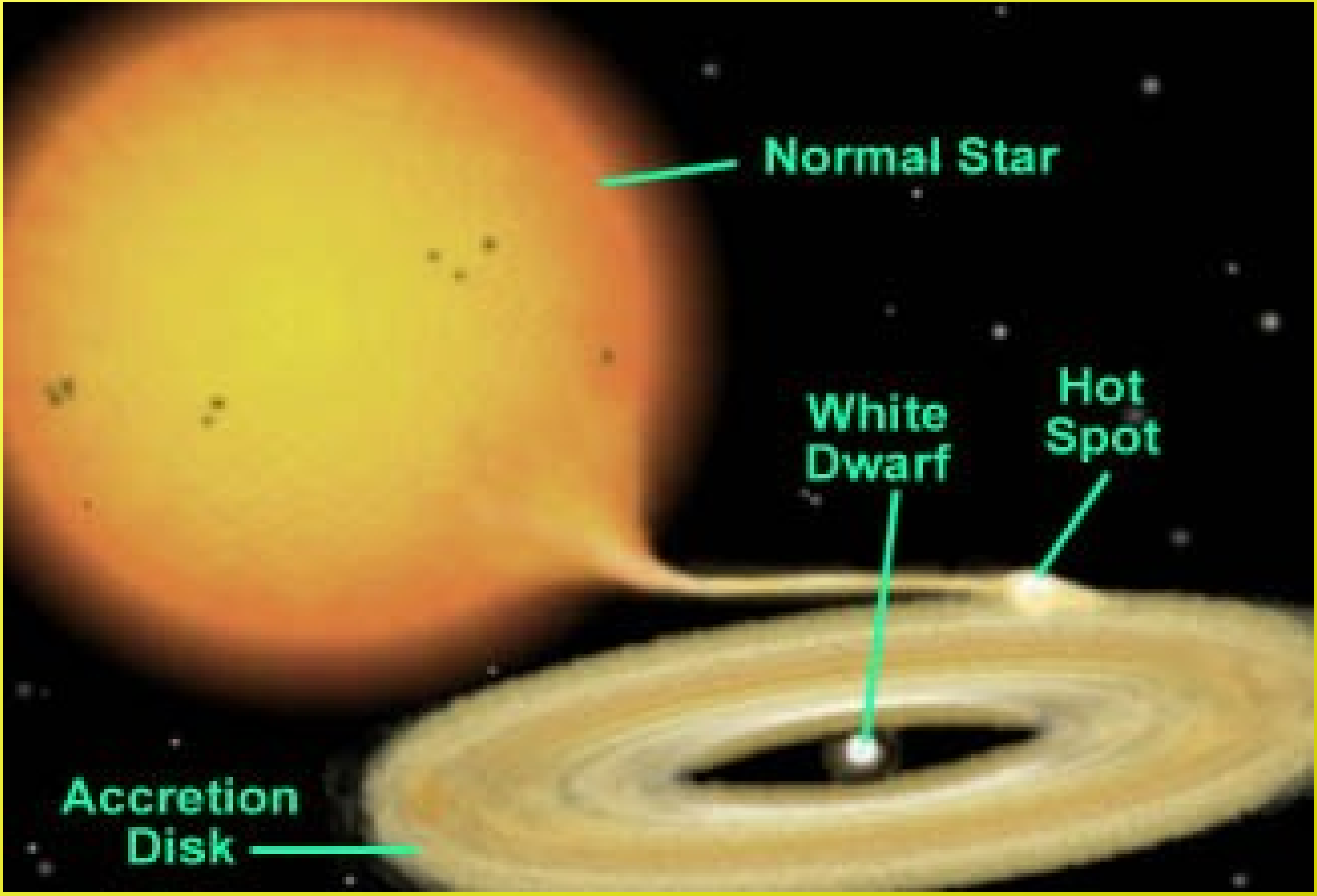
Synchrotron



Gratings



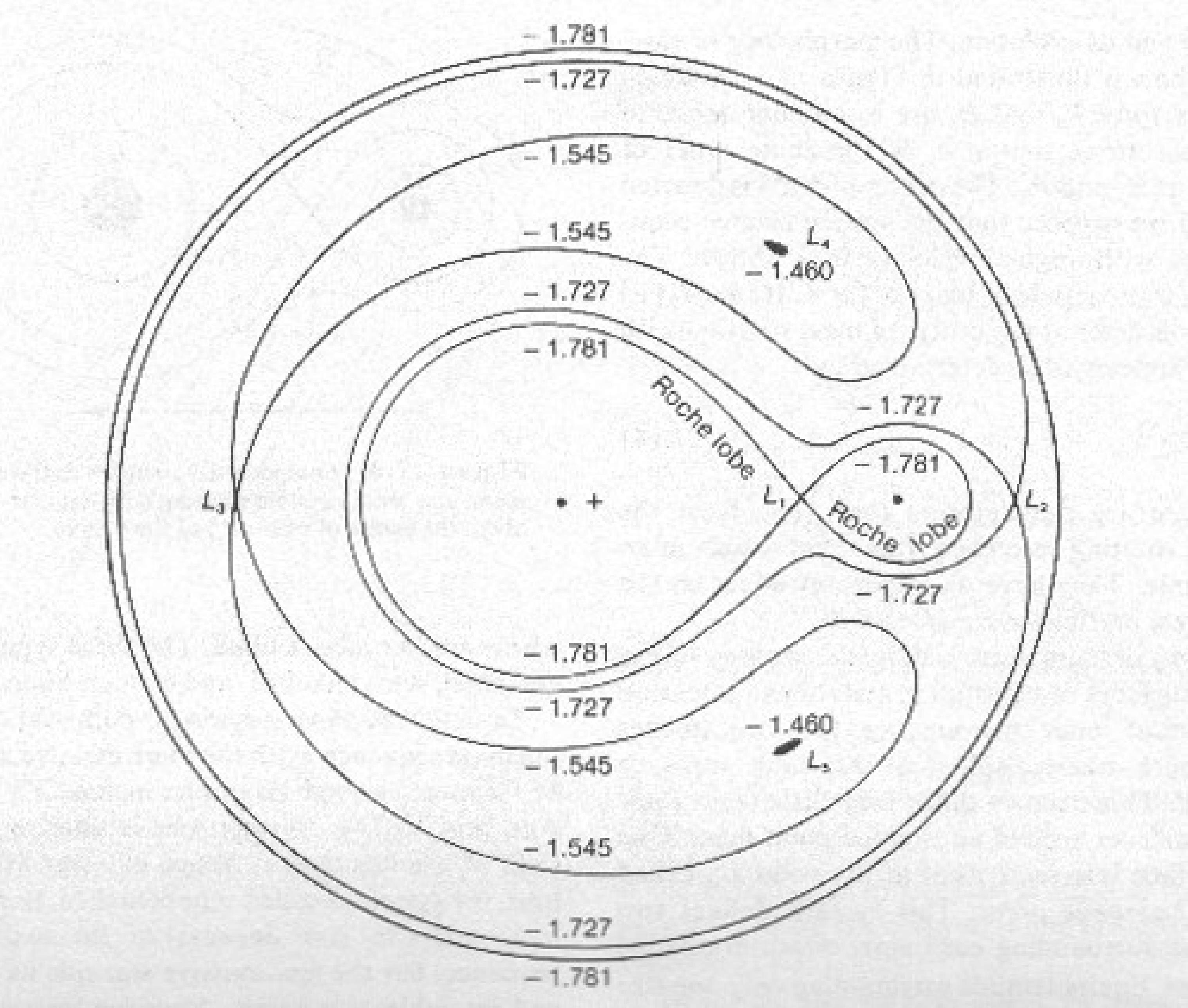
Cataclysmic Variable (schematic)



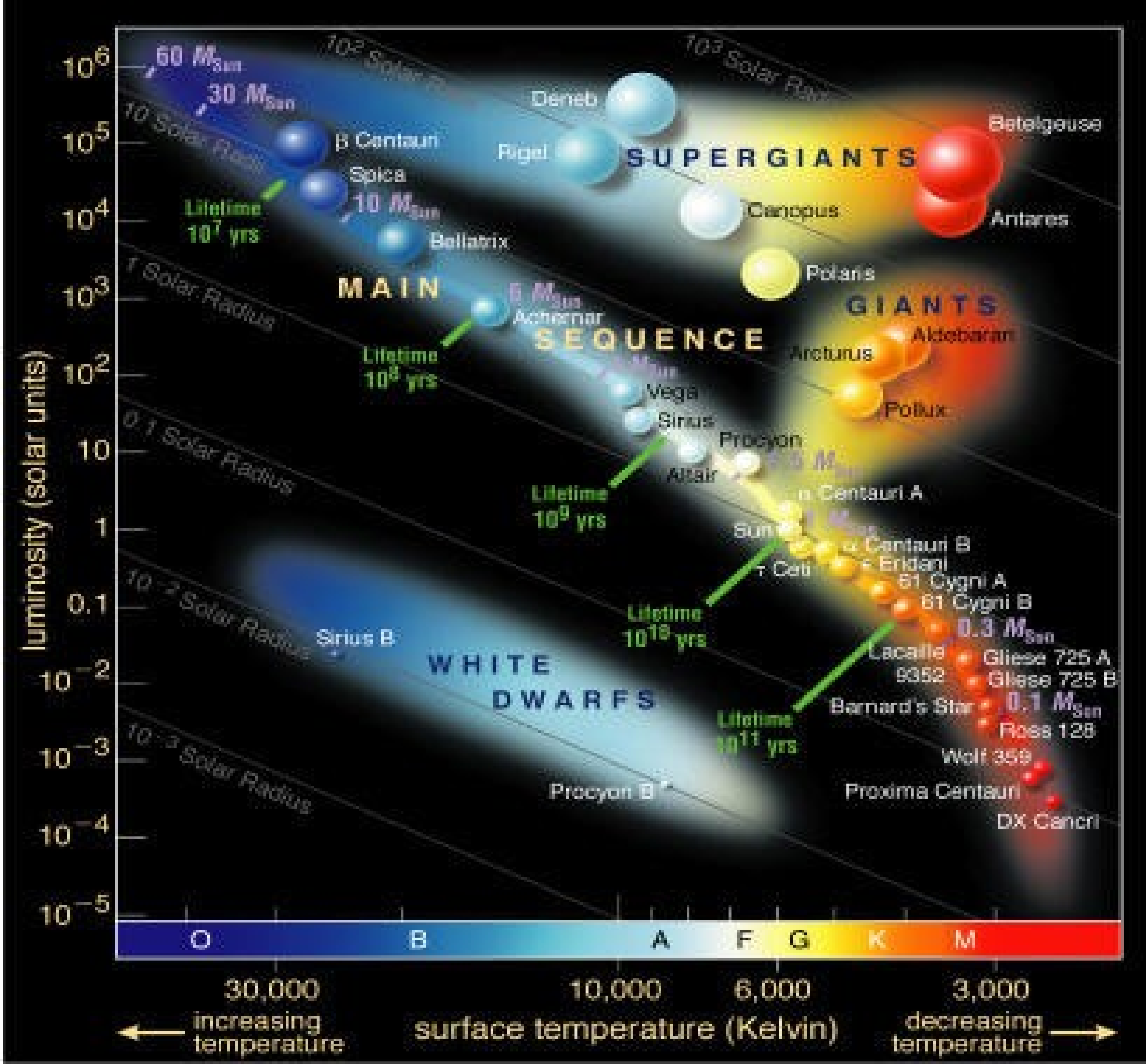
Cataclysmic Variables

- Interacting binary stars: white dwarf + red dwarf main sequence star
- typical orbital periods: hours
- Roche lobe overflow >> mass transfer stream
- angular momentum >> accretion disk
- X-ray emission: weak for disk systems; strong for magnetic systems

Roche Lobe



– 1.781
– 1.727
– 1.545
– 1.545
L4
– 1.460
– 1.727
– 1.781
Roche lobe
– 1.727
– 1.781
L3
L1
Roche lobe
L2
– 1.727
– 1.781
– 1.727
– 1.460
L5
– 1.545
– 1.545
– 1.727
– 1.781



luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
60 M_Sun
30 M_Sun
10 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
Deneb
Rigel
Betelgeuse
SUPERGIANTS
Antares
Canopus
Polaris
GIANTS
Aldebaran
Arcturus
Pollux
β Centauri
Spica
Bellatrix
MAIN
SEQUENCE
Achernar
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
Sirius B
WHITE
DWARFS
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

CV Subtypes

Outbursting systems:

- Dwarf novae
- Recurrent novae
- Classical novae

Magnetic systems

- Polars (AM Her stars)
- Intermediate polars (DQ Her stars)

Novalikes

Dwarf and Classical Novae

- Outbursts: build-up of H layer
- DNe: recur: cycles ~few days to months; rise 2-6 mag (5 mag = 100x)
- CNe: recur? rise 8-15 mag
- weak X-ray sources

Magnetic CVs

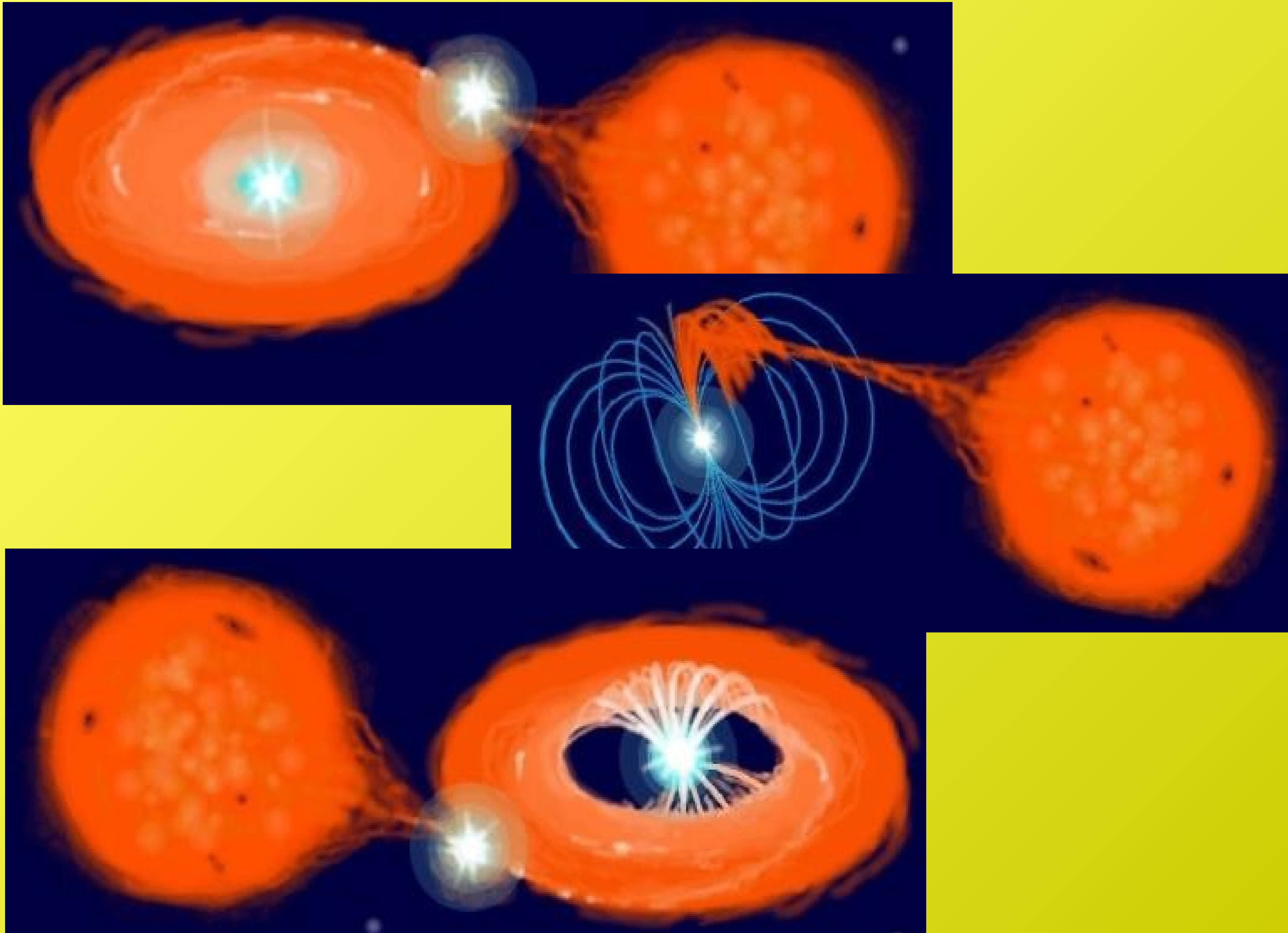
- CVs with disks have fields <~0.1 MG
- Magnetic CVs have fields > 1 MG
- (1 MG = 100 Tesla)

