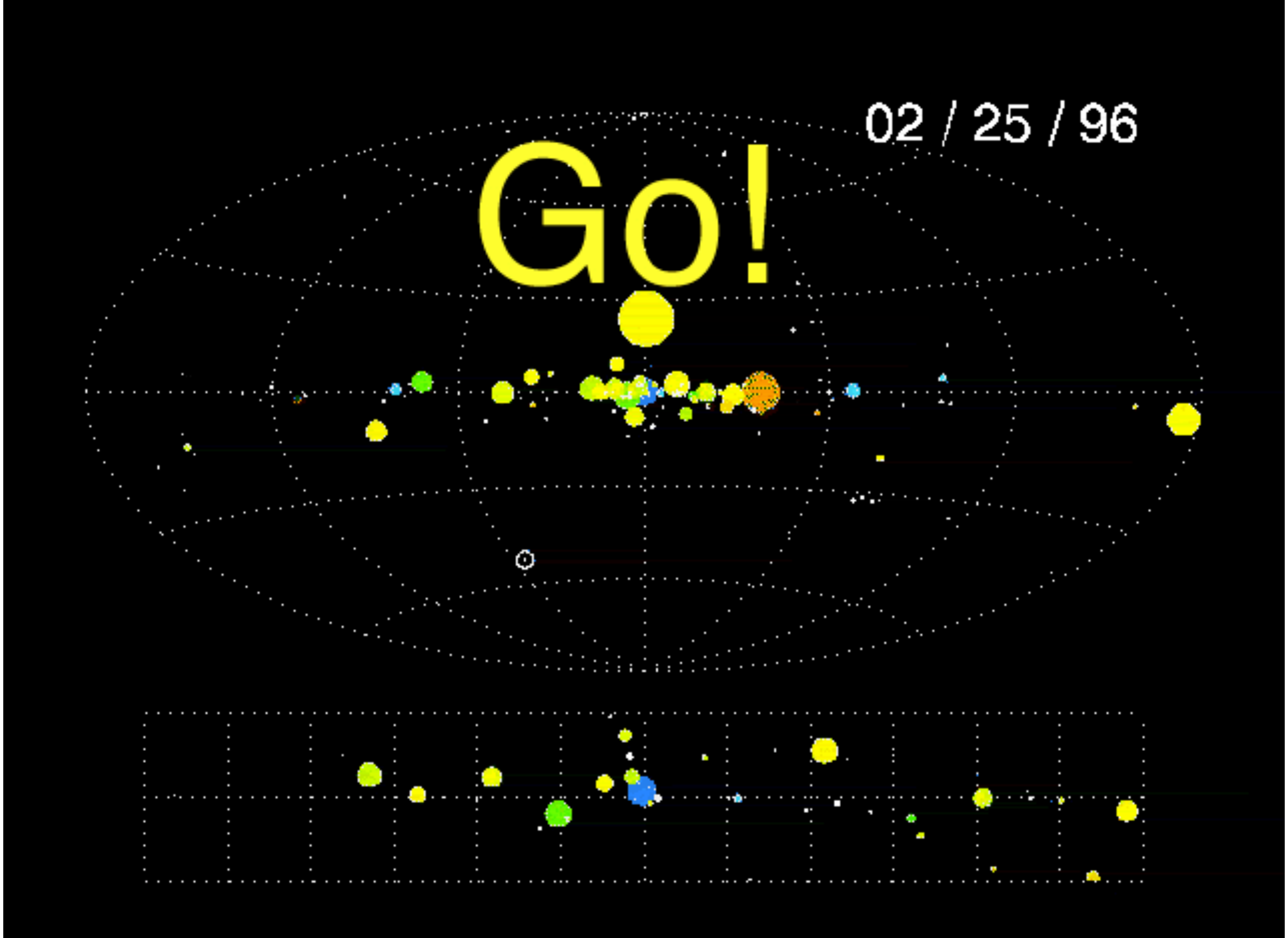
X-ray binaries

Victoria [Vici] Grinberg, ESA/ESTEC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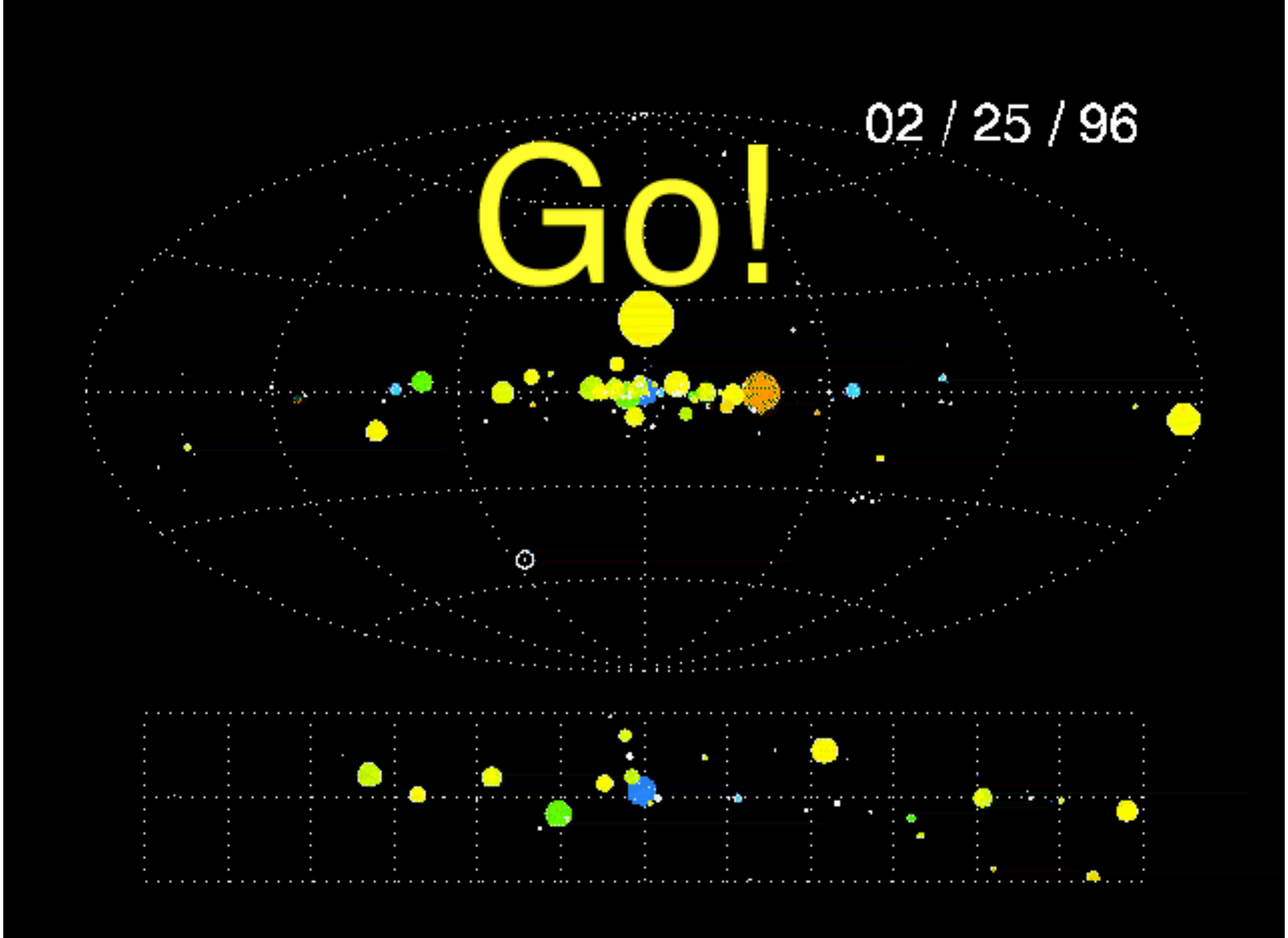
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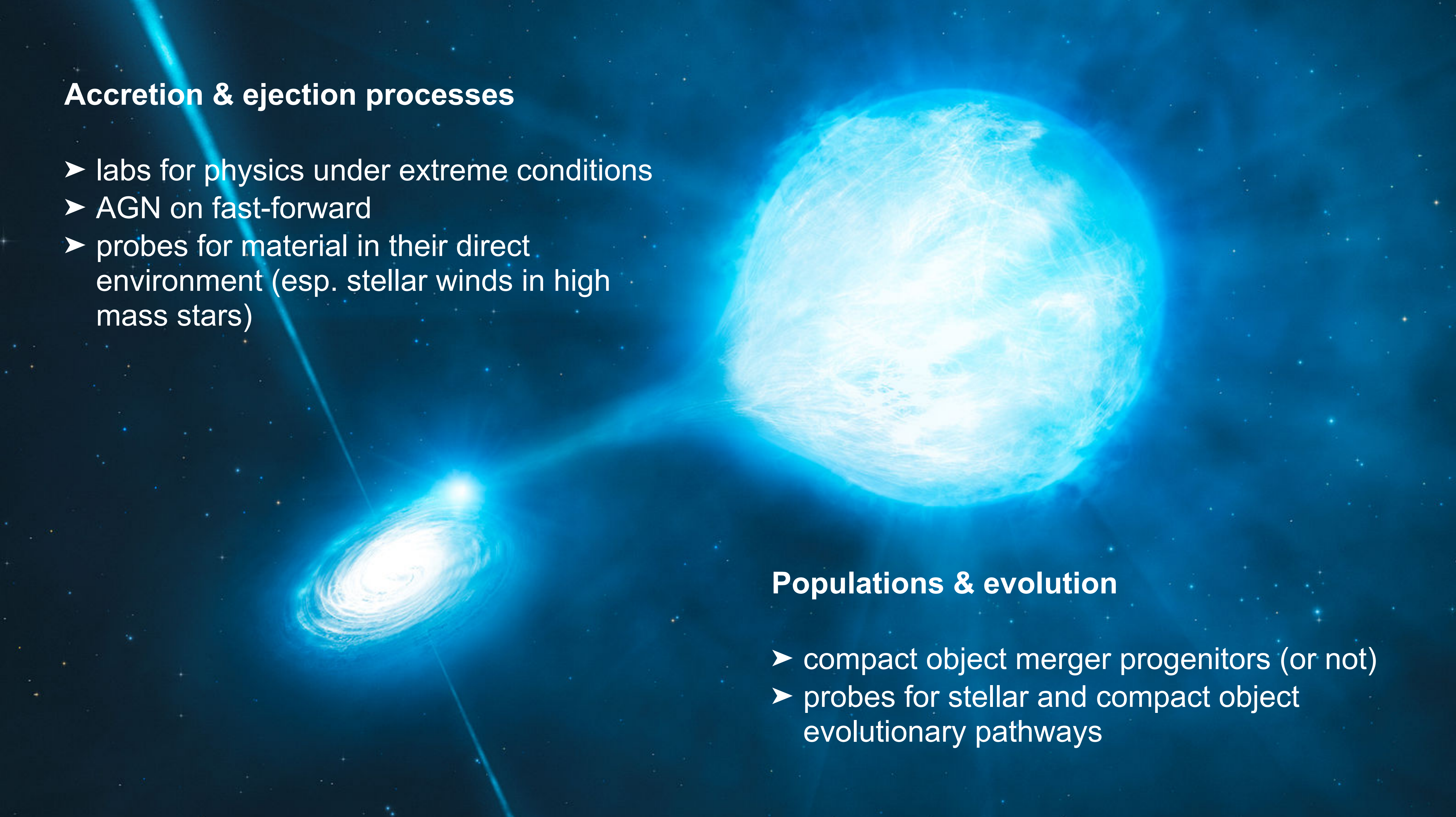

Accretion & ejection processes

- labs for physics under extreme conditions
- AGN on fast-forward
- probes for material in their direct environment (esp. stellar winds in high mass stars)

Populations & evolution

- compact object merger progenitors (or not)
- probes for stellar and compact object evolutionary pathways

X-ray binaries: The Zoo

A heterogeneous set of objects

- ➤ **classified by compact object**
  - ➤ black hole
  - ➤ neutron star
  - ➤ (white dwarf)
- ➤ **classified by companion**
  - ➤ low mass X-ray binary (companion ≲ 1 solar mass)
  - ➤ high mass X-ray binary (companion ≳ 8 solar masses)

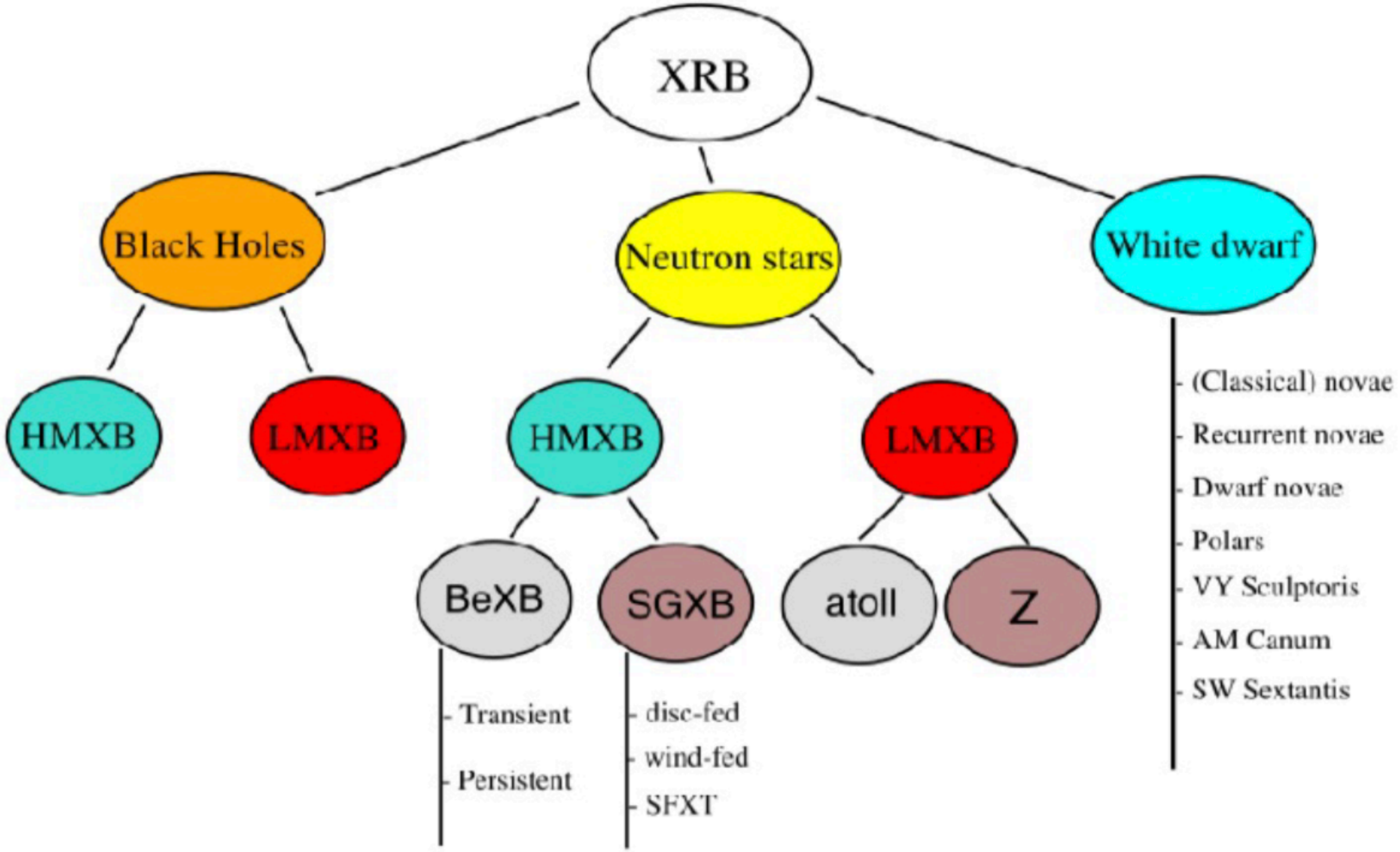

Figure 1.1: Classification of X-ray Binary Systems (Reig 2011)

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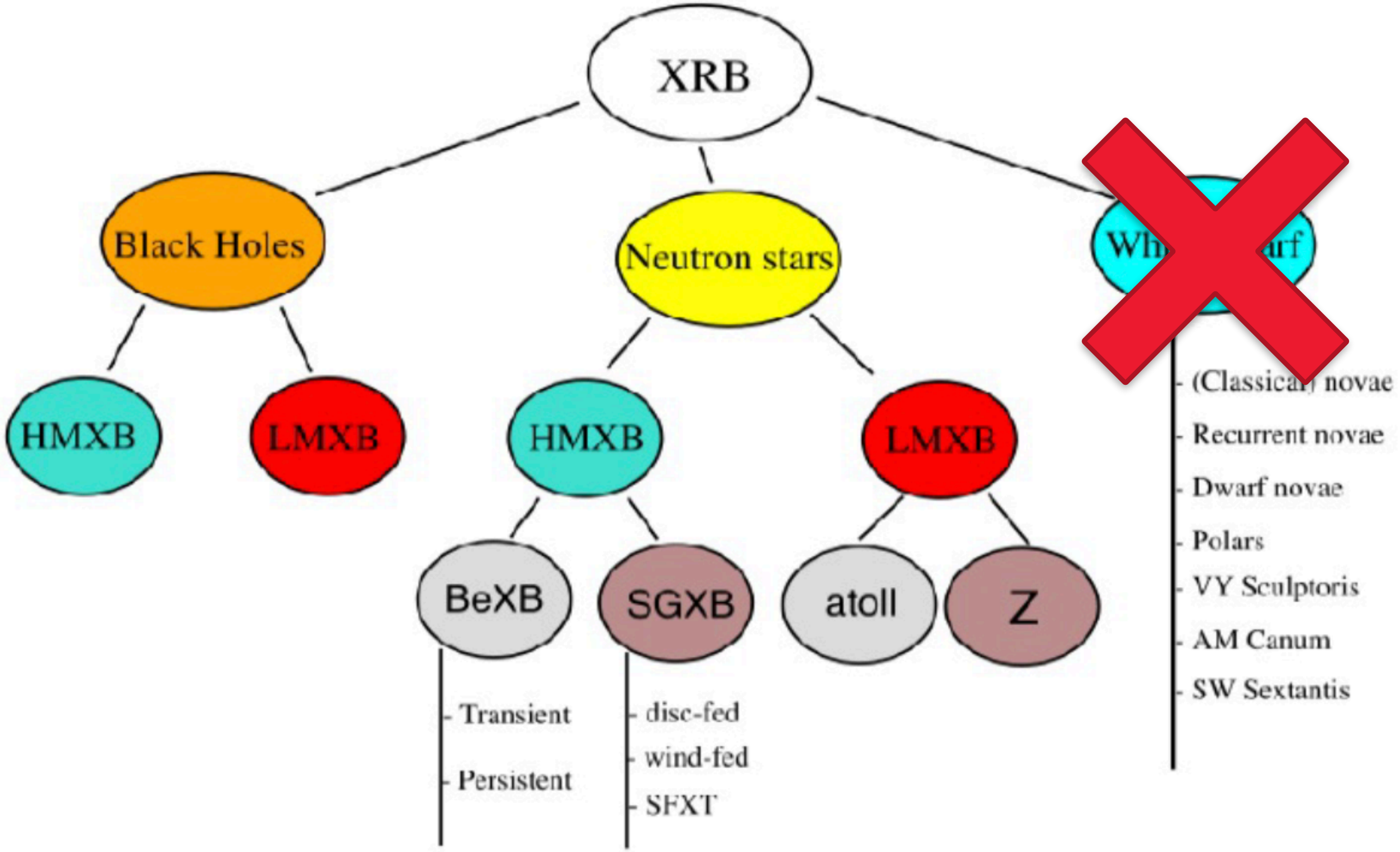

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LMXBs vs HXMBs

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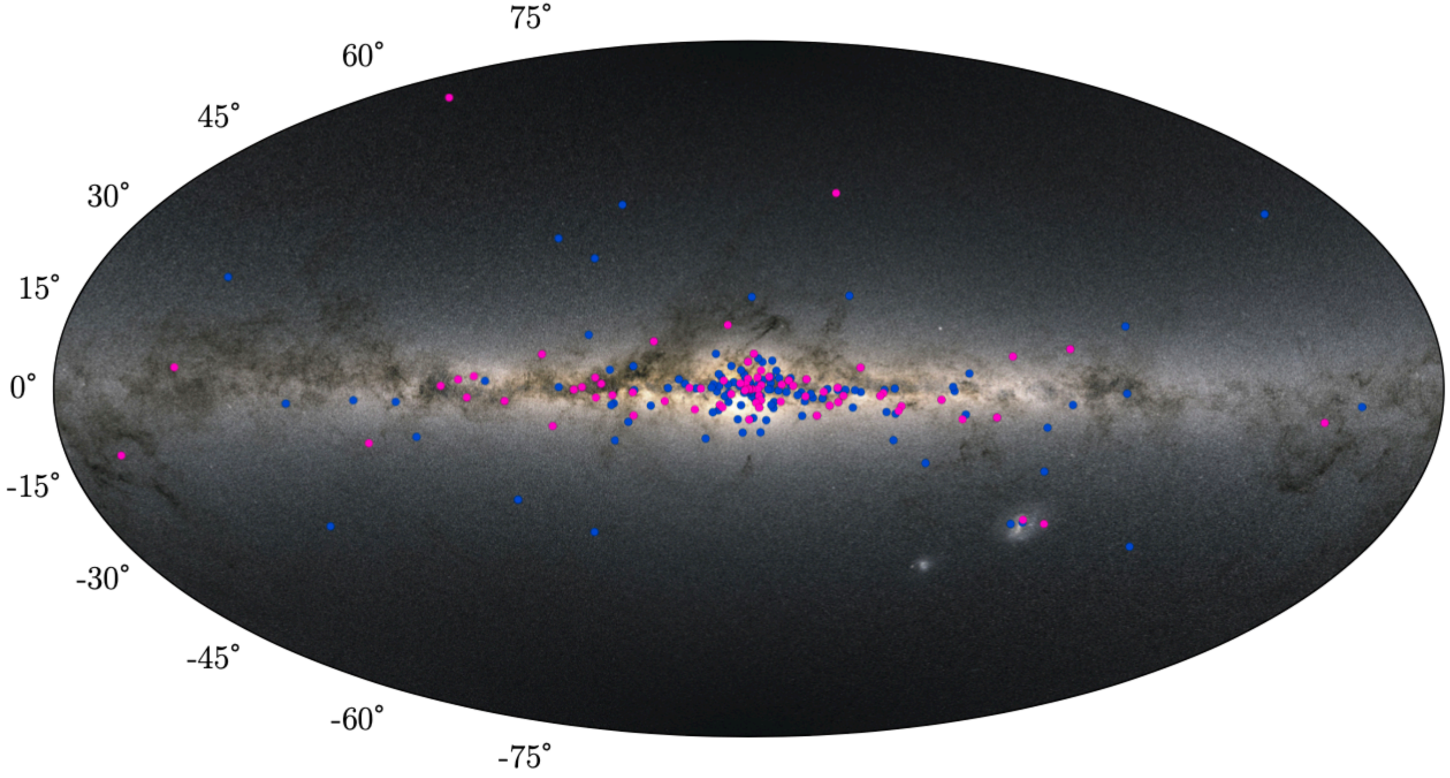
LMXBs