Polars = AM Her stars

- Field strengths >10 MG (> 1000 T)
- No accretion disk!
- Matter accretes to magnetic pole
- Strong, *soft* X-ray sources

Intermediate Polars = DQ Her stars

- ~1 < field <10 MG
- White dwarf, red dwarf **NOT** locked
- >> X-ray modulations at spin, orbit periods plus aliases
- Strong, *hard* X-ray sources



X-ray Emission

- $<L_X$ (DN)$>$ $\sim 10^{30-31}$ erg/sec $=10^{23-24}$ J/s
- $<L_X$ (AM)$>$ $\sim 10^{32-33}$ erg/sec $=10^{25-26}$ J/s:
  soft (0.5-2 keV) X-rays dominate
- $<L_X$ (IP)$>$ $\sim 10^{33}$ erg/sec $=10^{26}$ J/s:
  hard (2-10 keV) X-rays dominate

What's the science?

Accretion physics!

- Numerous questions: how does the accretion region work? What feedback is present? Uniform appearance with phase? Plasma conditions (T, density, …)? ...

Shocks

Expect hot gas:

simple thermal energy = gravitational potential yields ~15-20 keV

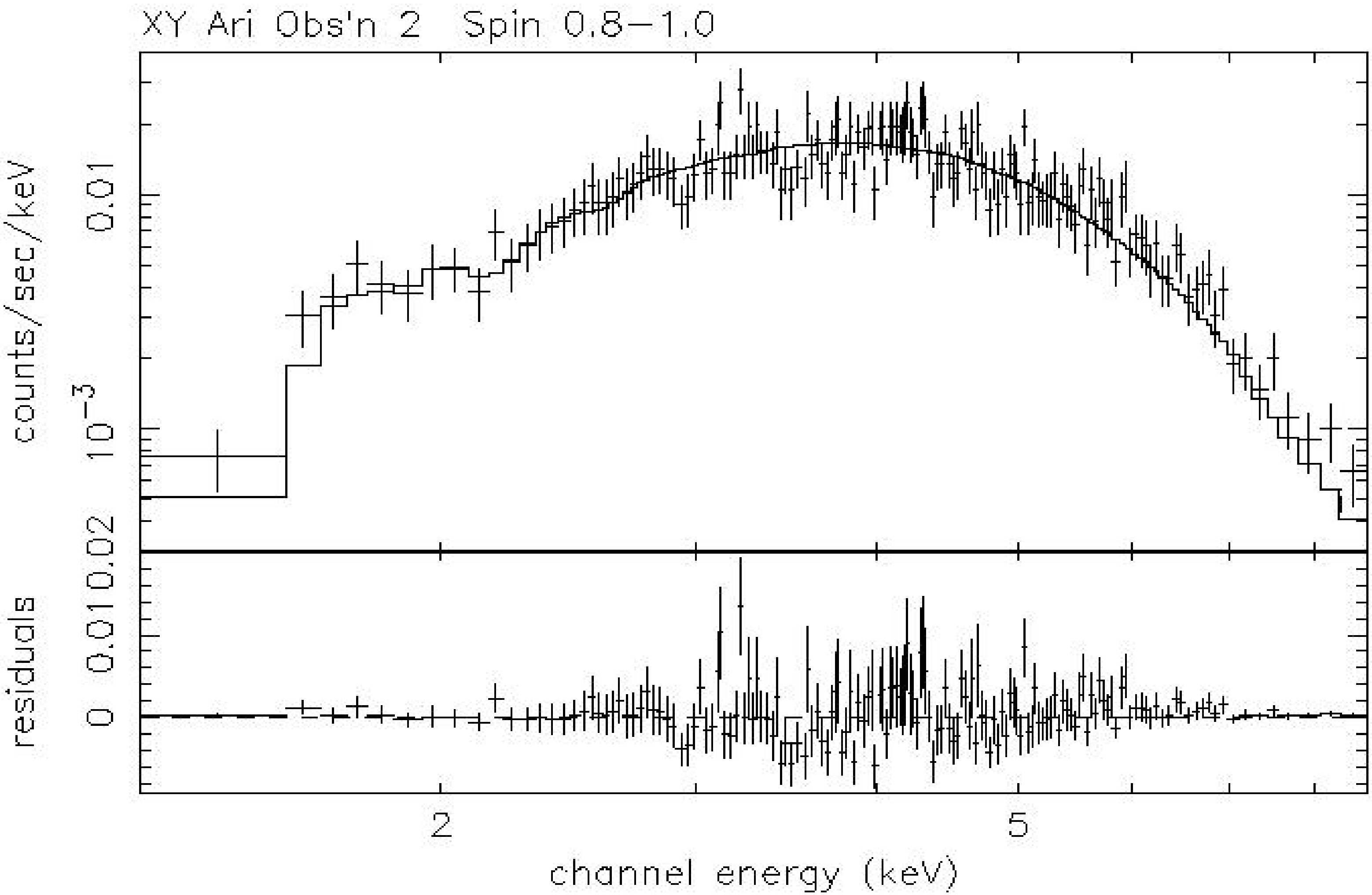
$kT_s = (3/8)(GM/R) \sim 16\ (M/0.5\ M_\odot)(10^9/R)$ keV

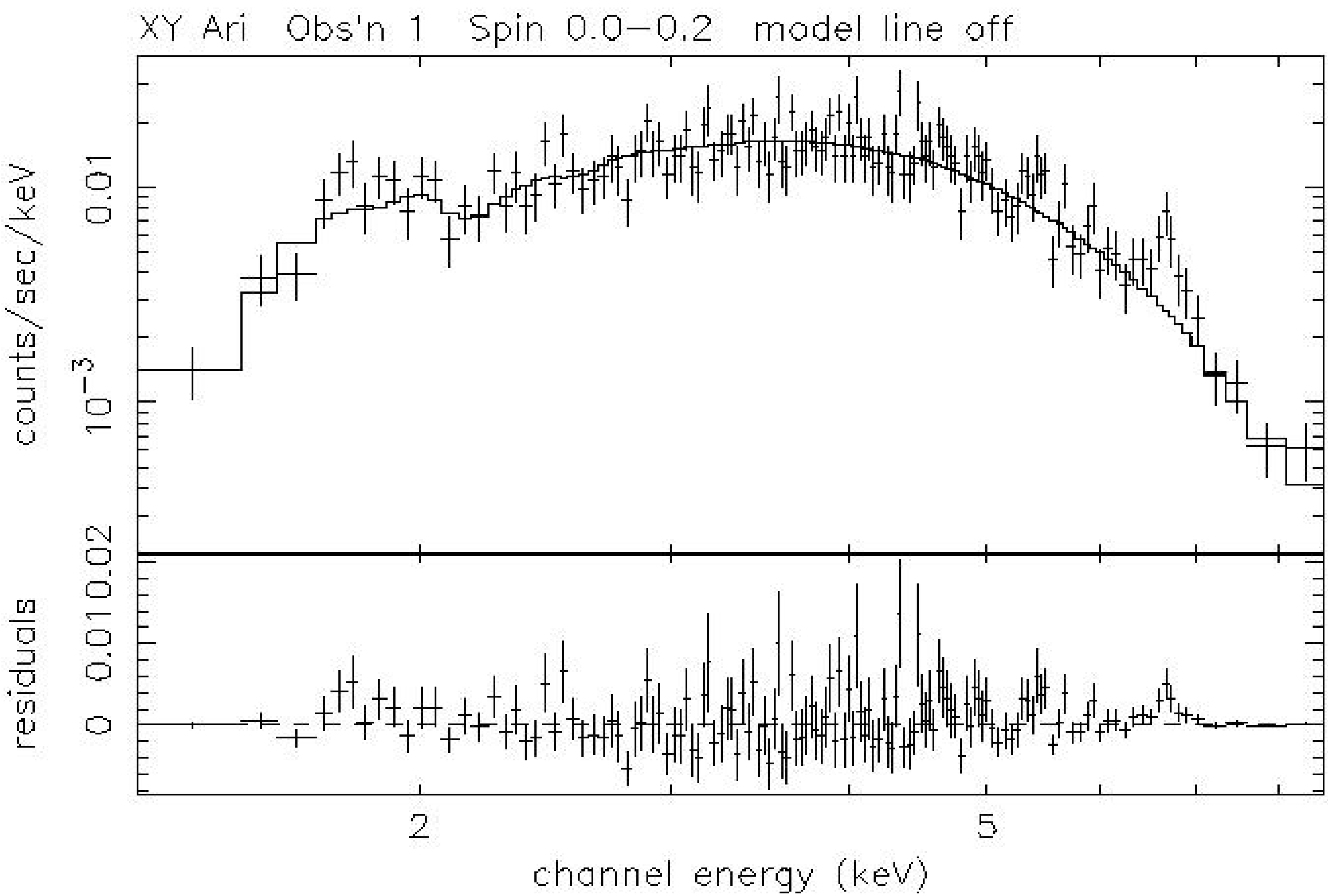
X-ray spectra ~ thermal

>> at low resolution, pure thermal spectrum adequately describes:

differential: $T^{-1/2}e^{-E/kt}$; total: $T^{1/2}$

>> at high resolution, post-shock emission lines


XY Ari Obs'n 2 Spin 0.8–1.0
counts/sec/keV
0.01
10^{-3}
residuals
0
0.01
0.02
2
5
channel energy (keV)


XY Ari Obs'n 1 Spin 0.0–0.2 model line off
counts/sec/keV
0.01
10^{-3}
residuals
0.02
0.01
0
2
5
channel energy (keV)

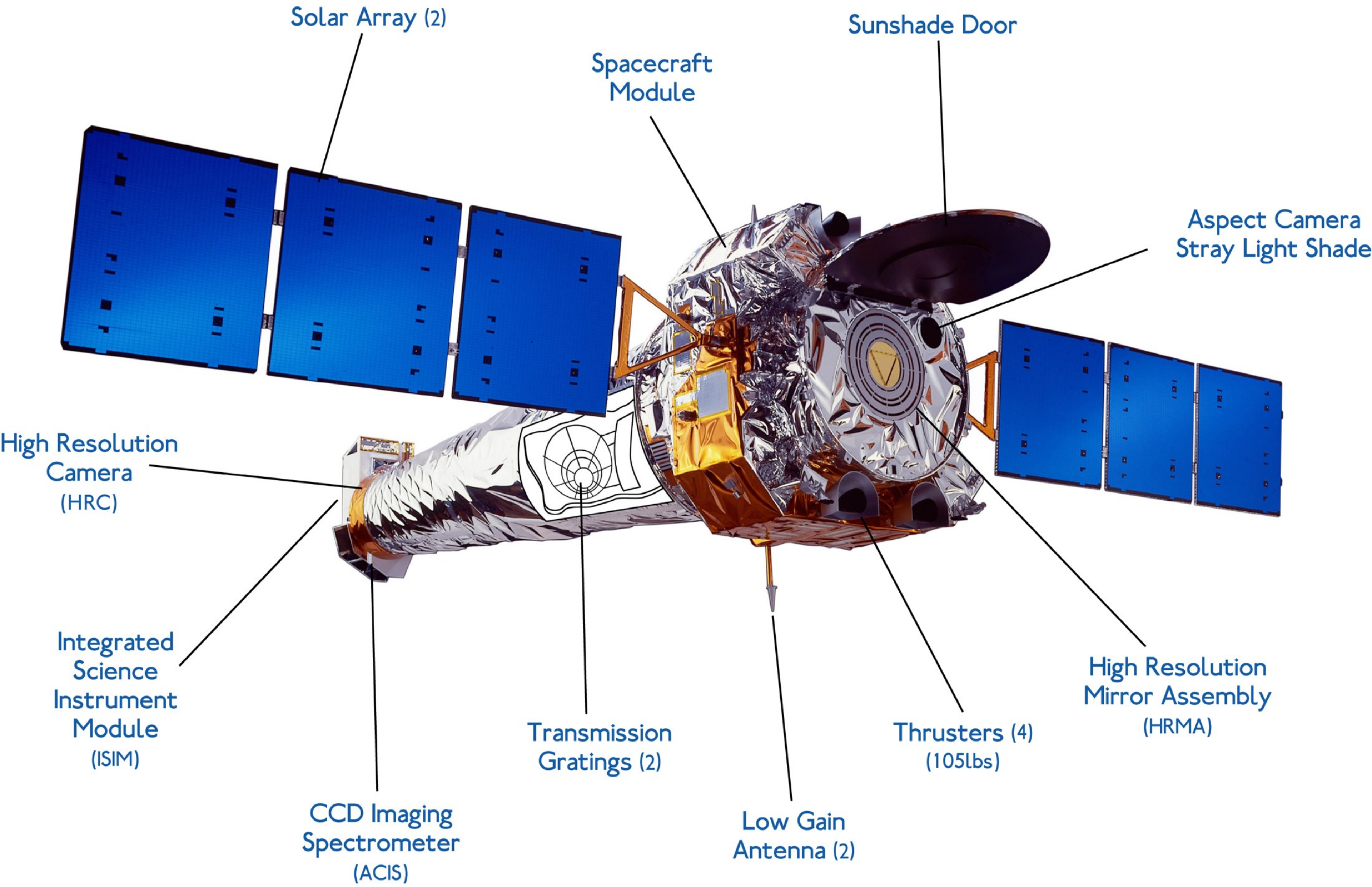
High-Resolution Era

Chandra X-ray Observatory (US)

- High-Energy Transmission Grating (HETG)
- Low-Energy Transmission Grating (LETG)

XMM-Newton (Europe)

- Reflection Grating Spectrometer (RGS)