- older systems, also seen at higher Galactic latitudes
- neutron stars: low magnetic fields
- catalogues: Avakyan et al. 2023 (XRBCats, astro.uni-tuebingen.de/~xrbcat), Liu et al. 2007



Bahramian & Degenaar 2023;
pink - BH LMXBs; blue - other LMXBs
note that this is NOT the full known sample

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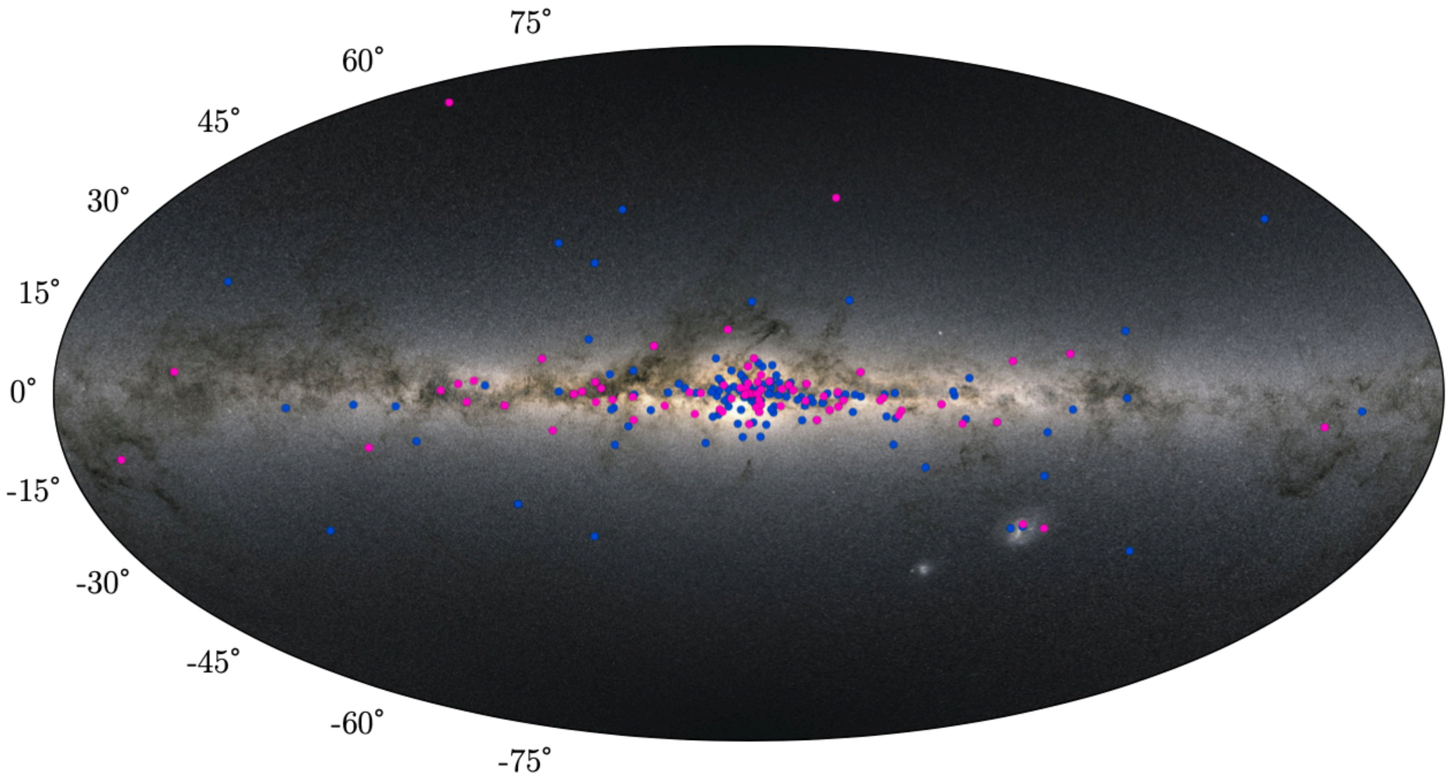
HMXBs

- ➤ young system, in the galactic place, tracing stellar formation regions
- ➤ neutron stars: can have very high magnetic fields (impact onto accretion phenomena!)
- ➤ catalogues: Fortin et al. 2023, Neumann et al. 2023



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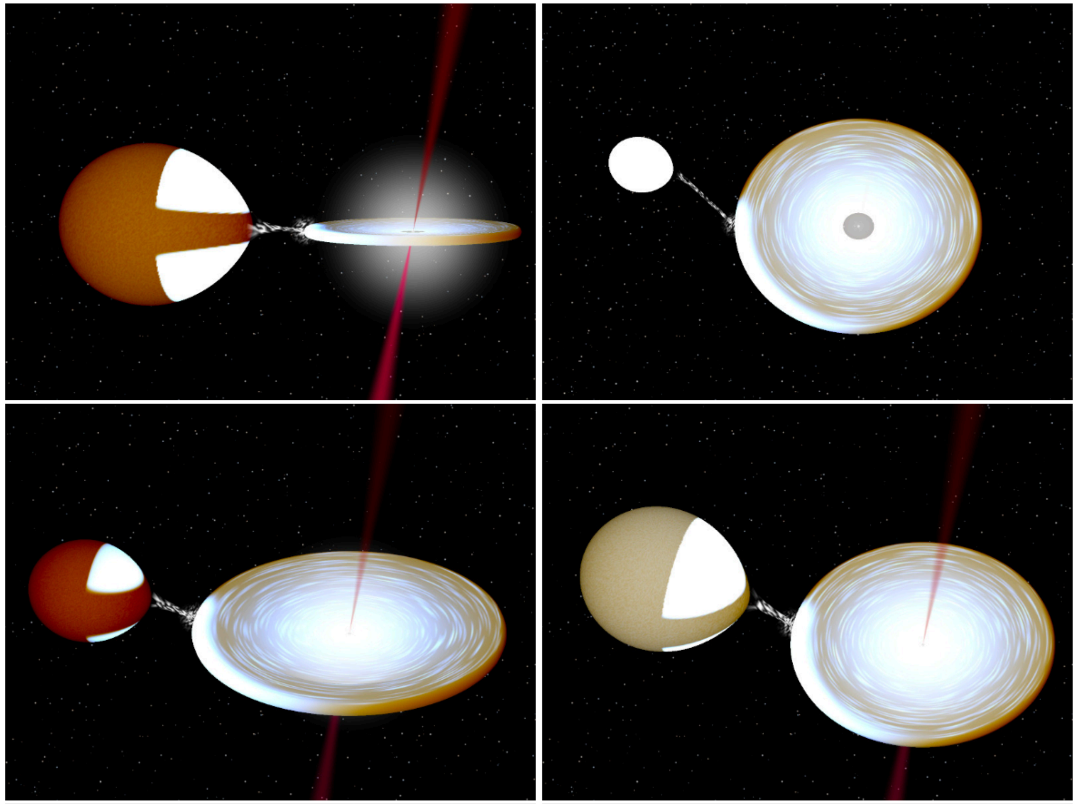
X-ray binaries: LMXBs

Physical & observational properties mainly linked to binary configuration properties & nature of donor star, less to type of compact object

- canonical Roche lobe overflow: main sequece or giant companion
  - most sources transients
- ultra-compact binaries (orbital period < 80 min)
  - most persistent, some transient
- symbiotic X-ray binaries (wind-fed)
  - accrete from wind of low-mass late-type supergiant
- accreting ms X-ray pulsars (AMXPs)
  - progenitors of millisecond radio pulsars

Esp. interesting: eclipsing sources!

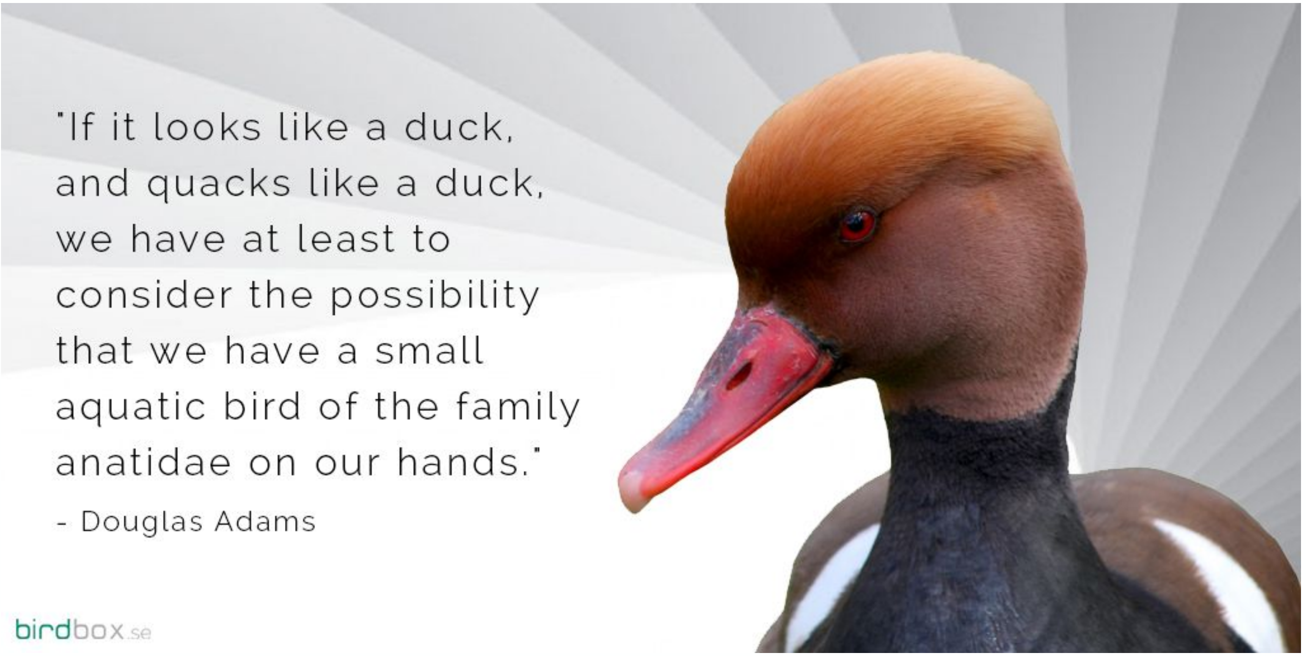


Bahramian & Degenaar 2023

X-ray binaries: LMXBs

The nature of compact object:

- **bursts & pulsations** $\Longrightarrow$ neutron star
- **radial velocity & mass estimates** $\Longrightarrow$ inclination dependence, but unambiguous identification for black holes if above 3 solar masses
- **disk-jet coupling** $\Longrightarrow$ both NS and BH show jets, but BHs are brighter in radio by factor 5-20 at same X-ray luminosity
- **quiescent X-ray properties** $\Longrightarrow$ NS have surface giving rise to black body emission in quiescence (note: absence not evidence for BH accretor!)
- … and many others



X-ray binaries: The Zoo

A heterogeneous set of methods

- spectral (broad band vs. high res)
- timing / short-term variability
- spectral-timing
- polarization (low- vs. high energies)
- multiwavelength approaches
- theory

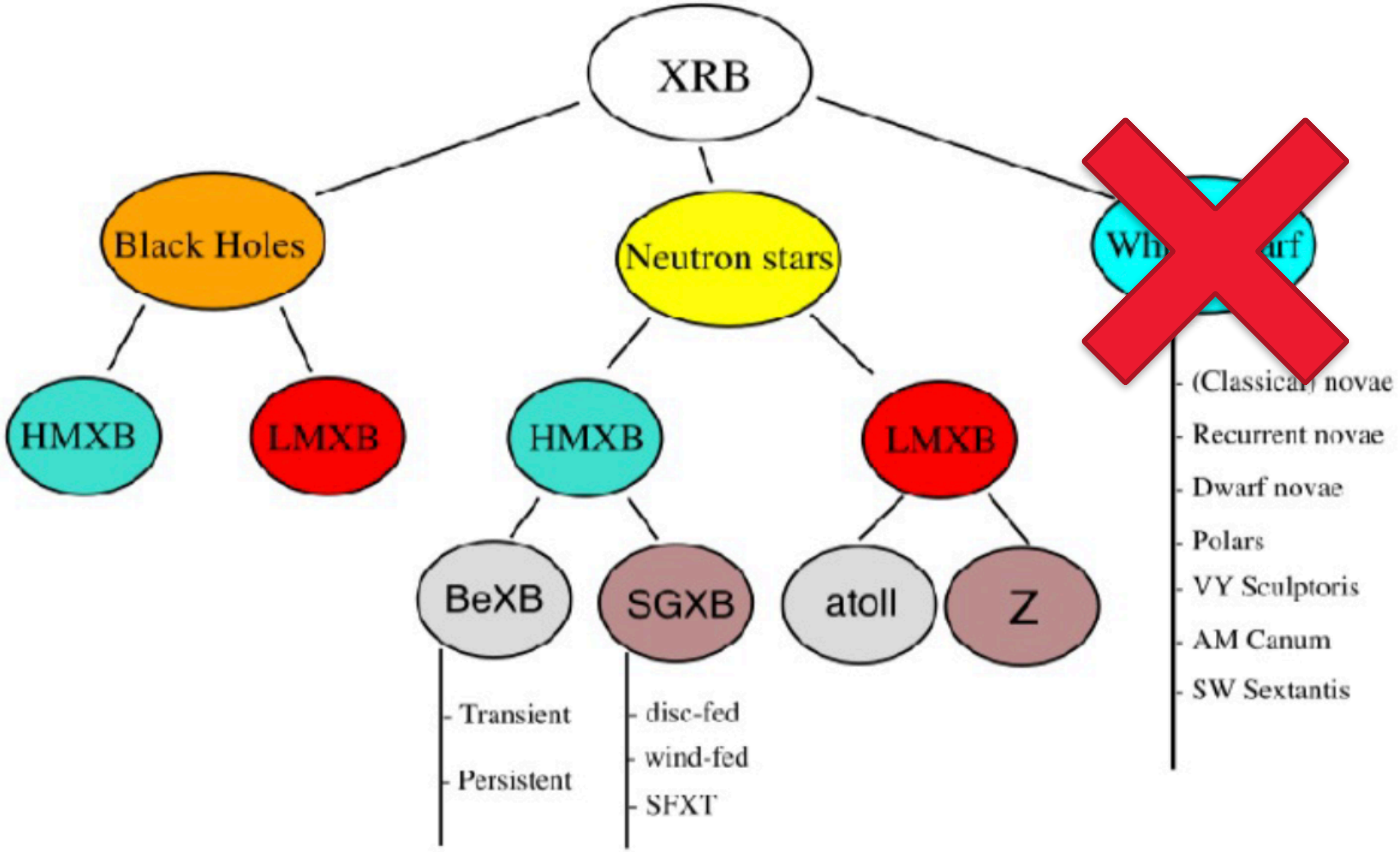


Figure 1.1: Classification of X-ray Binary Systems (Reig 2011)

Lecture aims & biases

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Aims

- ➤ enable you to (roughly) follow talks & papers on X-ray binaries
- ➤ enable you to find overlaps with your own research field -> enable collaborations
- ➤ give you a feeling for (some) open questions in the field
- ➤ less of “this is the one and only answer” and a lot of “the community does not agree on this”

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- the speaker & her perspective/knowledge
- basics vs. newest developments
- likely lots of unconscious bias

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Two parts to the lecture:
- accretion/ejection - an observational view using mainly BHs as example
- X-ray binaries as probes for their environment using winds of companion stars

X-ray binaries: The Zoo

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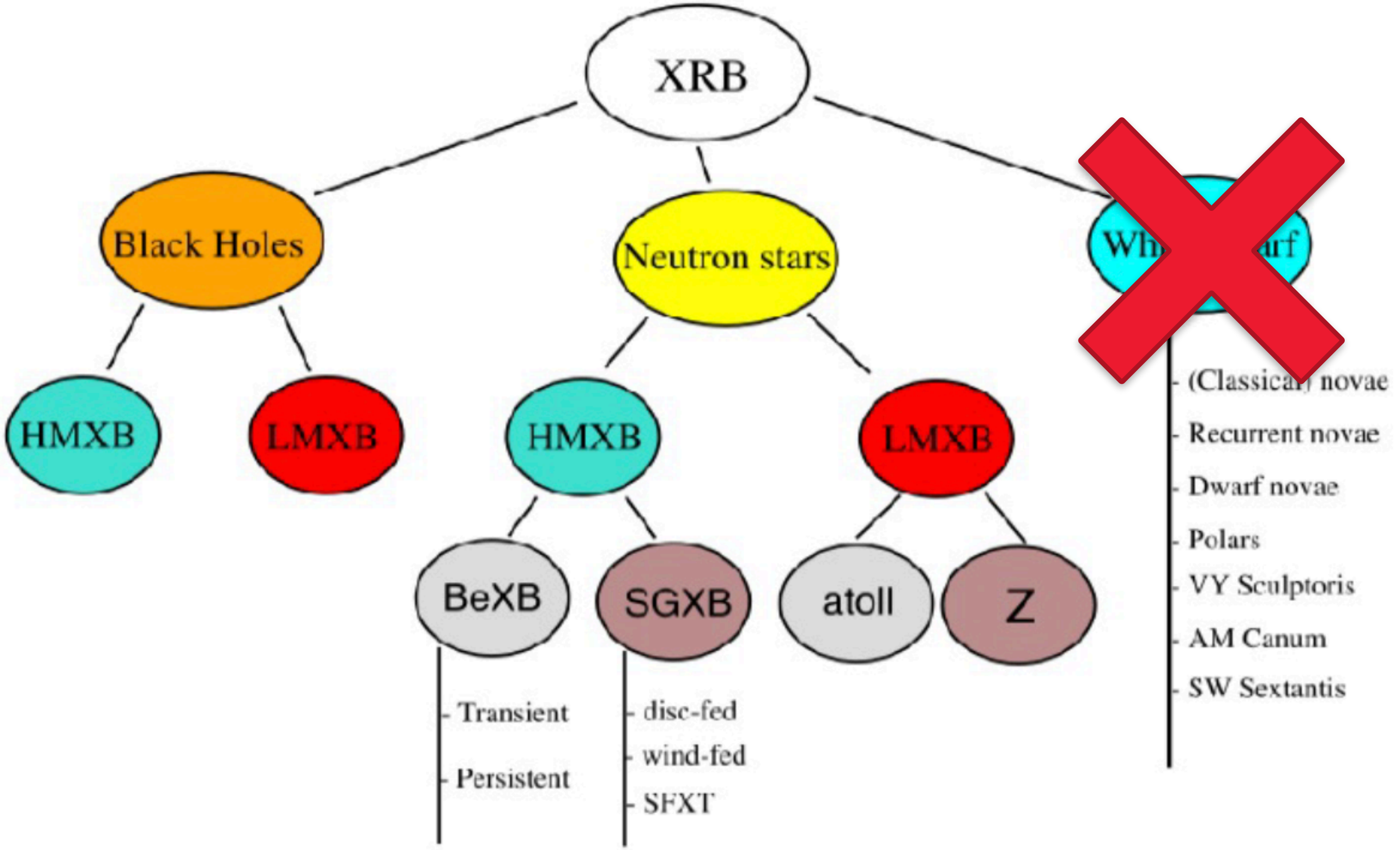

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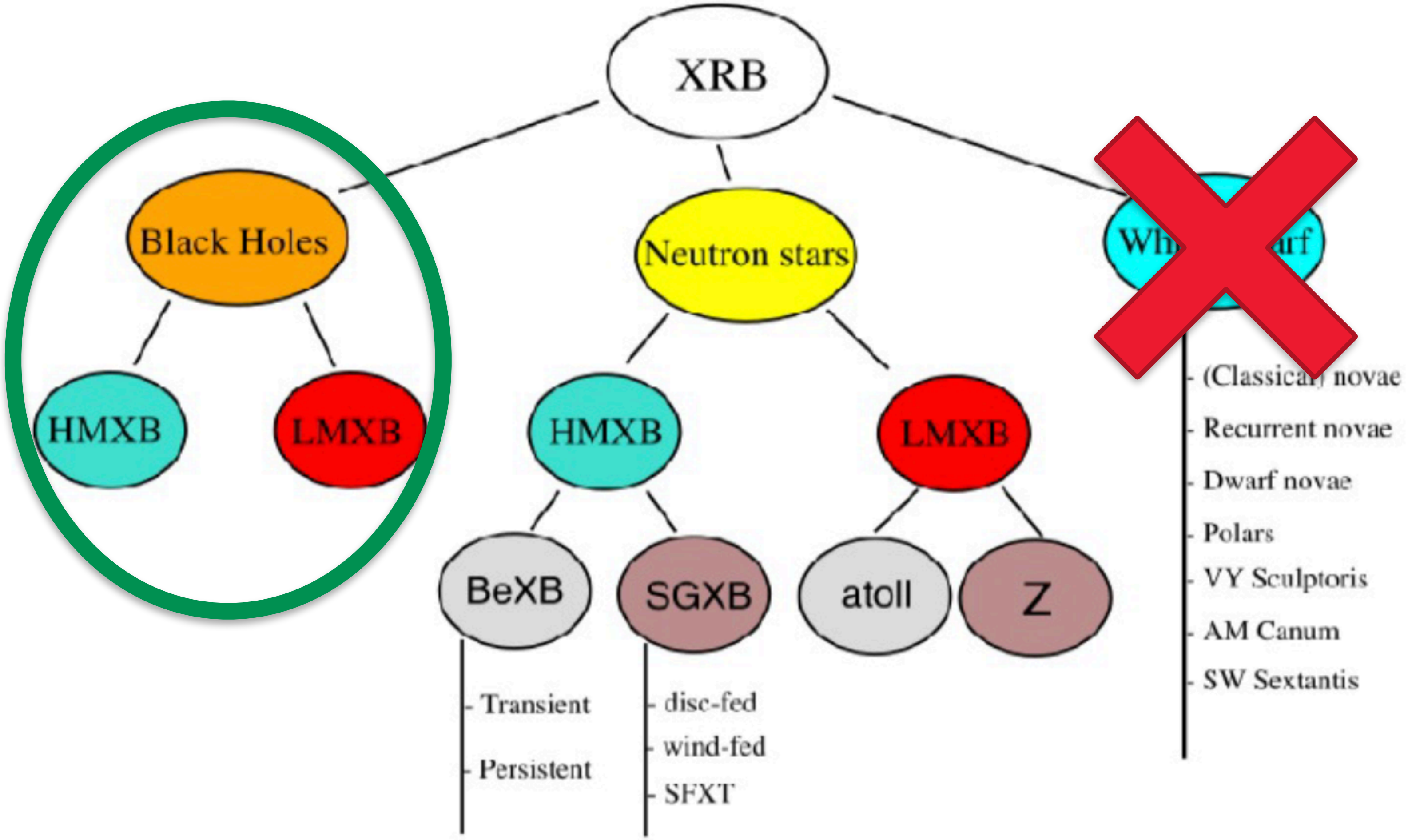