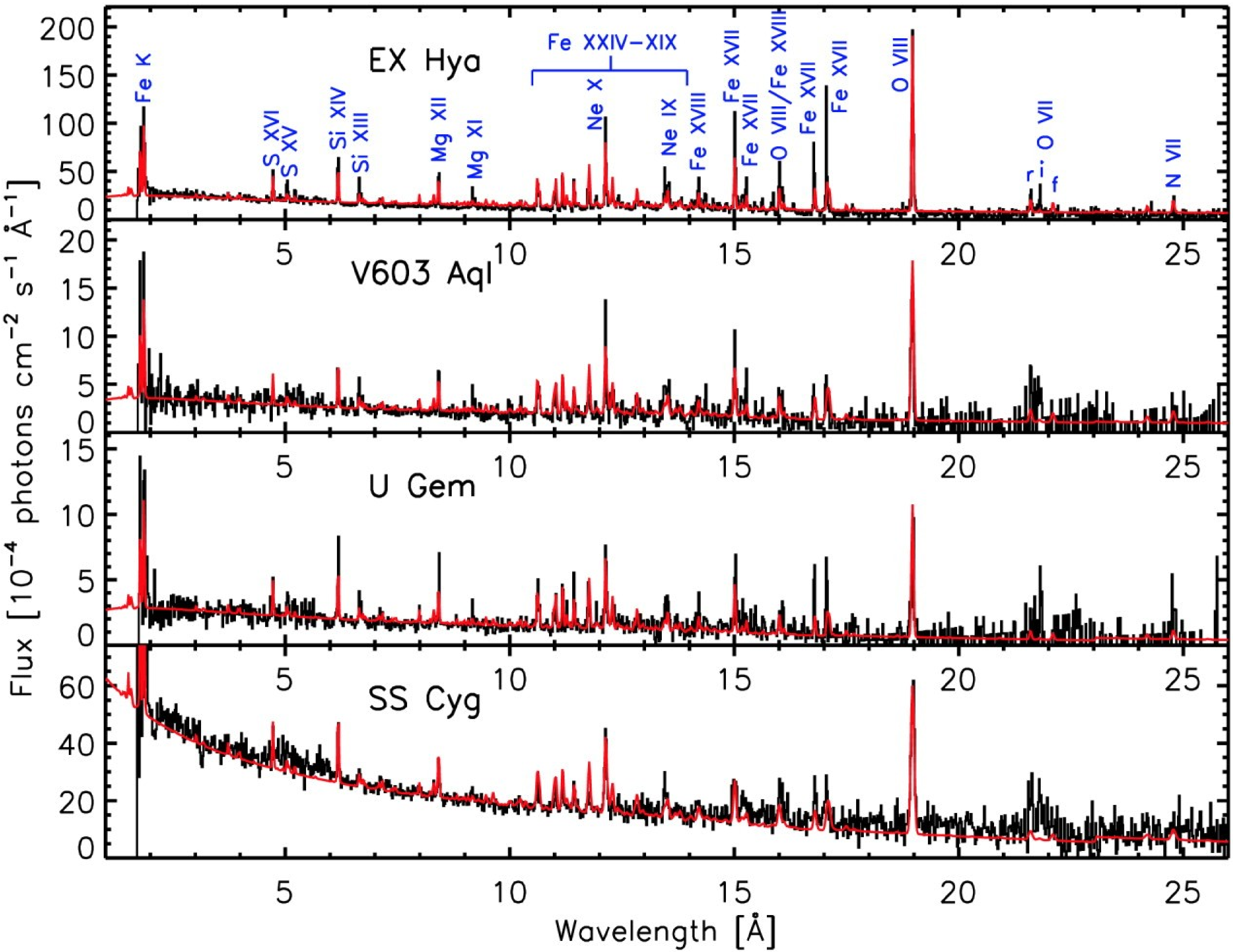

Solar Array (2)
Sunshade Door
Spacecraft Module
Aspect Camera Stray Light Shade
High Resolution Camera (HRC)
Integrated Science Instrument Module (ISIM)
CCD Imaging Spectrometer (ACIS)
Transmission Gratings (2)
Low Gain Antenna (2)
Thrusters (4) (105lbs)
High Resolution Mirror Assembly (HRMA)

Chandra Gratings: High-Energy Transmission Grating (HETG)

Grating Resolutions: (1 Å = 0.1 nm)

- HEG: 0.012 Å = 0.0012 nm
- MEG: 0.023 Å = 0.0023 nm

- Energy Resolutions E/△E:
  - HEG (at 6 keV): ~1000
  - MEG (at 1 keV): ~500



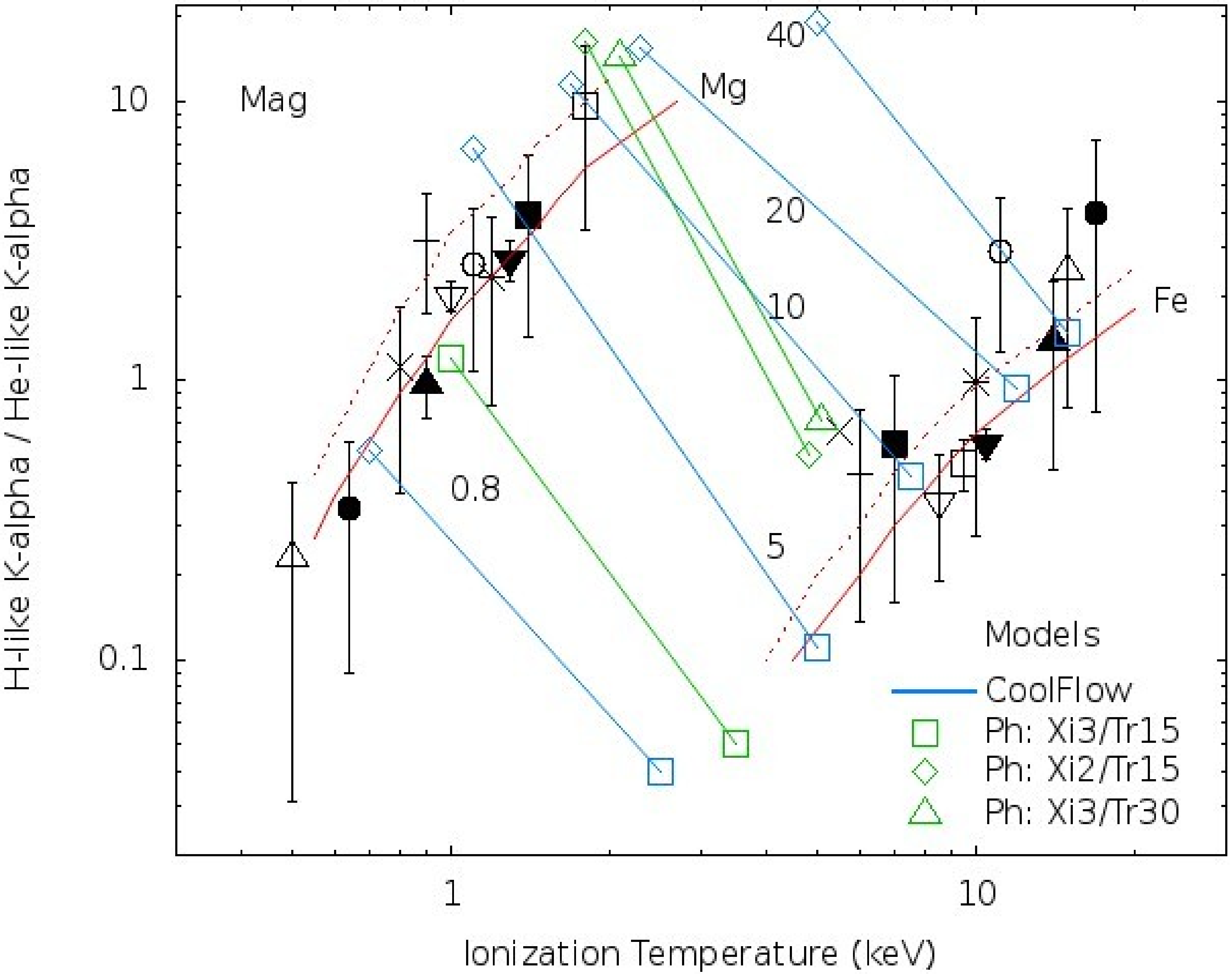
EX Hya
Fe XXIV–XIX
Fe K
S XVI
S XV
Si XIV
Si XIII
Mg XII
Mg XI
Ne X
Ne IX
Fe XVIII
Fe XVII
Fe XVII
O VIII/Fe XVIII
Fe XVII
Fe XVII
O VIII
r
i
f
O VII
N VII
V603 Aql
U Gem
SS Cyg
Flux [10^{-4} photons cm^{-2} s^{-1} $Å^{-1}$]
Wavelength [Å]

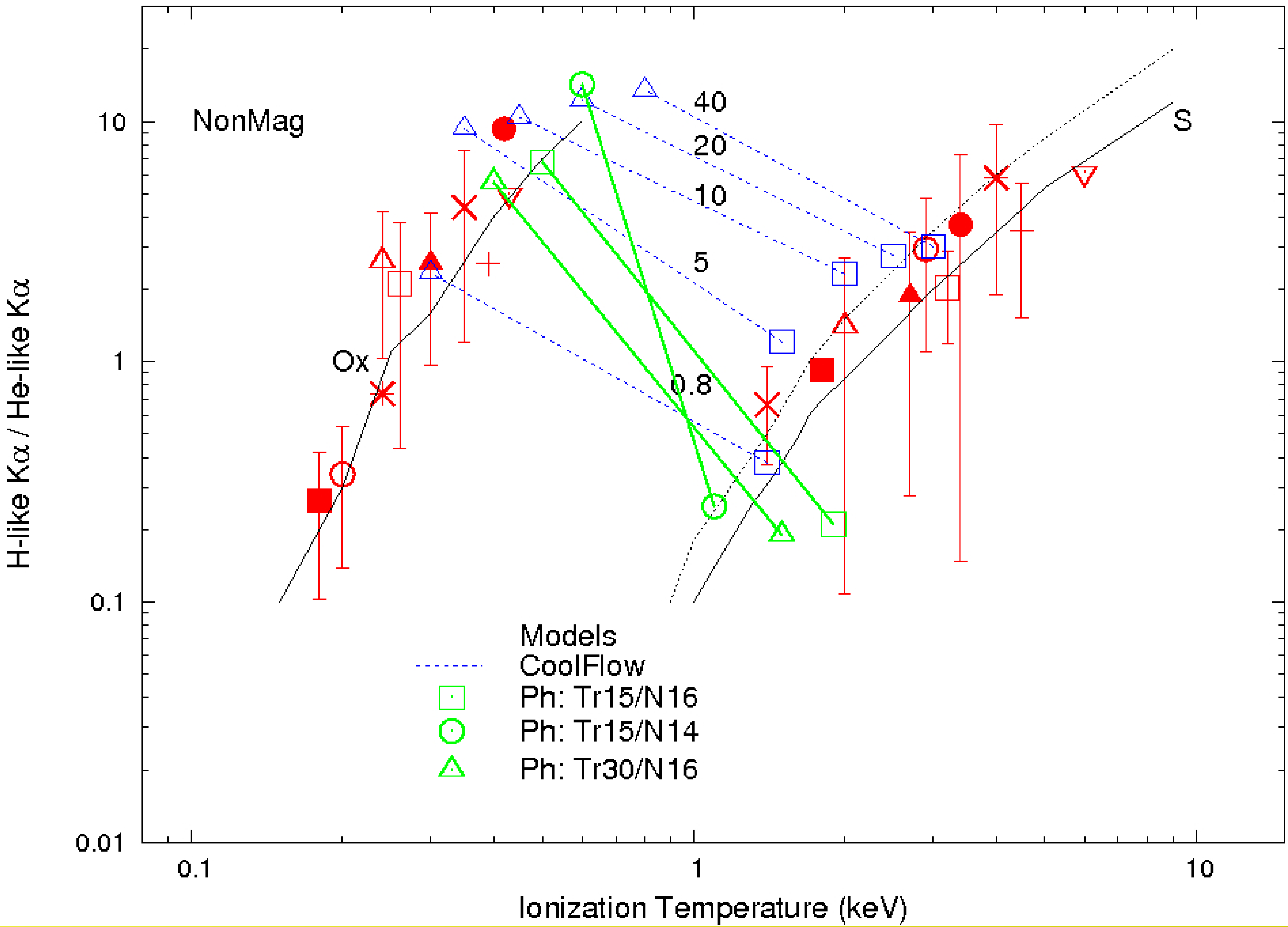
Diagnostics

- T: H-alpha / He-r
- T, density: He-like atoms
- notation: neutral atom = I;
  once-ionized = II; …

  so O VII = 6-times ionized O = He-like

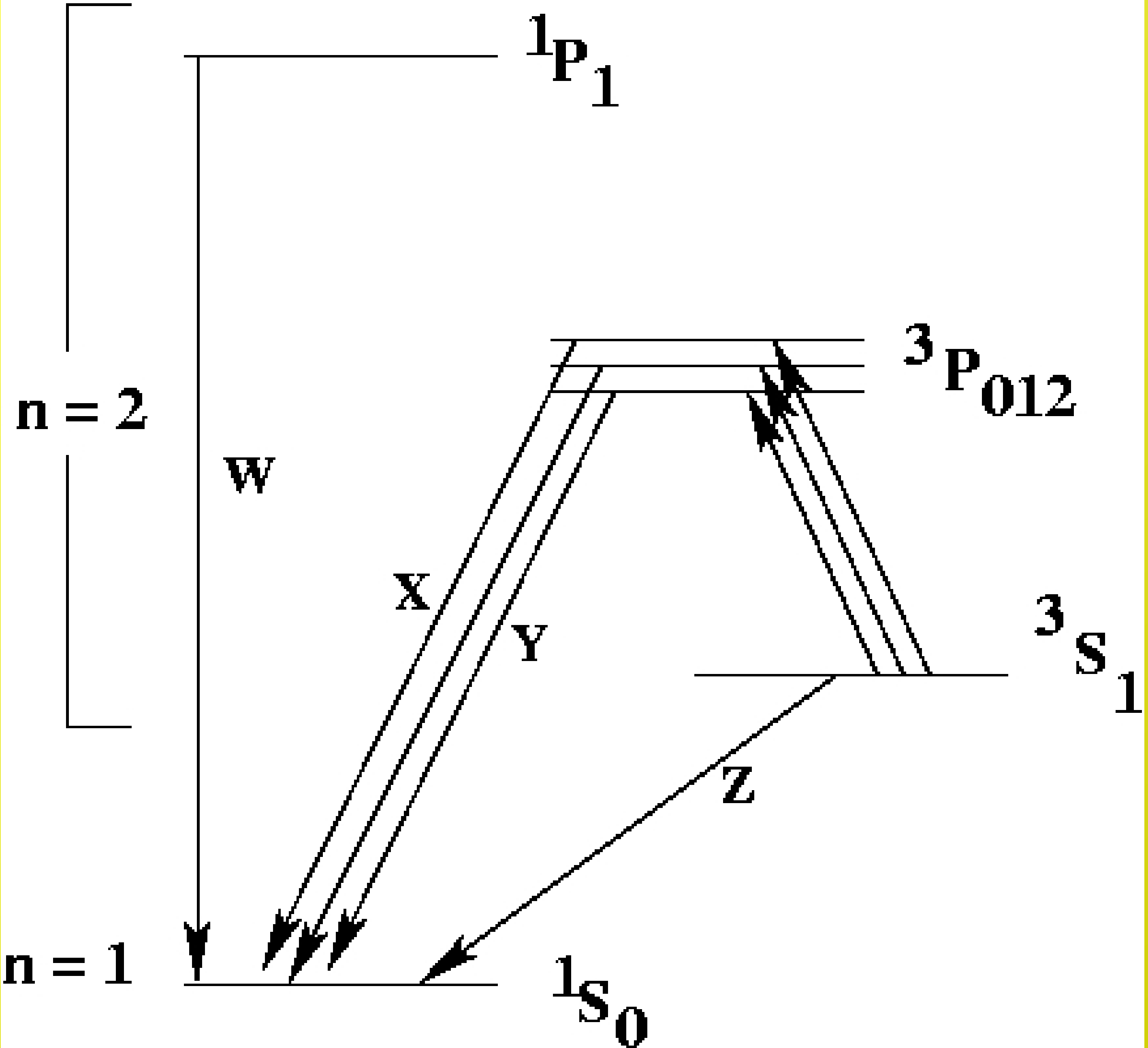
  O VIII = 7-times ionized O = H-like


Mag
Mg
Fe
40
20
10
5
0.8
10
1
0.1
1
10
H-like K-alpha / He-like K-alpha
Ionization Temperature (keV)
Models
CoolFlow
Ph: Xi3/Tr15
Ph: Xi2/Tr15
Ph: Xi3/Tr30