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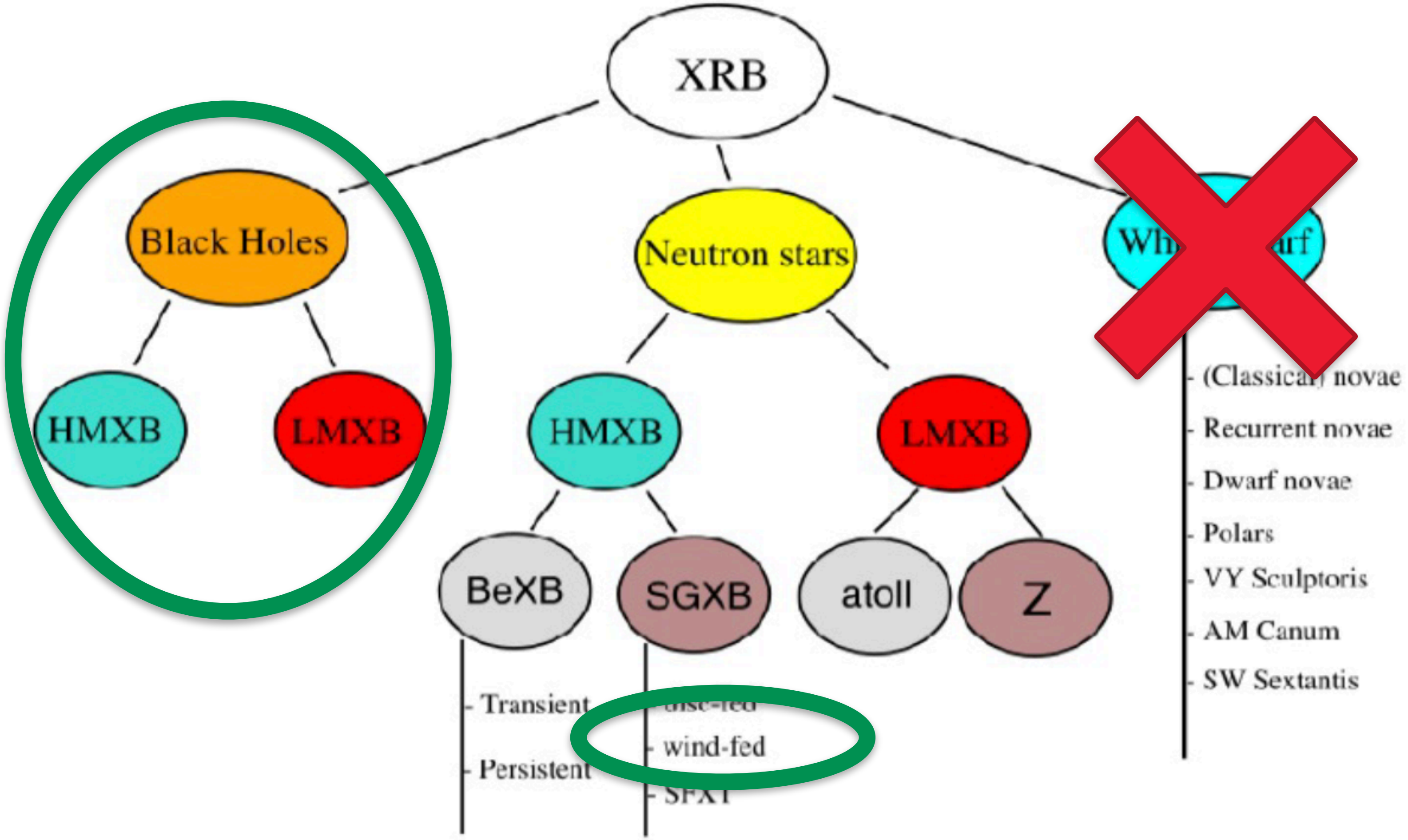

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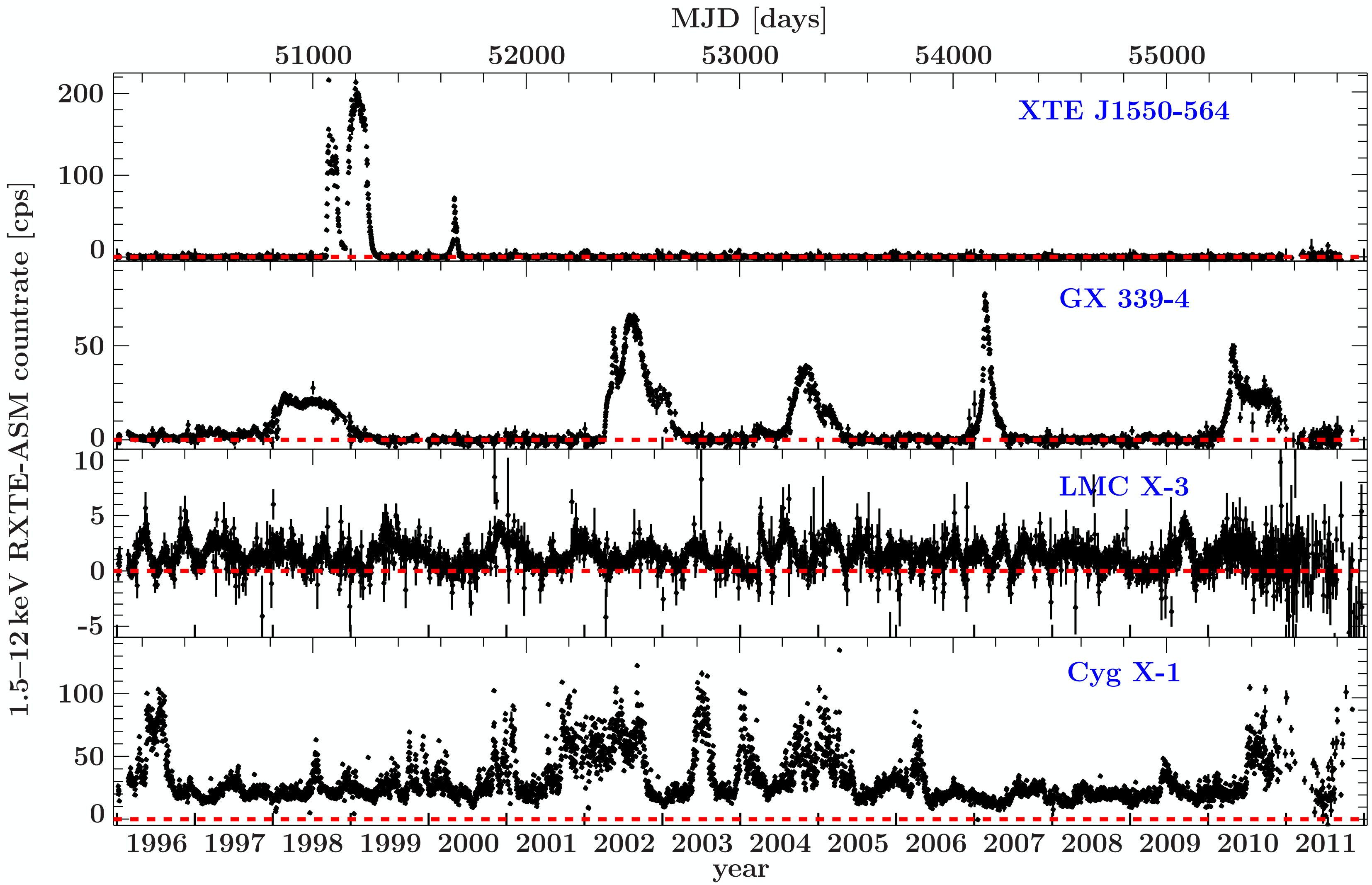
Questions?

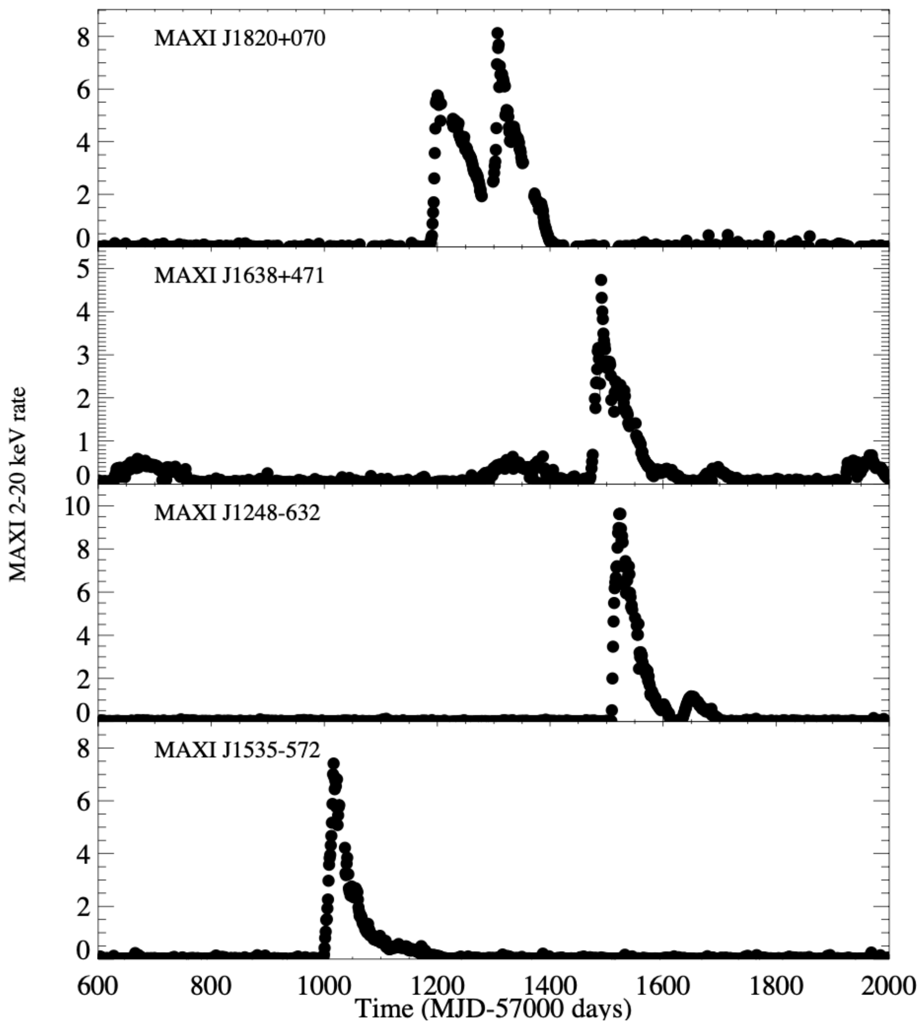
Accretion/ejection in BH (LM)XBs

Black holes: Variability & Outbursts



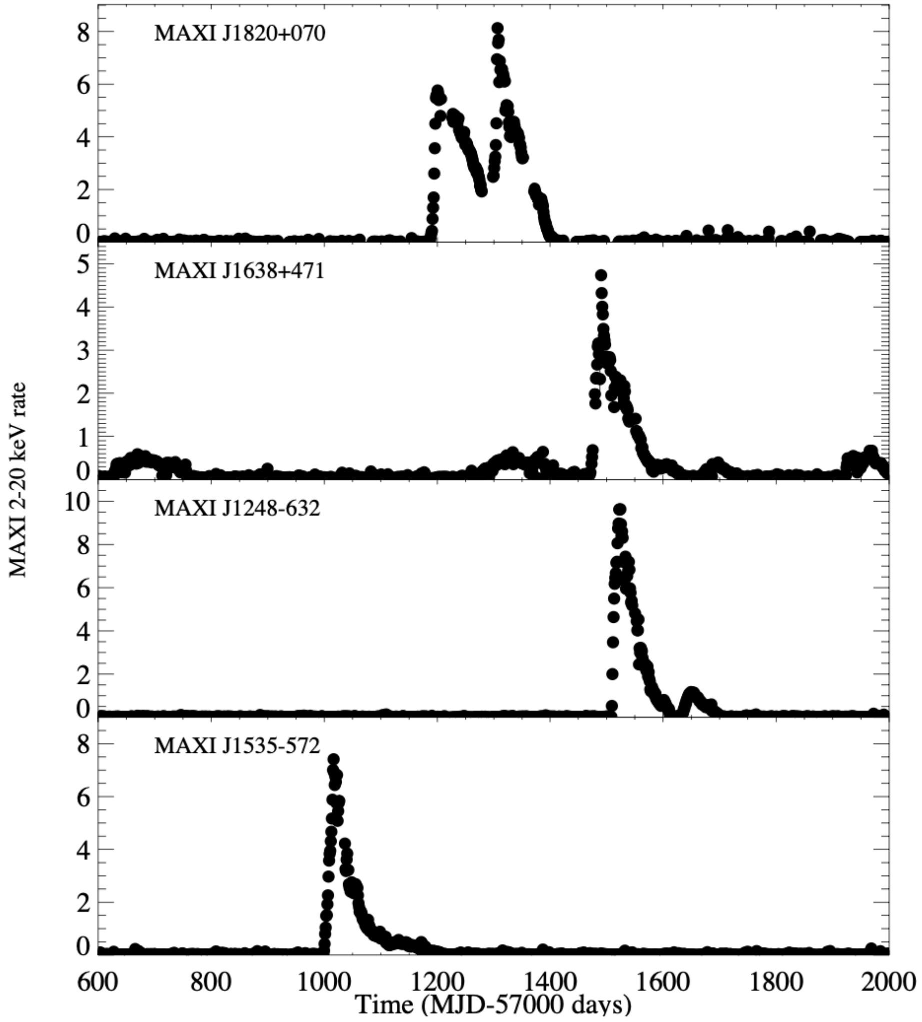
- transient sources
- persistent souces
- quasi-persistent, e.g. GRS 1915+105 extended outburst