NonMag
Ox
S
40
20
10
5
0.8
Models
CoolFlow
Ph: Tr15/N16
Ph: Tr15/N14
Ph: Tr30/N16
H-like Kα / He-like Kα
Ionization Temperature (keV)
0.01
0.1
1
10

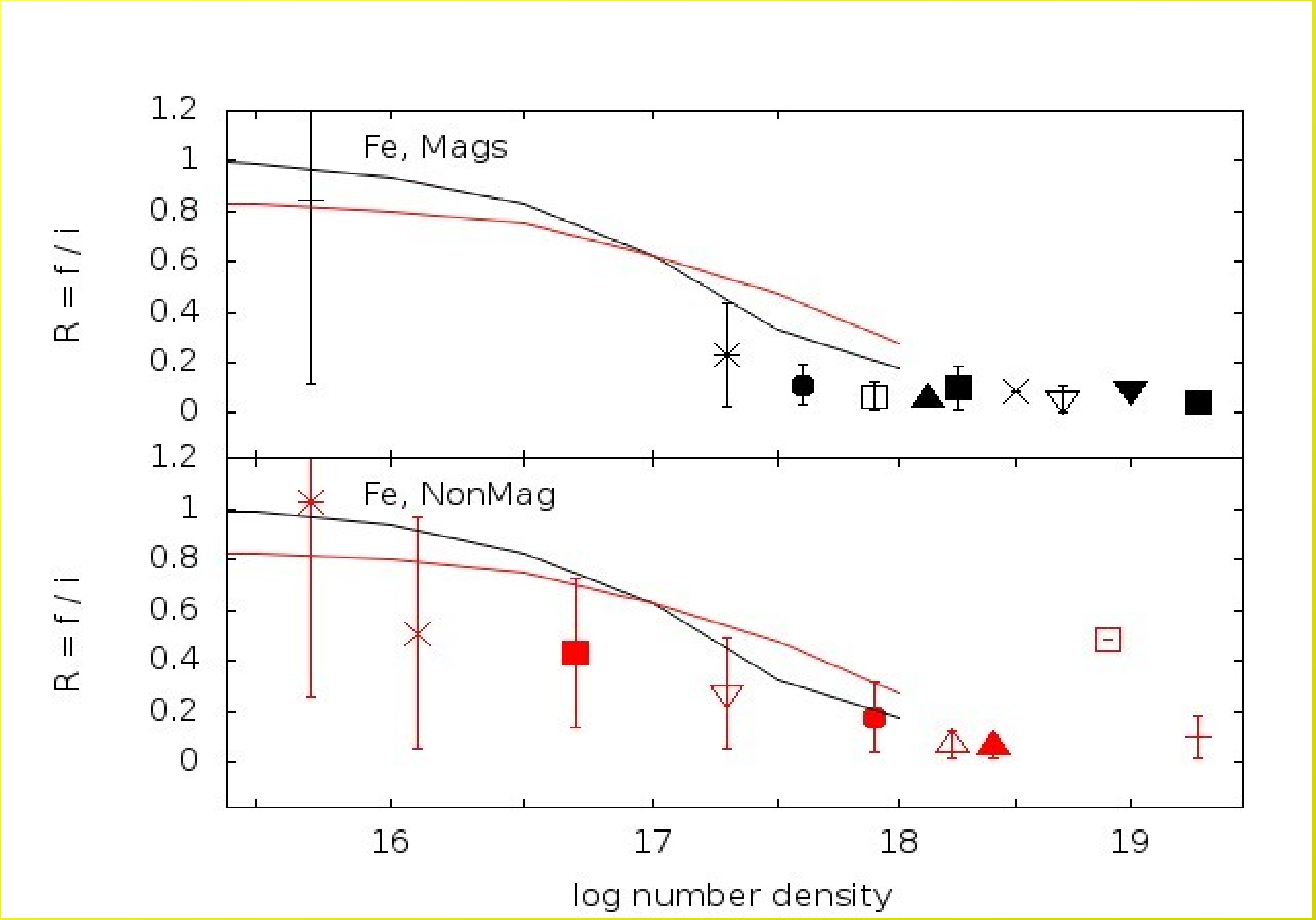
Schematic He–like atom



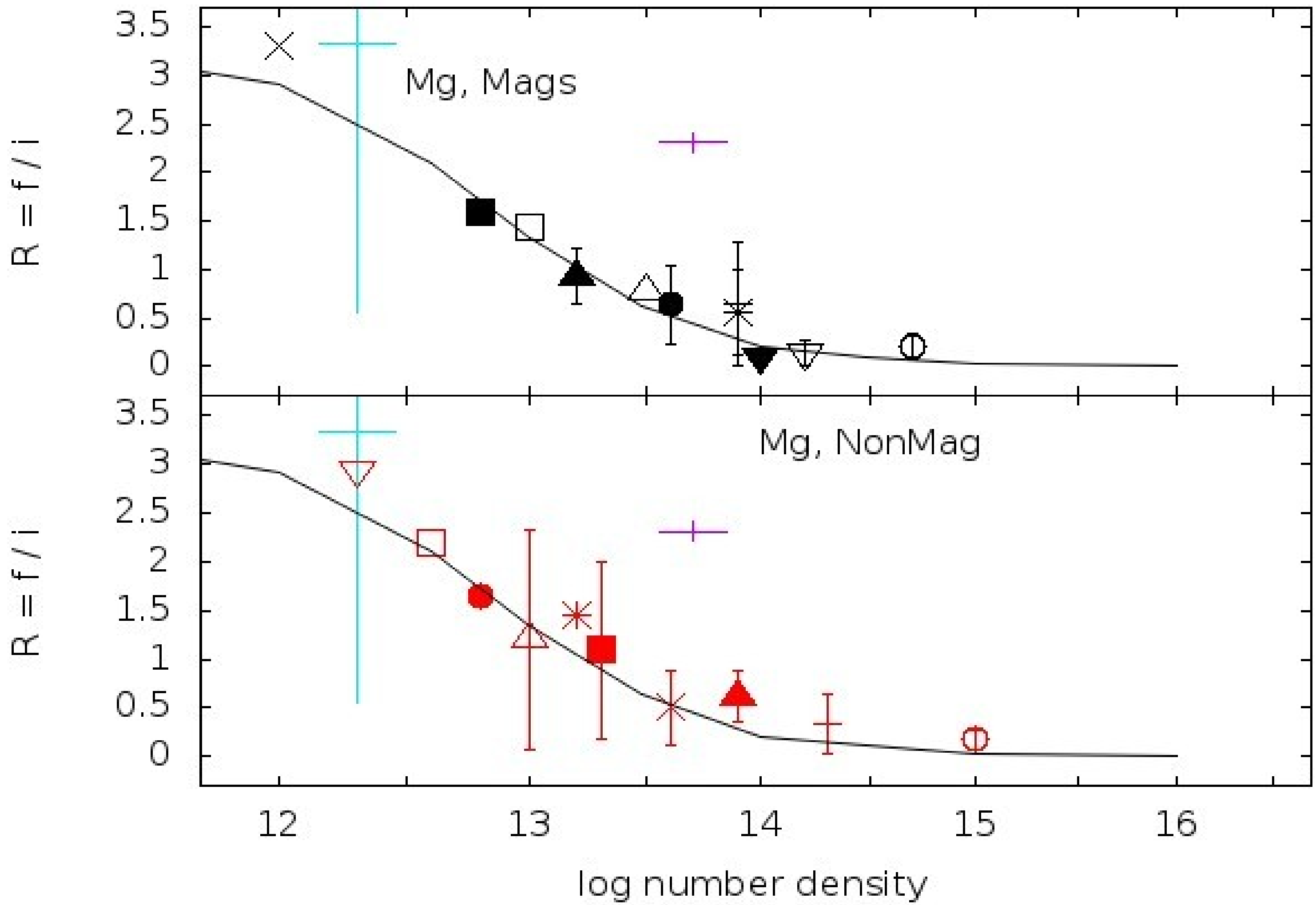
Diagnostics

- He-like atoms --> *rfi* diagnostics:
- $G = (z + x + y) / w = (f + i) / r \sim T$
- $R = z / (x + y) = f / i \sim$ density

R Ratio <<>> Number Density

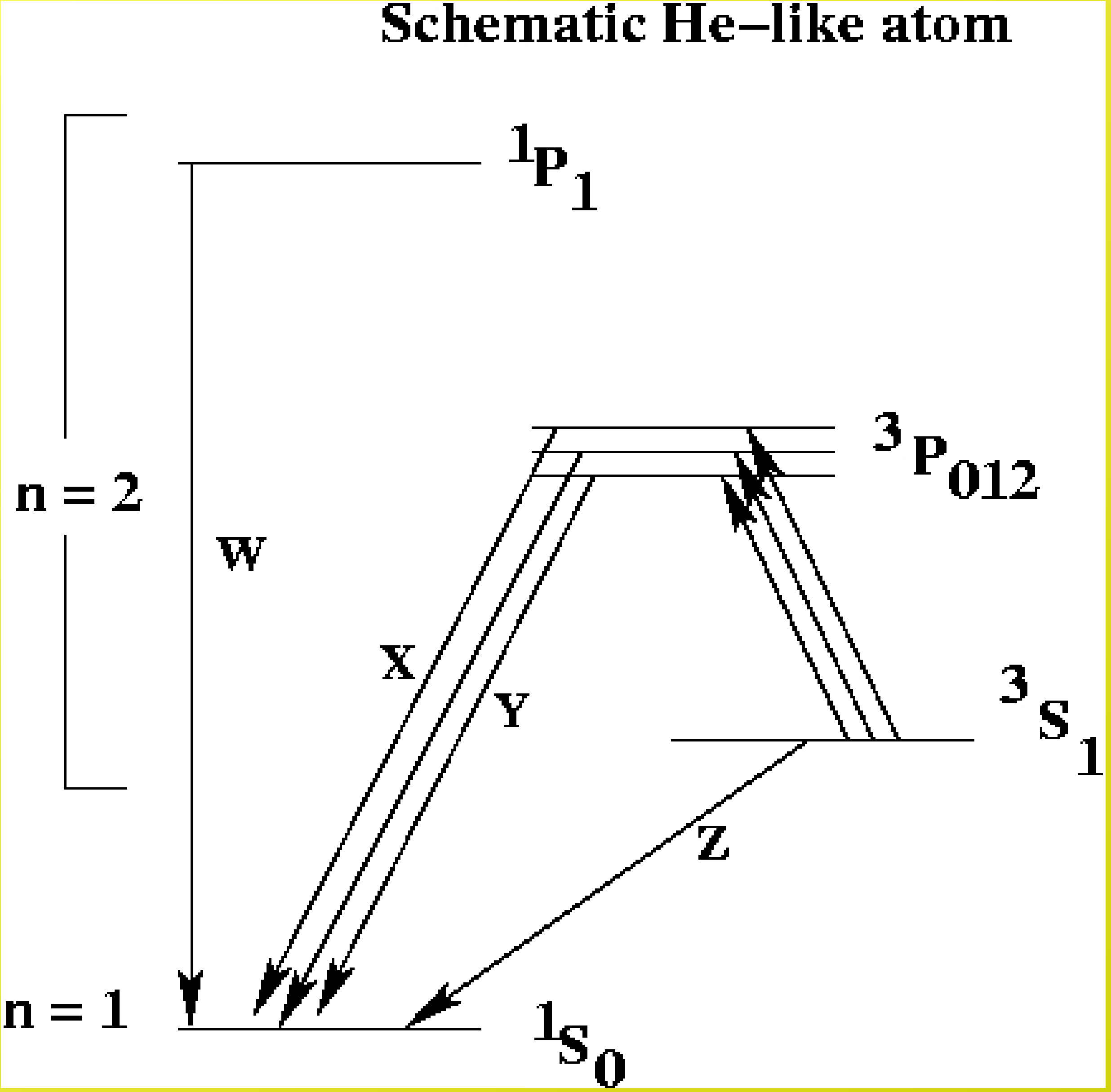


Fe, Mags
Fe, NonMag
R = f / i
R = f / i
1.2
1
0.8
0.6
0.4
0.2
0
16
17
18
19
log number density