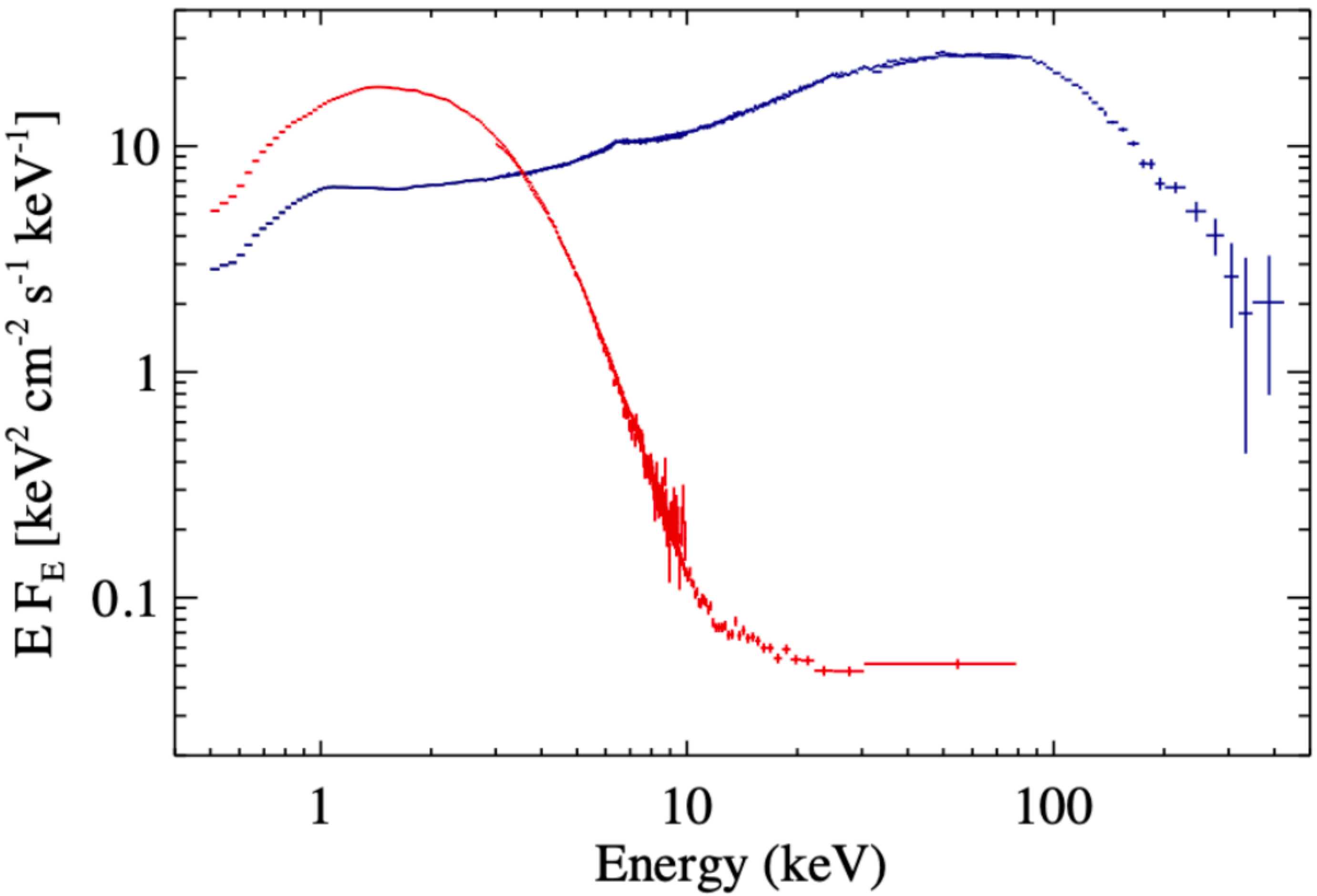
Black holes: Variability & Outbursts



Kalemci et al. 2023

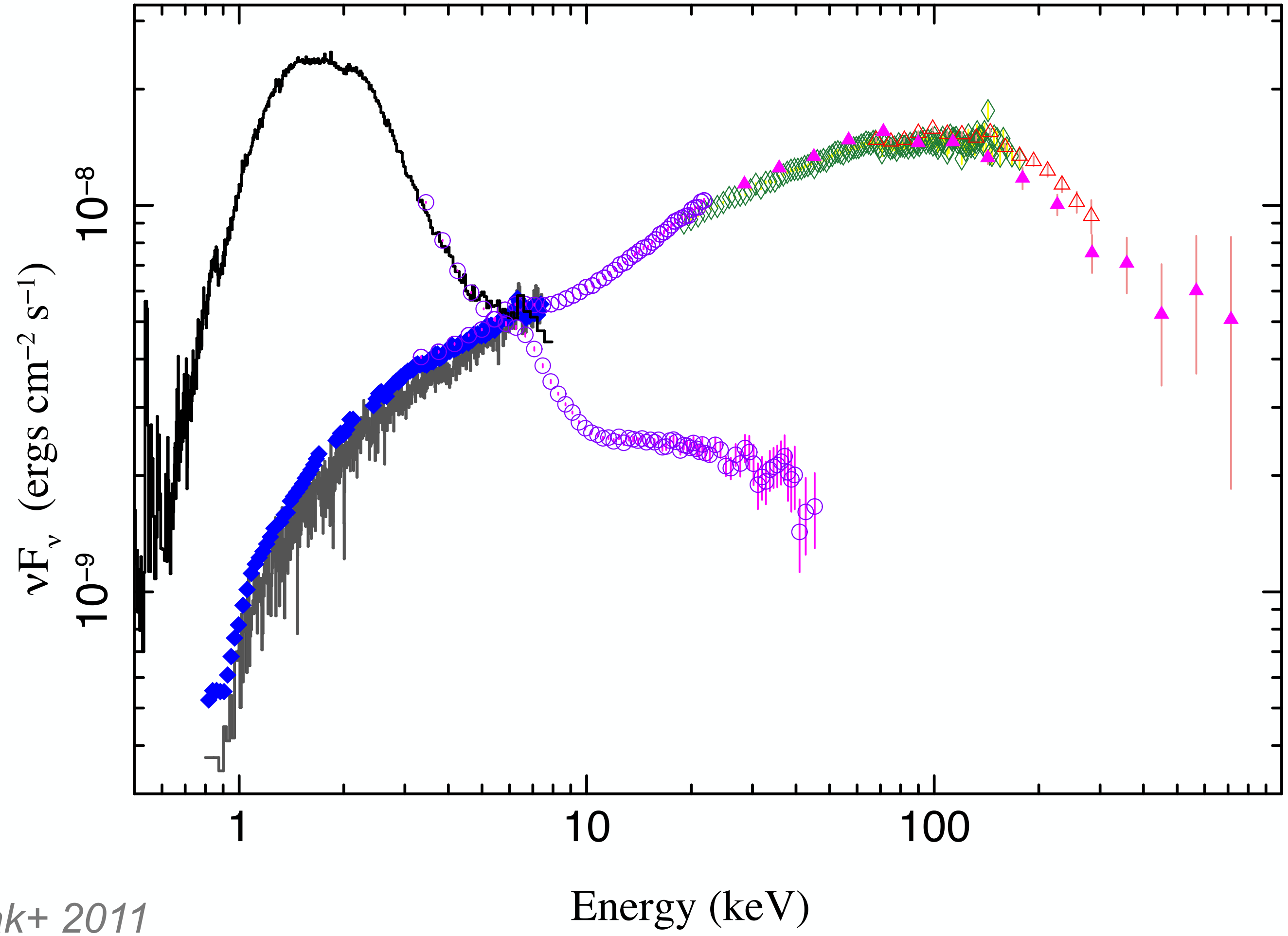
Black holes: Variability & Outbursts





Kalemci et al. 2023

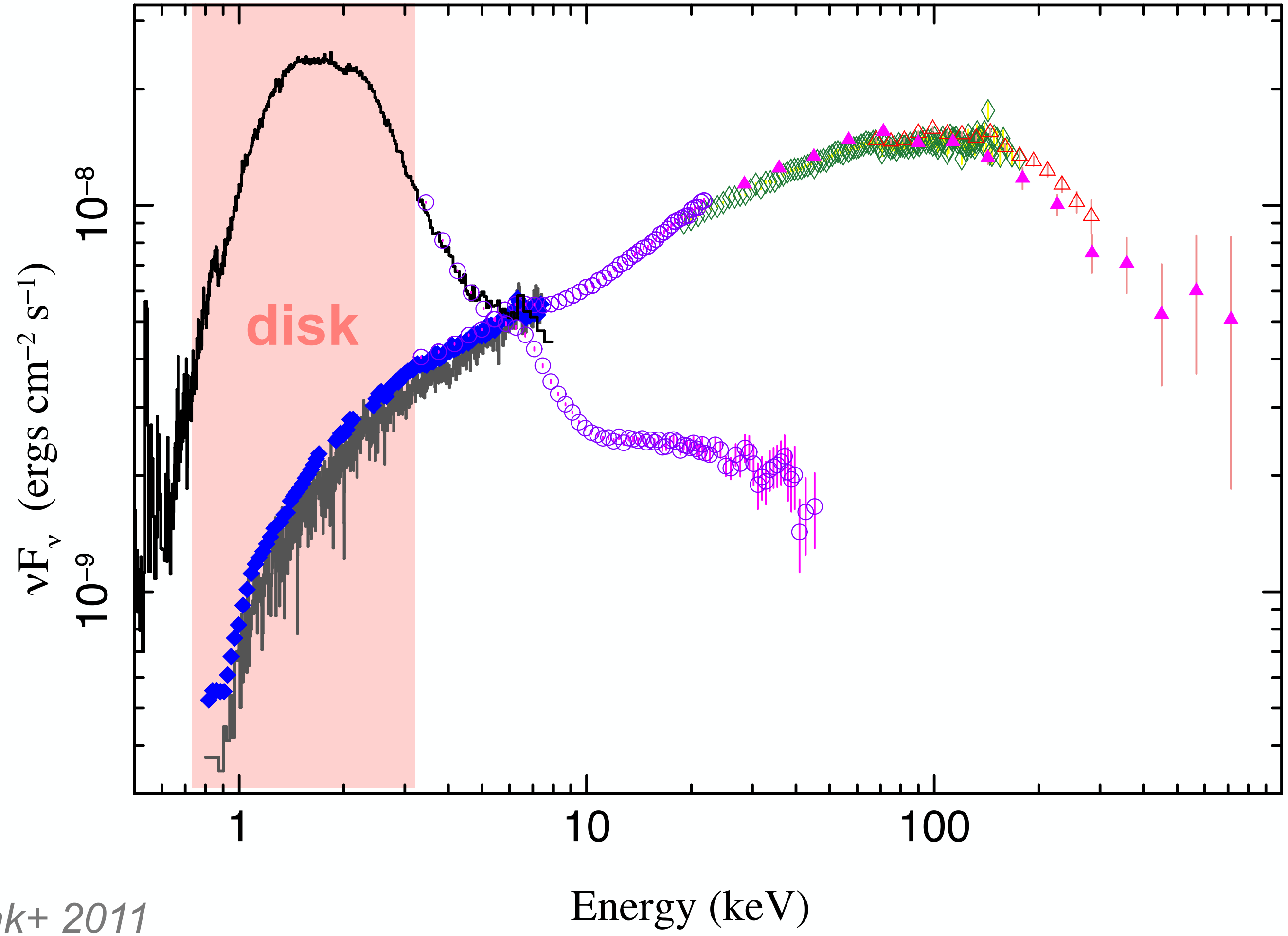
Black holes: States



Nowak+ 2011

Chandra + Suzaku/XIS + Suzaku/GSO + RXTE/PCA + RXTE/HEXTE + INTEGRAL/ISGRI

Black holes: States



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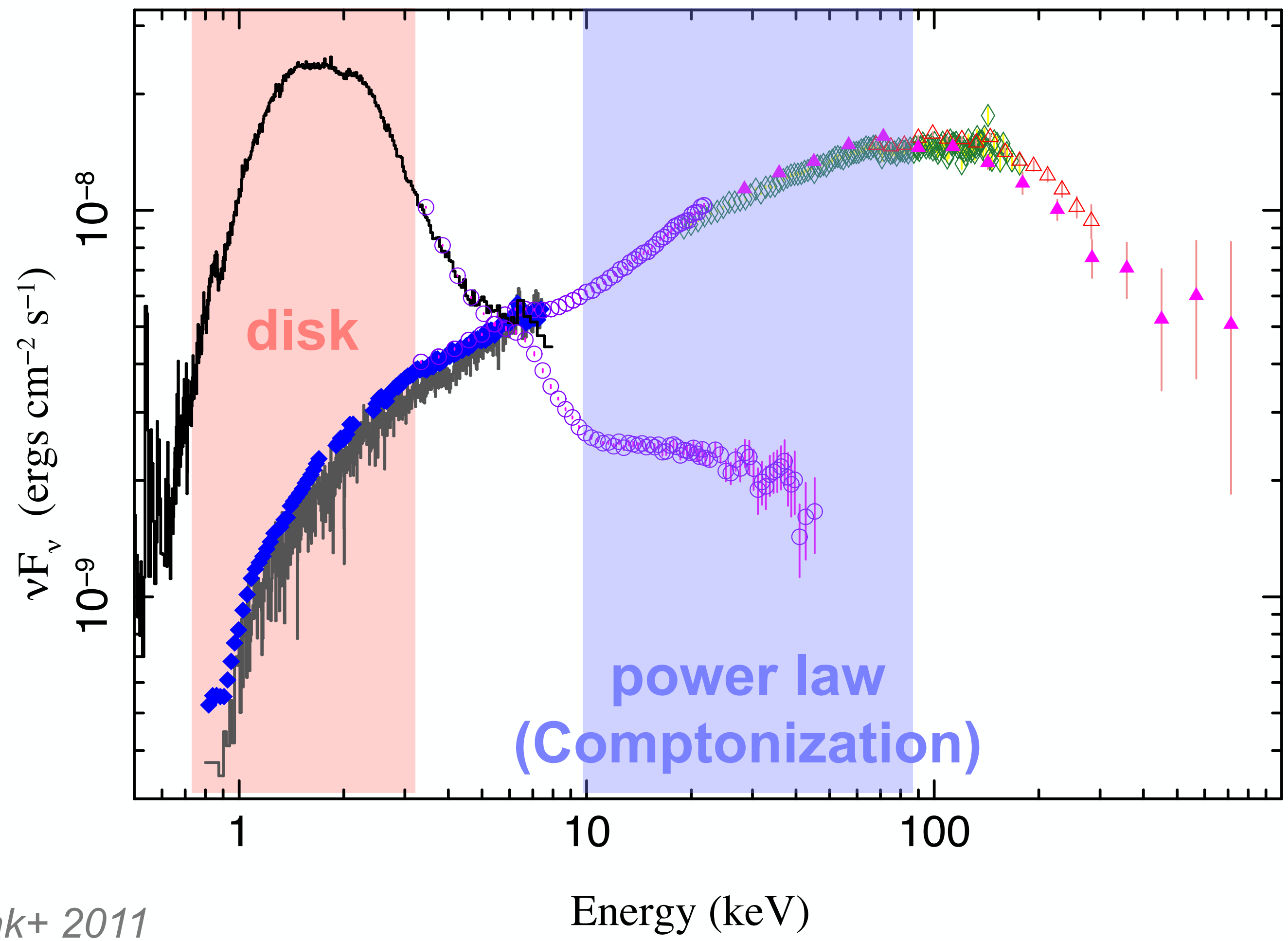

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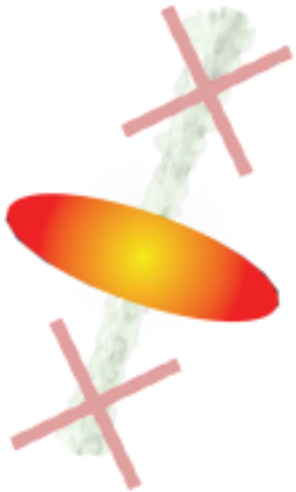
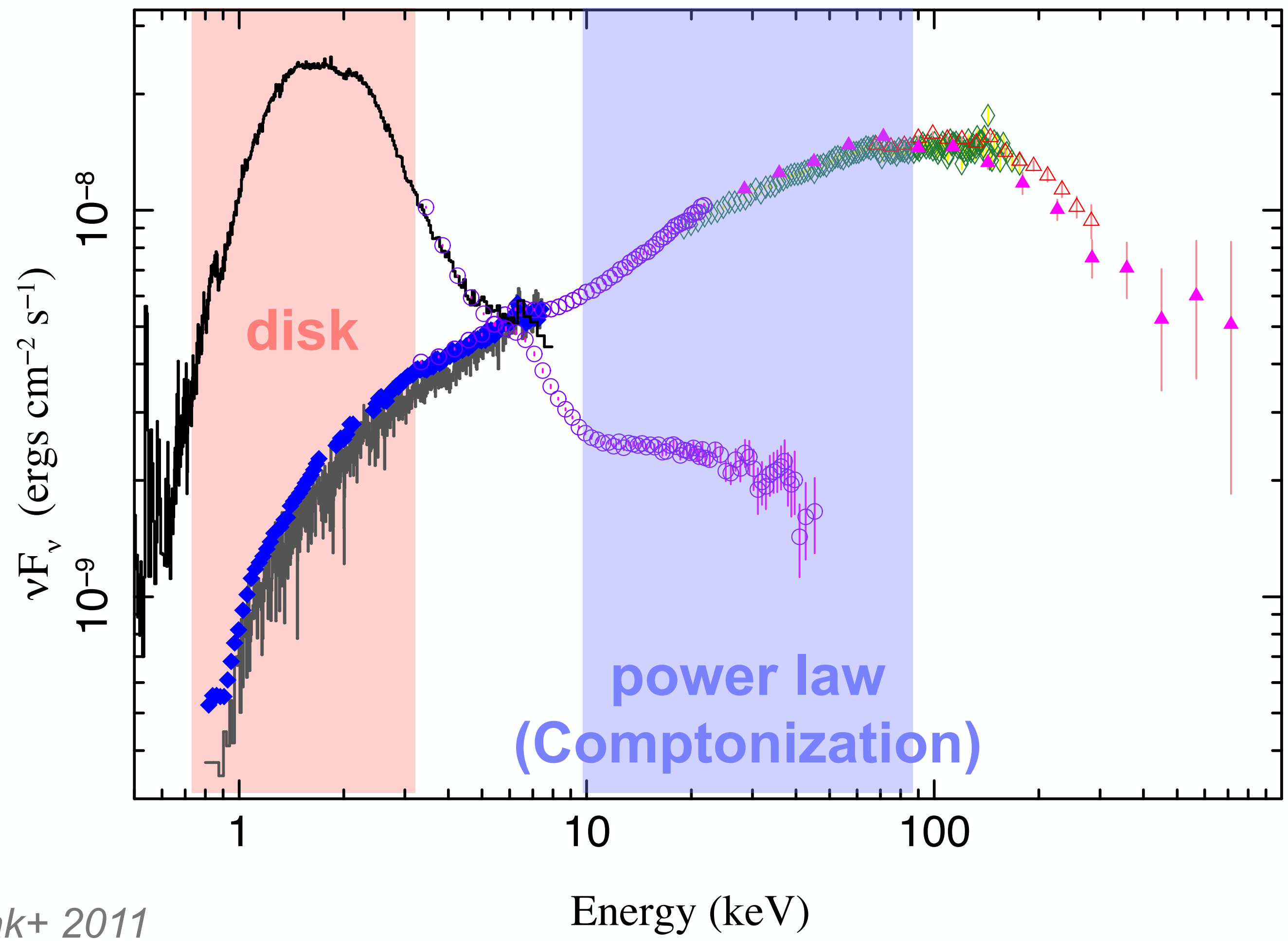
Black holes: States