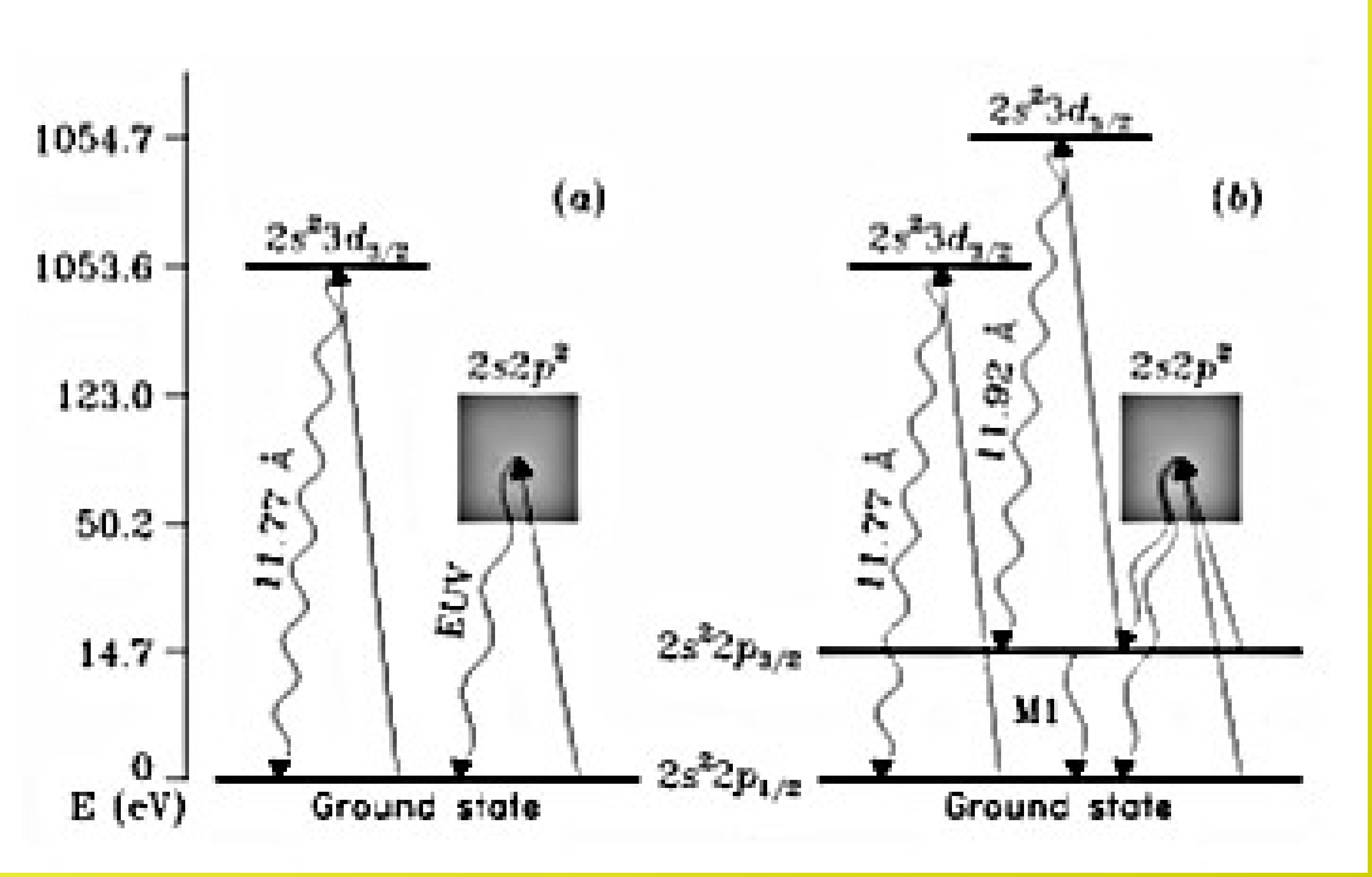


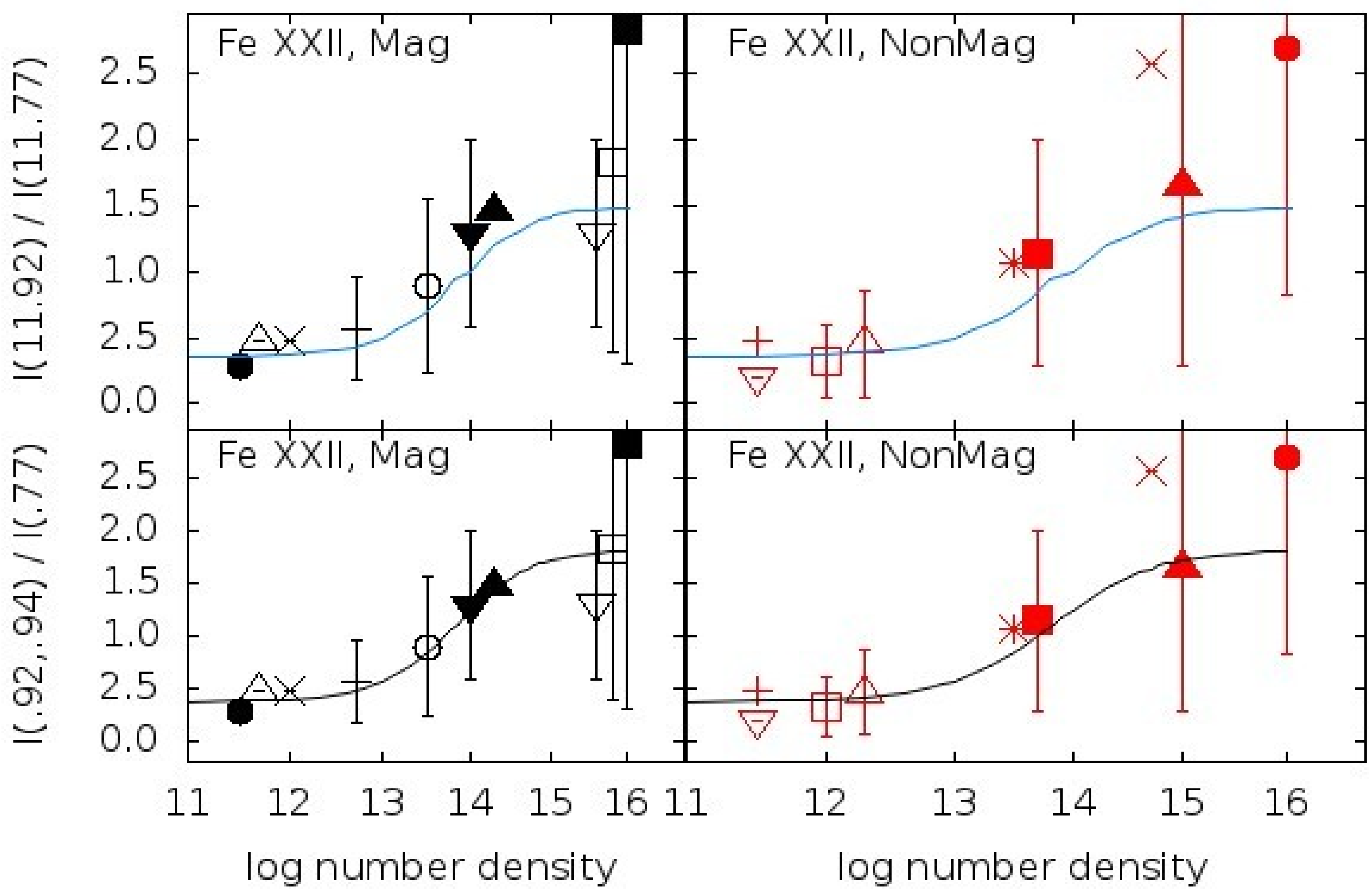
Mg, Mags
Mg, NonMag
R = f / i
R = f / i
3.5
3
2.5
2
1.5
1
0.5
0
3.5
3
2.5
2
1.5
1
0.5
0
12
13
14
15
16
log number density

Problem with R: radiation!



One Approach: Use Density Diagnostic less affected by radiation





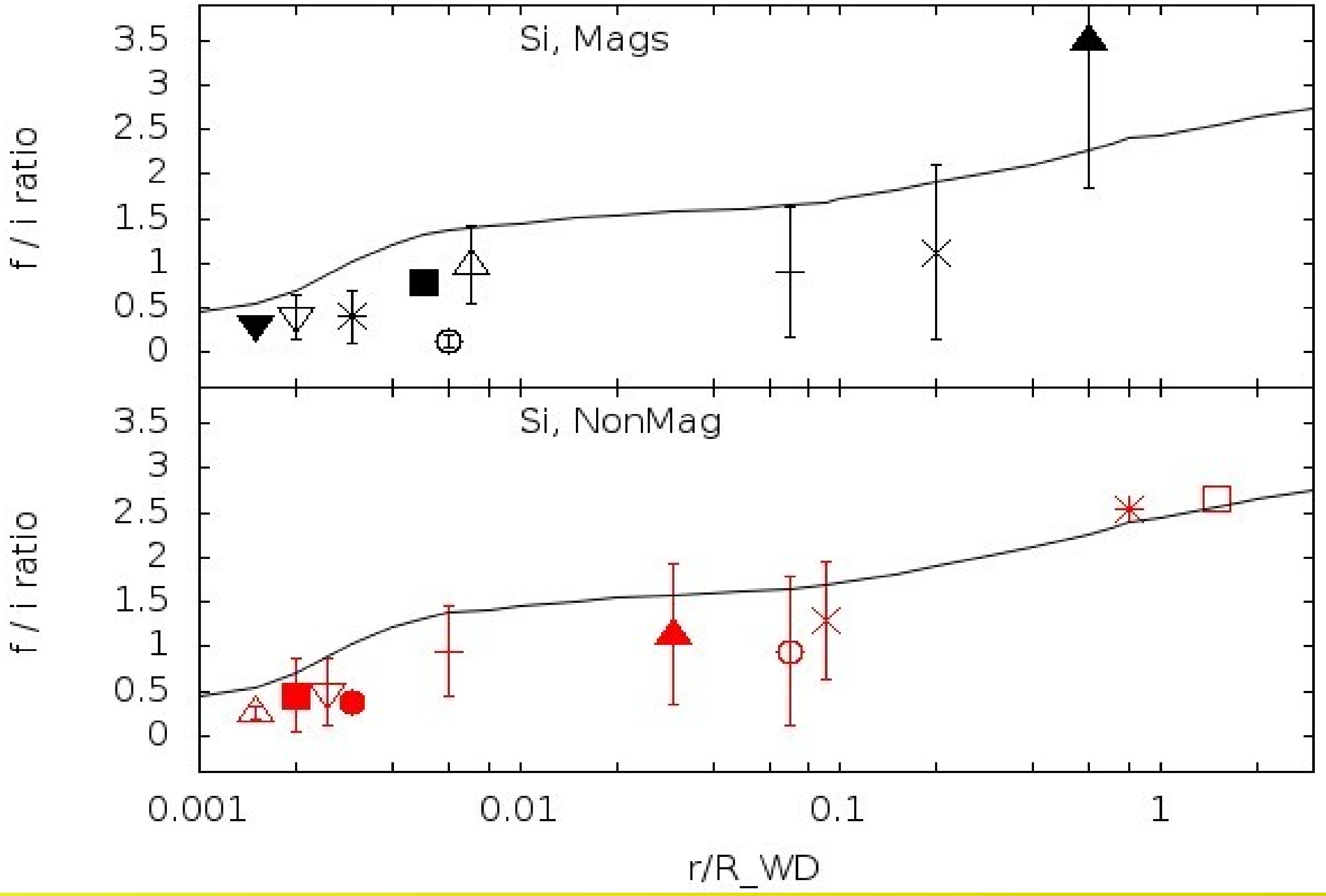
Fe XXII, Mag
Fe XXII, NonMag
Fe XXII, Mag
Fe XXII, NonMag
I(11.92) / I(11.77)
I(.92,.94) / I(.77)
0.0
2.5
1.0
1.5
2.0
2.5
11
12
13
14
15
16
log number density
log number density

Alternative: consider R ratio modified by distance

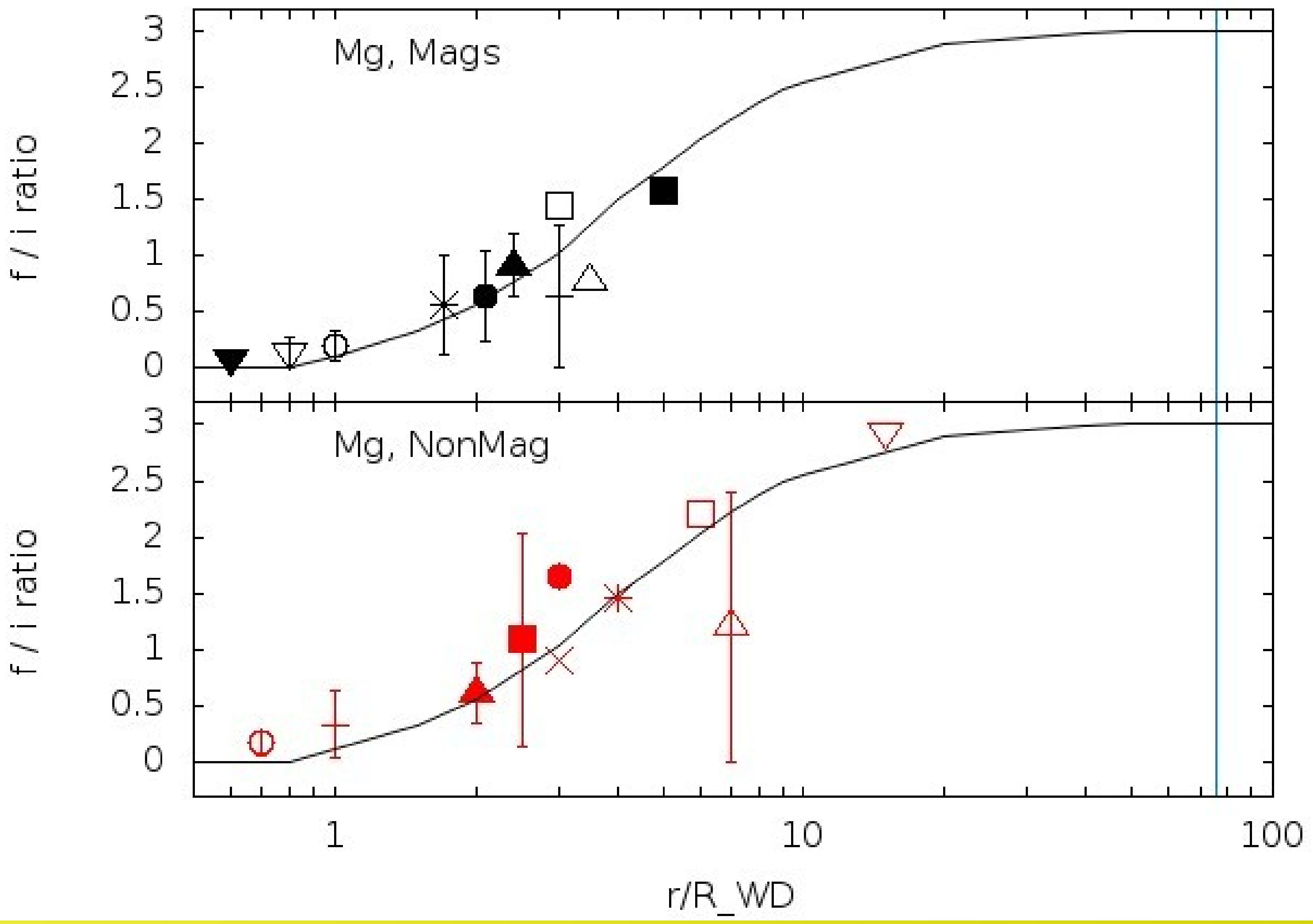
$$R(r) = \frac{R_{obs}}{1+n_e(r)/N_C+W(r)\phi/\phi_C},$$

where $W(r) = \frac{\phi}{\phi_C}[\frac{R_{obs}}{R(r)} - 1]$ and $\phi = \frac{c^3}{8\pi h\nu^3}U_\nu$

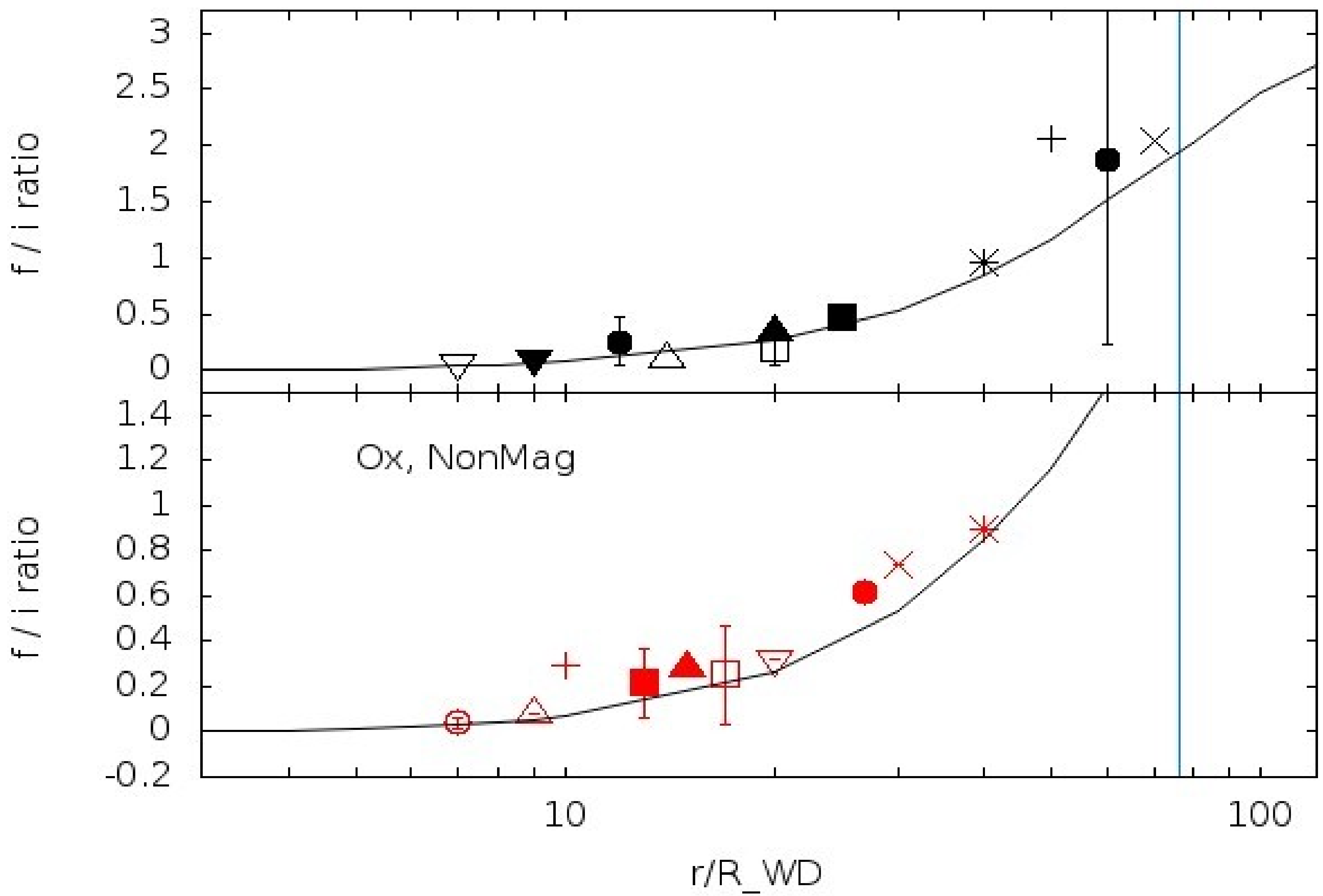
is the photoexcitation rate.



Si, Mags
Si, NonMag
f / i ratio
f / i ratio
3.5
3
2.5
2
1.5
1
0.5
0
0.001
0.01
0.1
1
r/R_WD

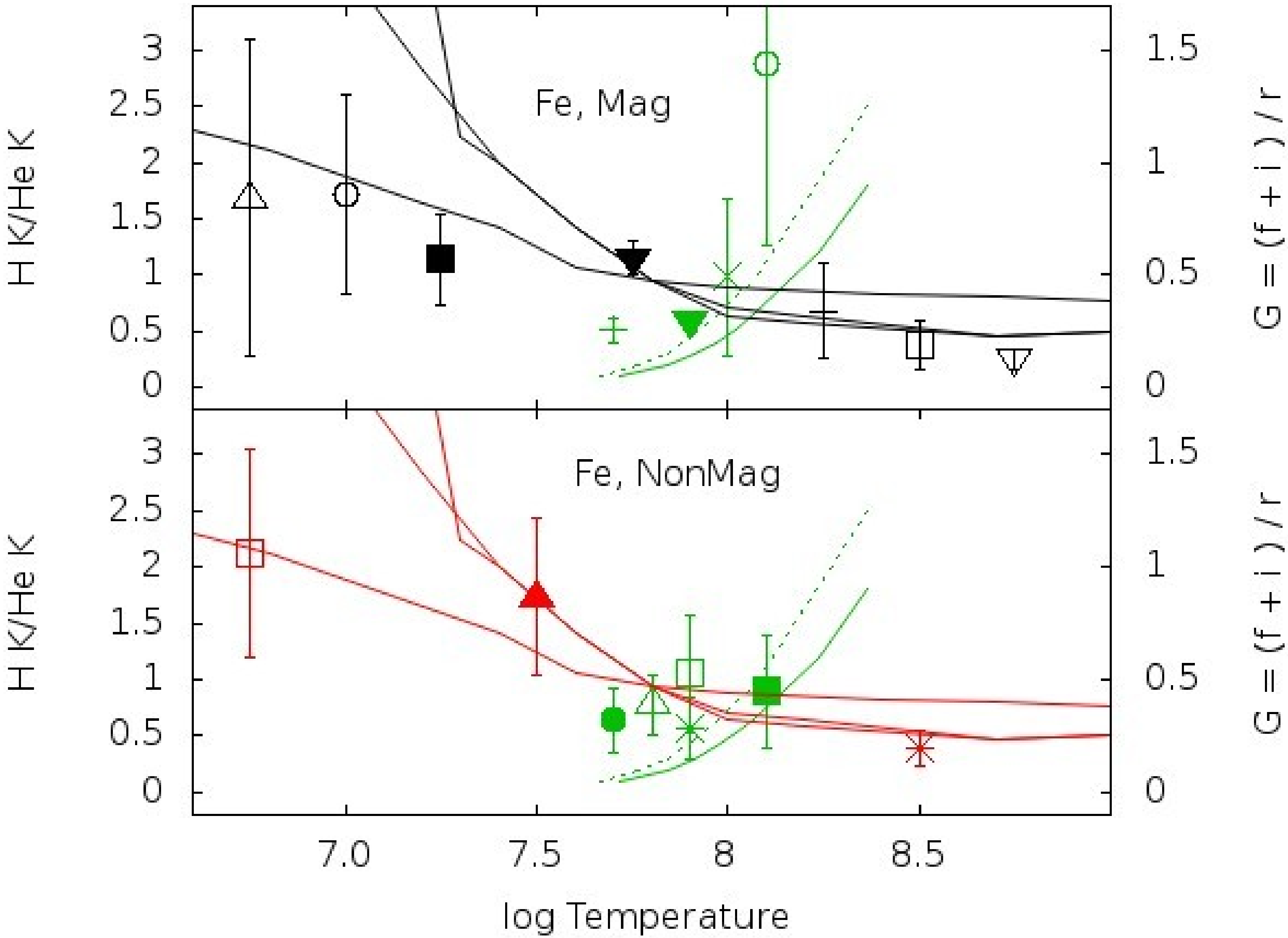


Mg, Mags
Mg, NonMag
f / i ratio
f / i ratio
r/R_WD
0
0.5
1
1.5
2
2.5
3
1
10
100

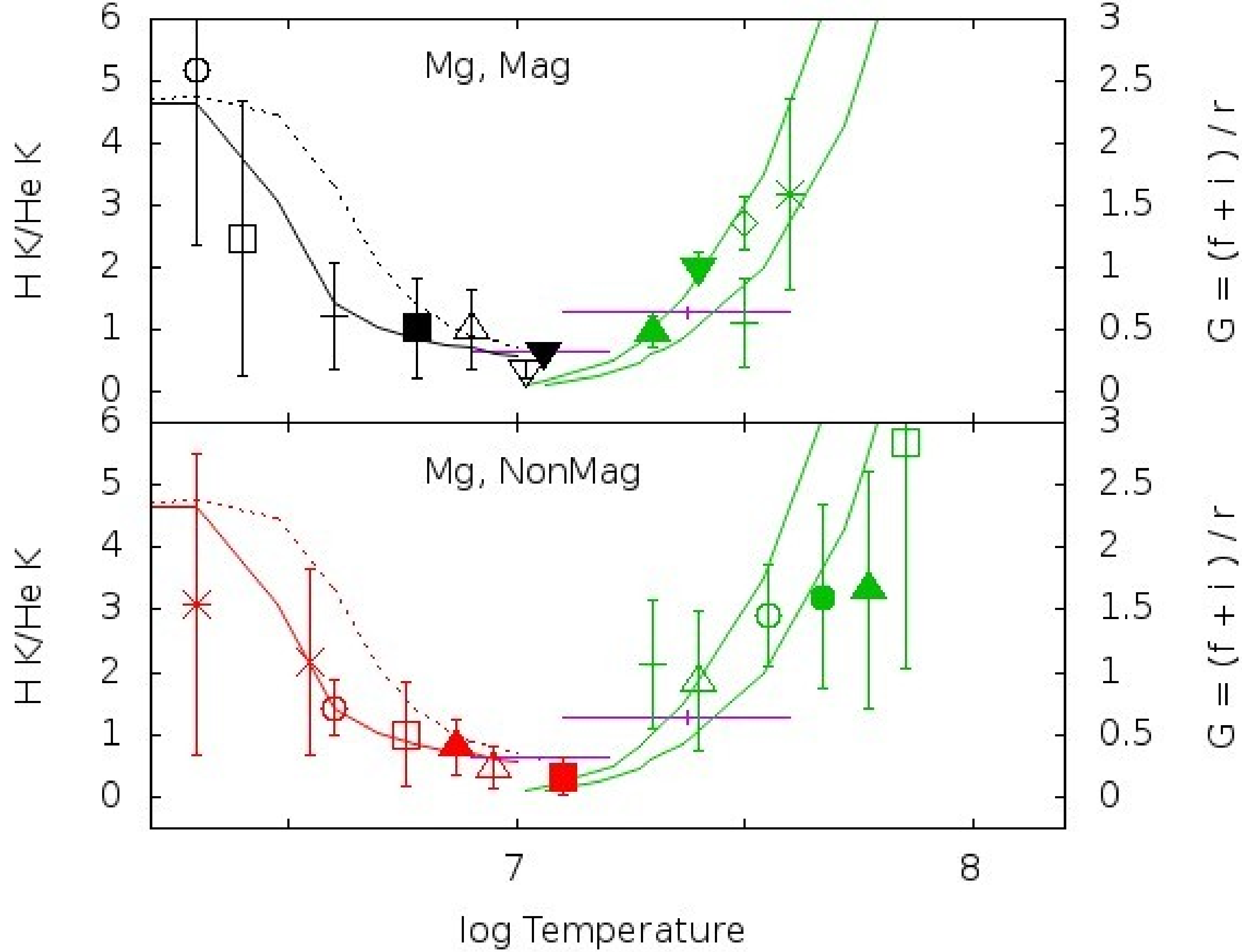


3
2.5
2
1.5
1
0.5
0
f / i ratio
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
f / i ratio
Ox, NonMag
10
100
r/R_WD

Check thermal equilibrium: combined G and H/He ratios

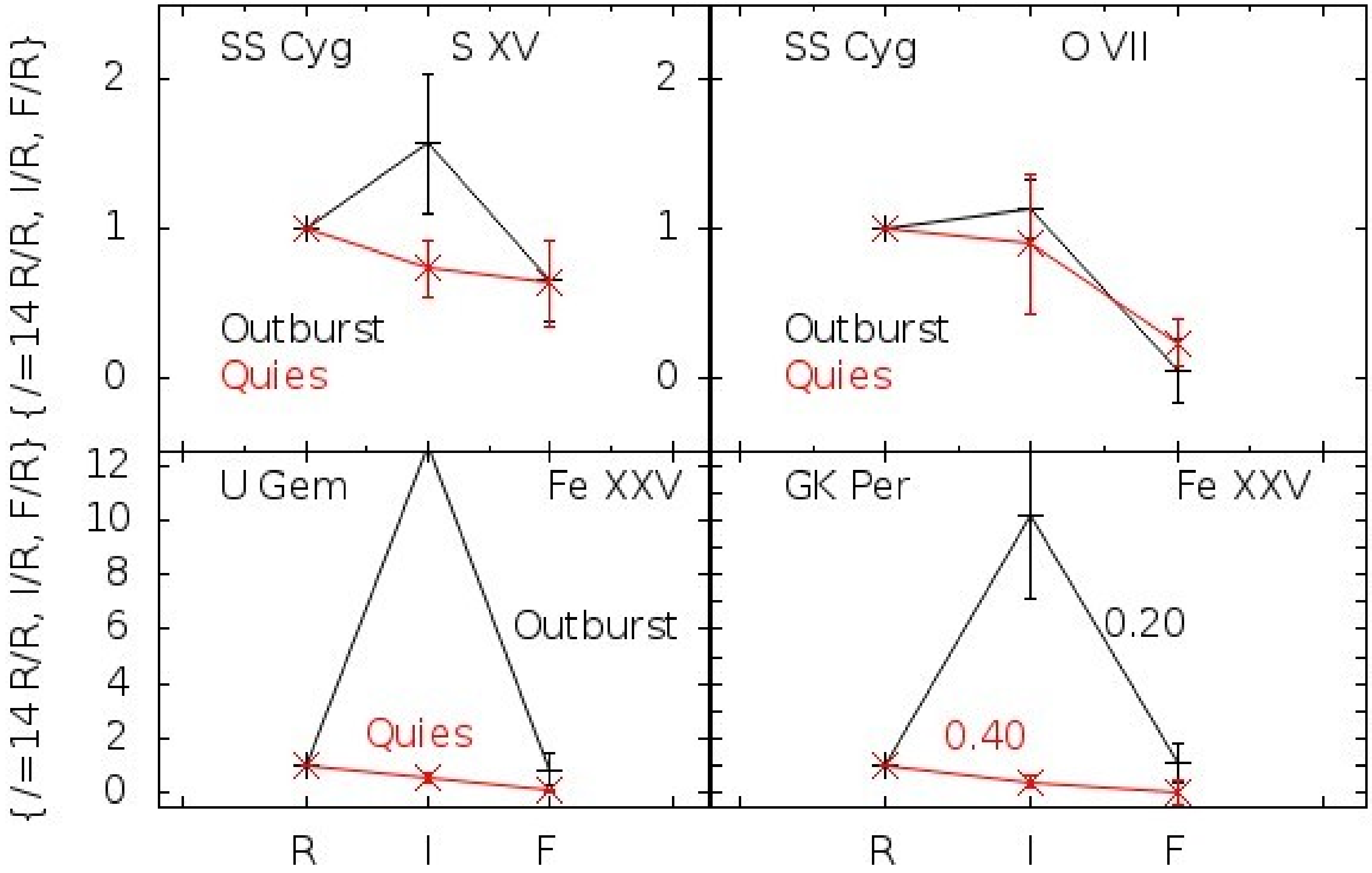


Fe, Mag
Fe, NonMag
H K/He K
H K/He K
G = (f + i) / r
G = (f + i) / r
0
0.5
1
1.5
2
2.5
3
7.0
7.5
8
8.5
log Temperature



Mg, Mag
Mg, NonMag
H K/He K
G = (f + i) / r
log Temperature
0
1
2
3
4
5
6
0.5
1.5
2.5
7
8

Time Dependence: outburst, phases!



Three Lines of Summary

- High resolution X-ray lines will lead to T, density, possibly UV radiation field, and atomic physics processes, but...

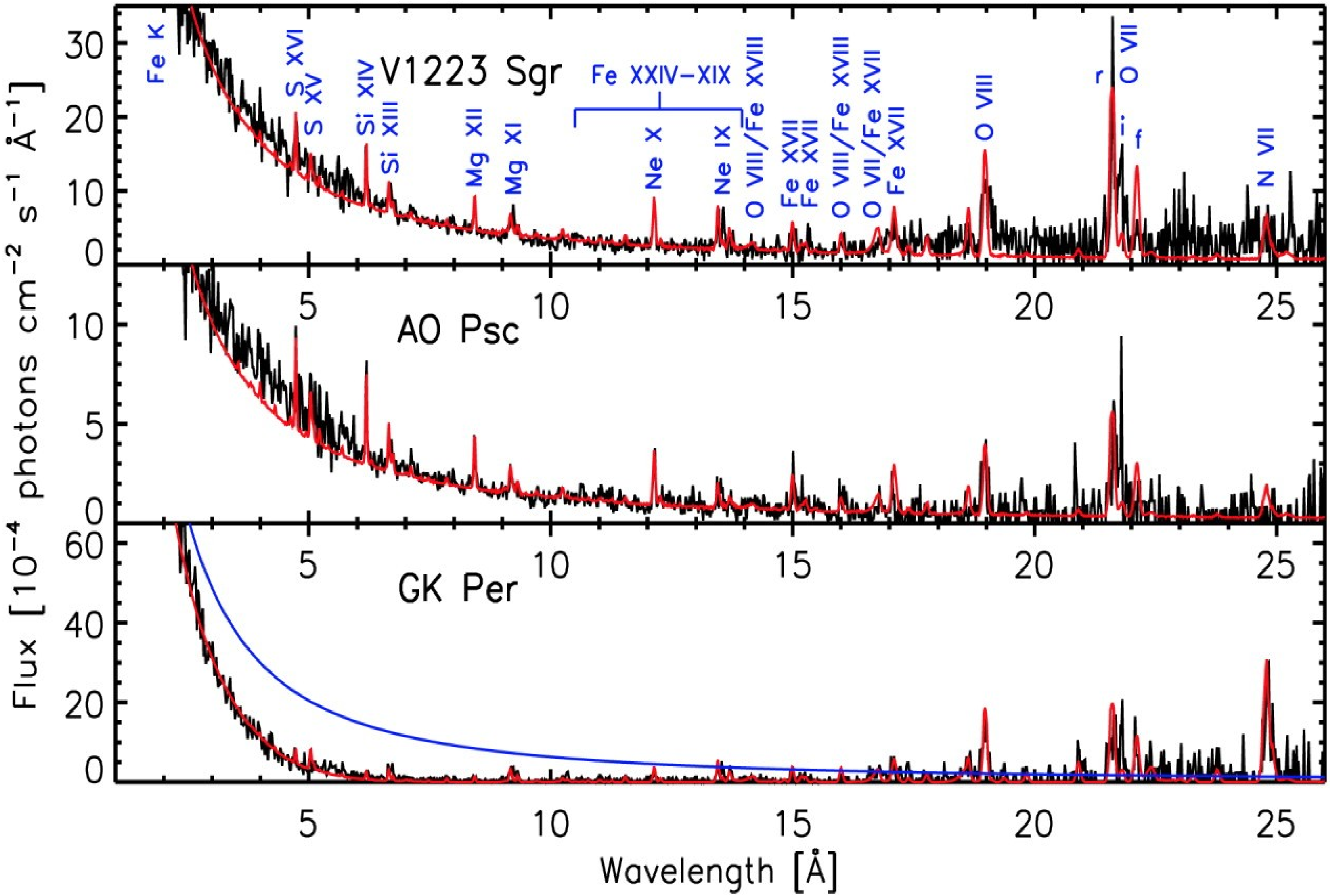
... requires larger effective area and higher spectral resolution: $E/\Delta E\sim$ 1000-2000 instead of $E/\Delta E\sim500$

- Current data: *very* tantalizing clues on detailed physics of accretion process: especially time dependence, vertical extent

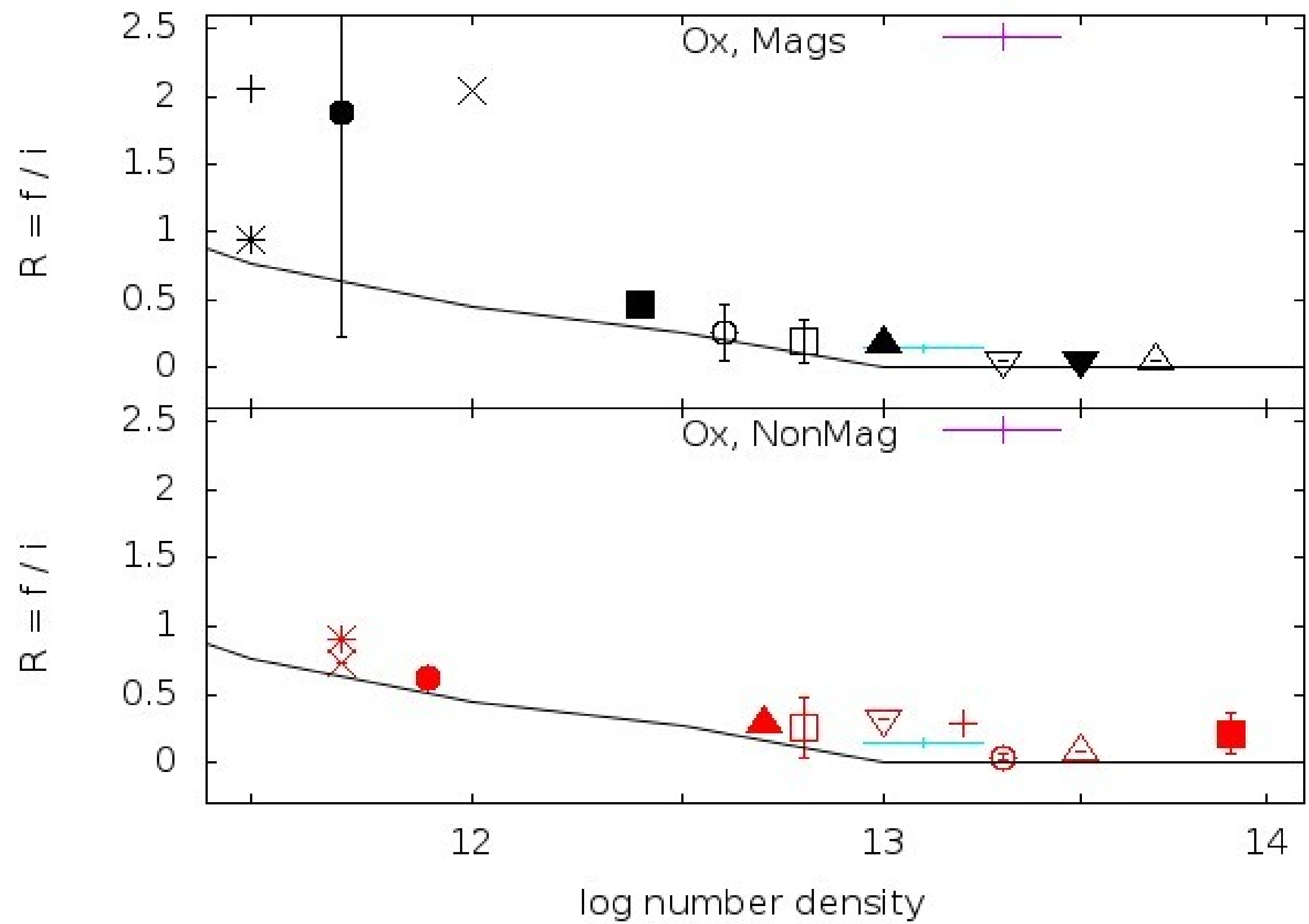
Future Science

- 2014/2015: *Astro-H/NeXT* launch
- Carries X-ray calorimeter,
  - $E/\Delta E \sim 1200\text{-}1500$,
  - *non*-dispersive spectrograph
- Gain: *phase*-resolved spectroscopy

Thank you for your attention!



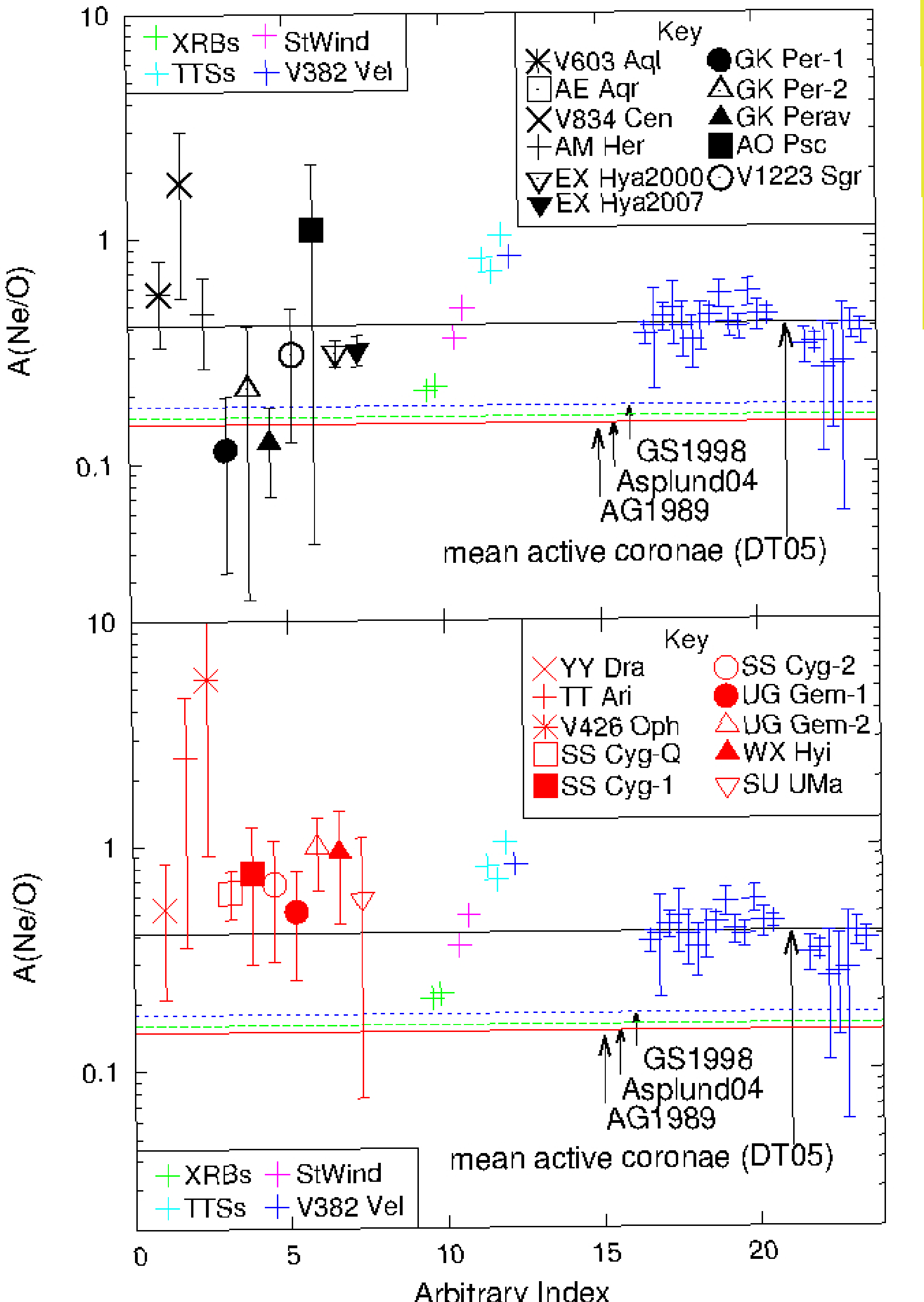
V1223 Sgr
AO Psc
GK Per
Fe K
S XVI
S XV
Si XIV
Si XIII
Mg XII
Mg XI
Fe XXIV−XIX
Ne X
Ne IX
O VIII/Fe XVIII
Fe XVII
Fe XVII
O VIII/Fe XVIII
O VII/Fe XVII
Fe XVII
O VIII
r
i
O VII
f
N VII
Flux [10⁻⁴ photons cm⁻² s⁻¹ Å⁻¹]
Wavelength [Å]



Ox, Mags
Ox, NonMag
R = f / i
2.5
2
1.5
1
0.5
0
12
13
14
log number density

Ne/O Ratio

- $A(Ne)/A(O) \propto Flux(Ne\text{-}r) / Flux(O\text{-}r)$



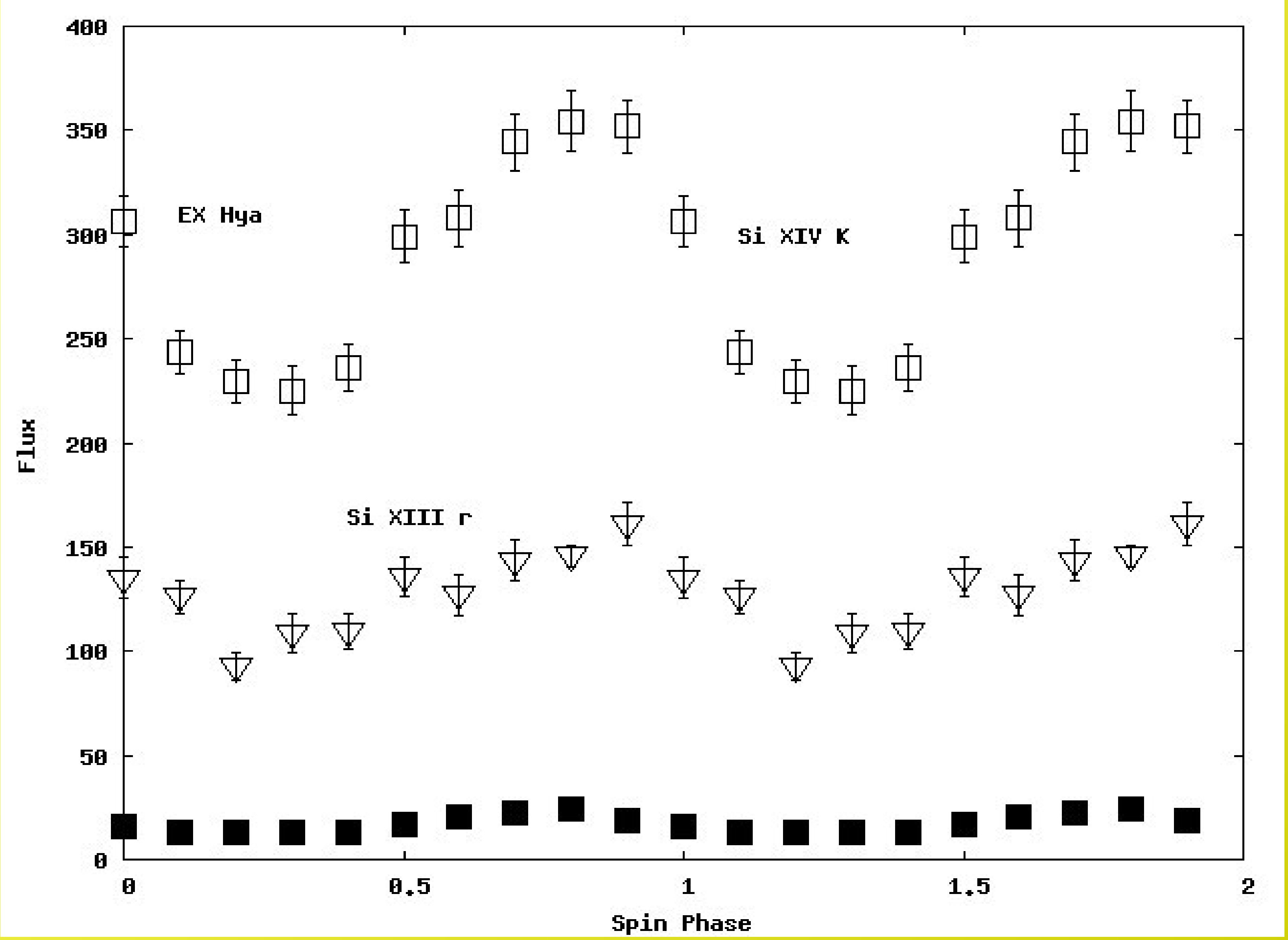
XRBs
StWind
TTSs
V382 Vel
Key
V603 Aql
GK Per-1
AE Aqr
GK Per-2
V834 Cen
GK Perav
AM Her
AO Psc
EX Hya2000
V1223 Sgr
EX Hya2007
GS1998
Asplund04
AG1989
mean active coronae (DT05)
Key
YY Dra
SS Cyg-2
TT Ari
UG Gem-1
V426 Oph
UG Gem-2
SS Cyg-Q
WX Hyi
SS Cyg-1
SU UMa
A(Ne/O)
10
1
0.1
Arbitrary Index
0
5
10
15
20

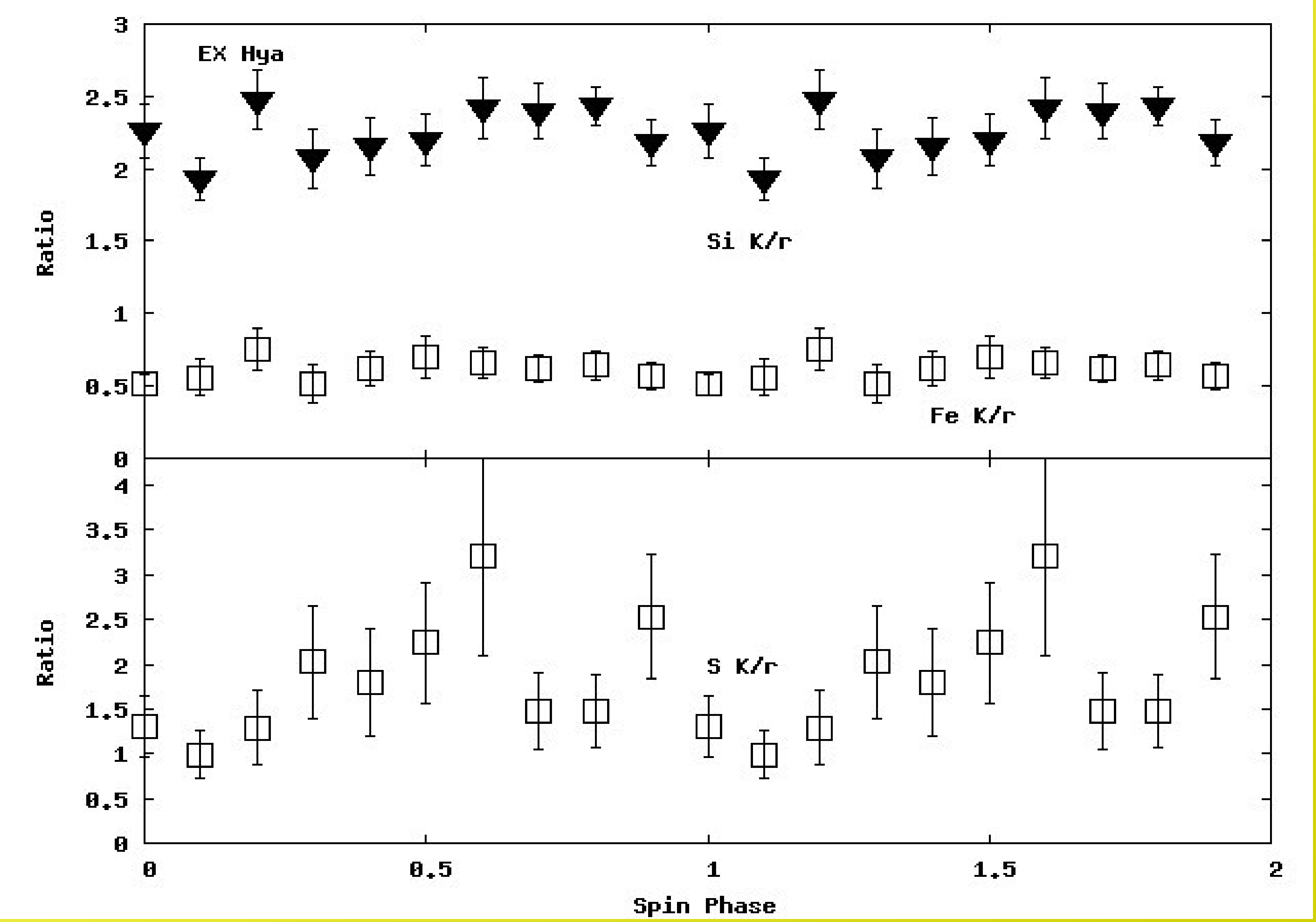
- Ne / O for CVs similar to Ne/O for active corona stars
- Puzzle?

- expect CVs to undergo mass transfer
  --> why does Ne/O match for all
    subtypes?

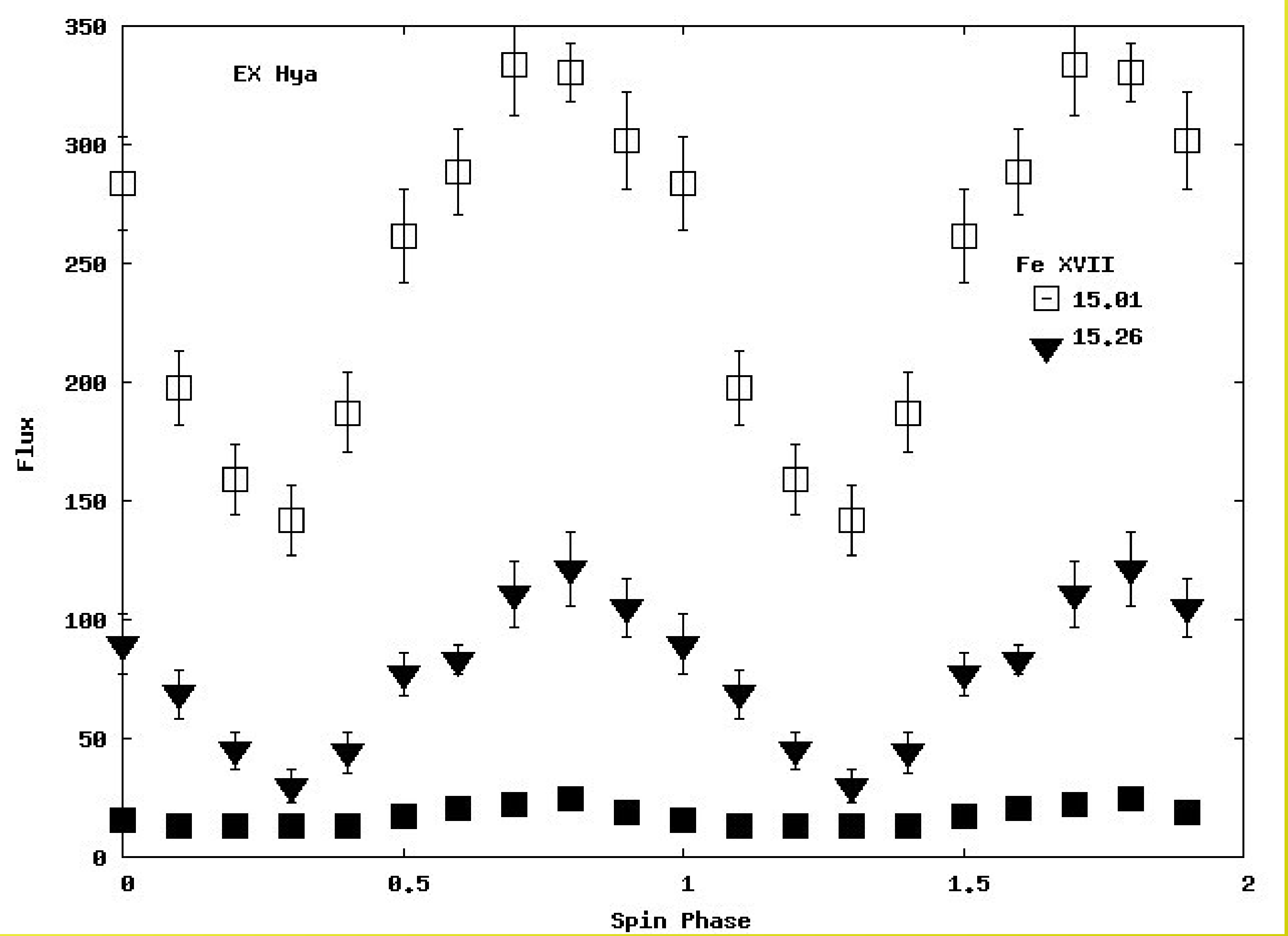
EX Hya

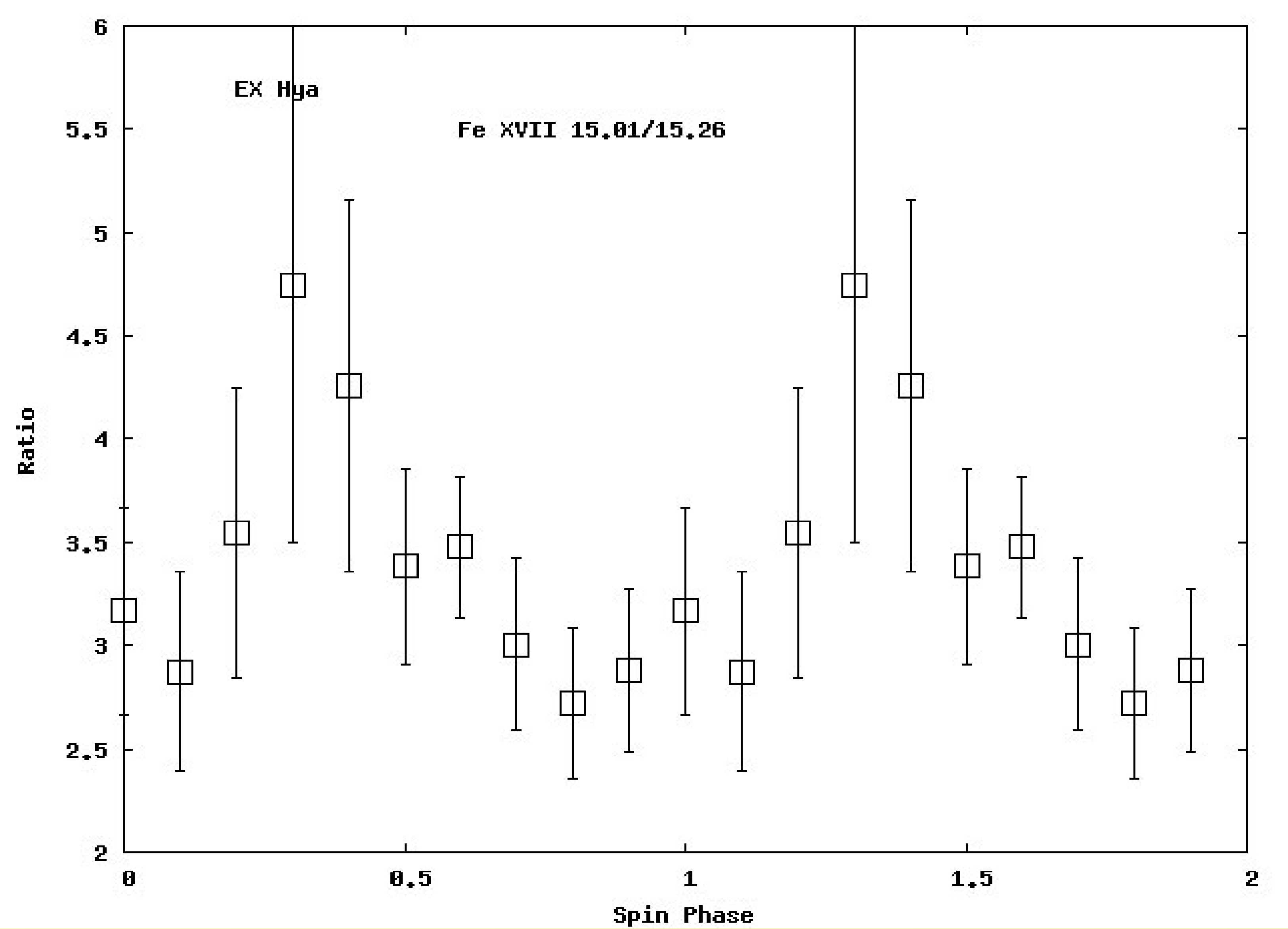
- CV-IP
- orbital period ~90 min
- close: ~38 pc ⇒ X-ray bright
- goal: time-resolved X-ray spectroscopy


400
350
300
250
200
150
100
50
0
Flux
EX Hya
Si XIV K
Si XIII r
0
0.5
1
1.5
2
Spin Phase



EX Hya
Si K/r
Fe K/r
S K/r
Ratio
Ratio
Spin Phase
0
0.5
1
1.5
2
2.5
3
3.5
4


EX Hya
Fe XVII
15.01
15.26
Flux
Spin Phase
350
300
250
200
150
100
50
0
0
0.5
1
1.5
2


EX Hya
Fe XVII 15.01/15.26
Ratio
Spin Phase
6
5.5
5
4.5
4
3.5
3
2.5
2
0
0.5
1
1.5
2