soft state
strong disk
no radio





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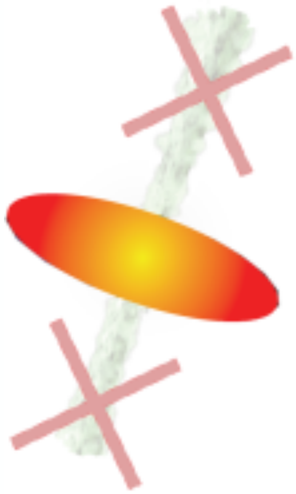
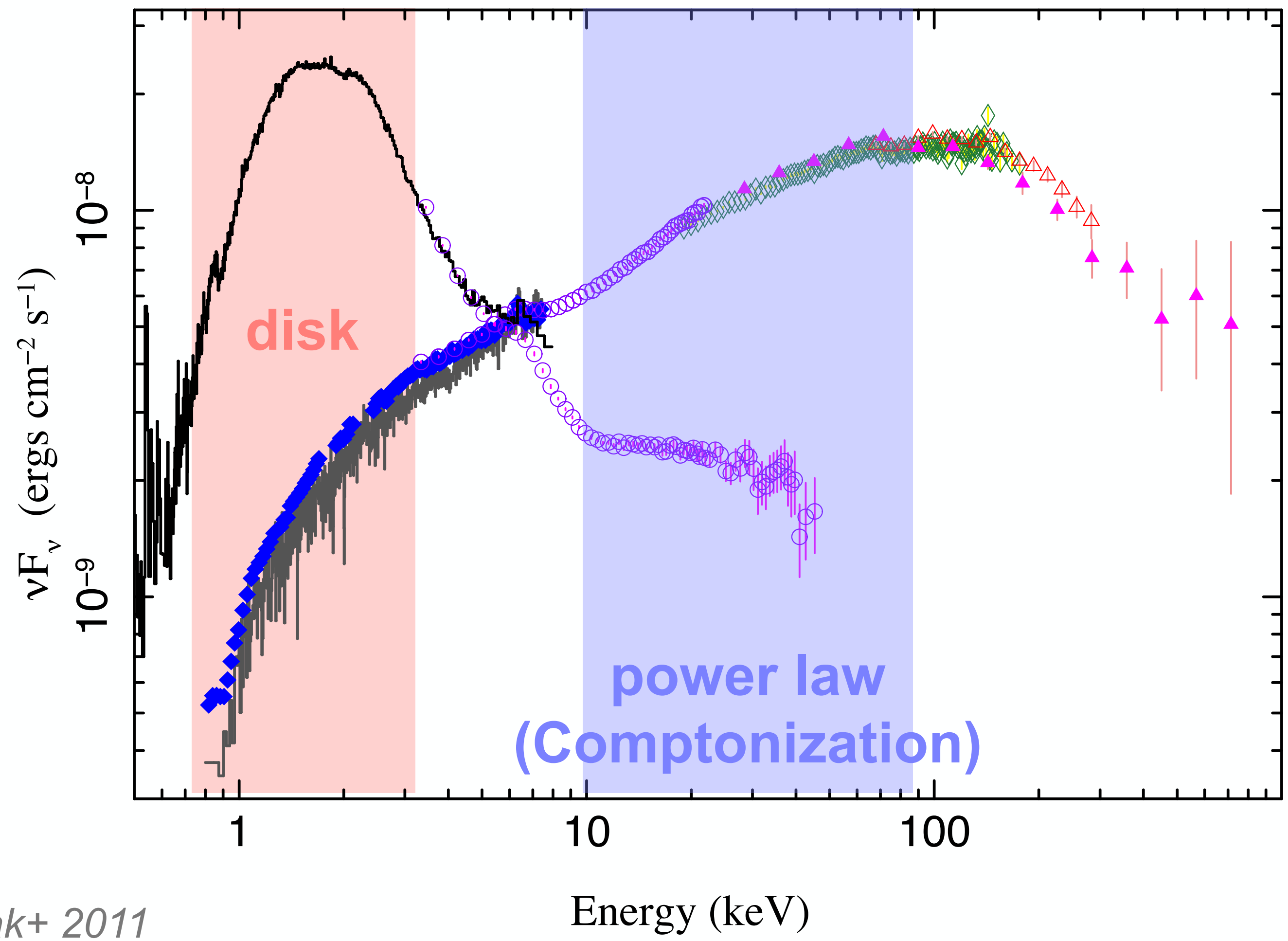
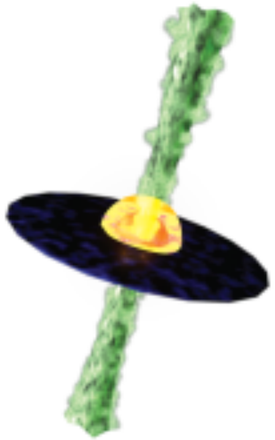




hard state
weak disk
radio



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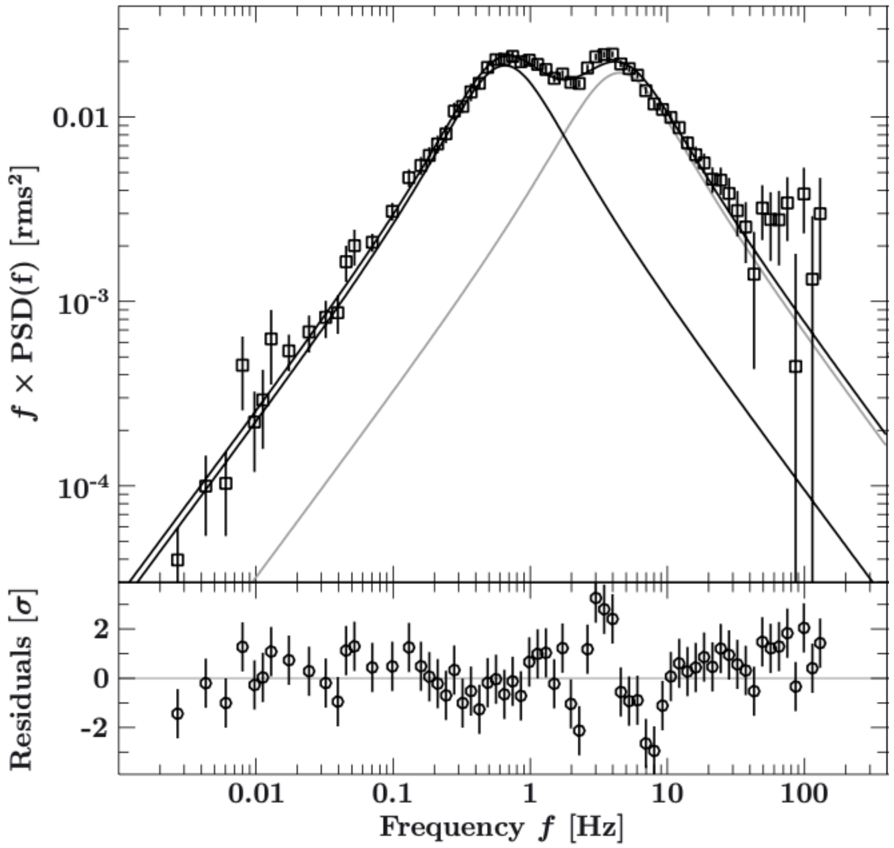
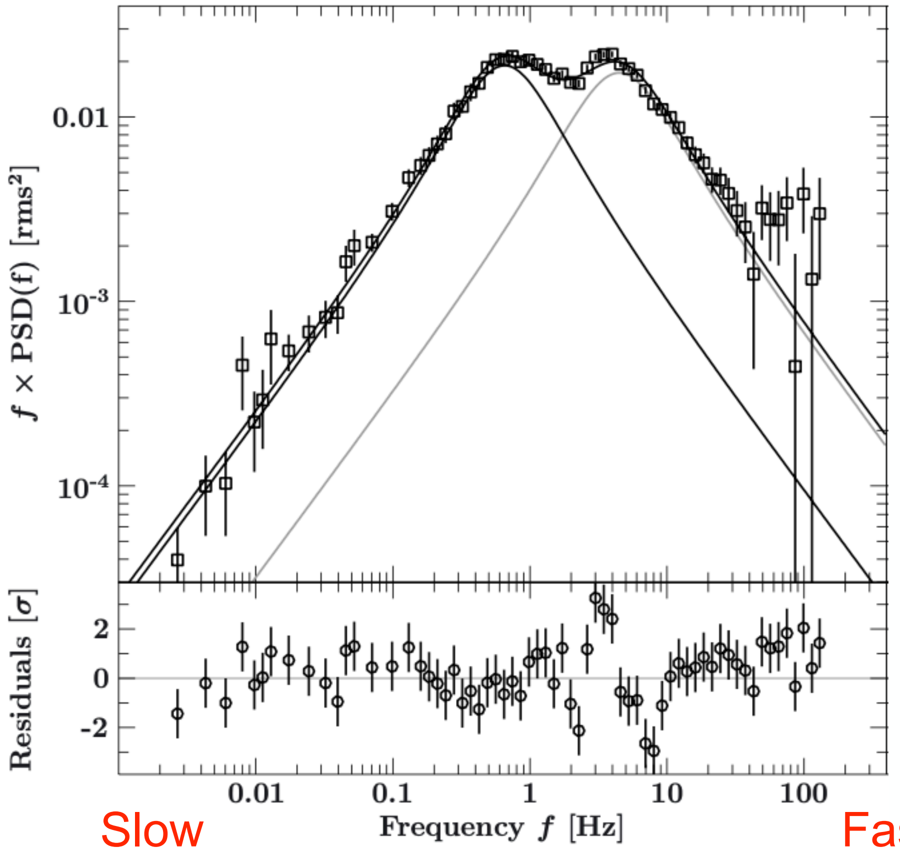
Chandra + Suzaku/XIS + Suzaku/GSO + RXTE/PCA + RXTE/HEXTE + INTEGRAL/ISGRI

Black holes: Power spectra



Boeck et al. 2011

Black holes: Power spectra

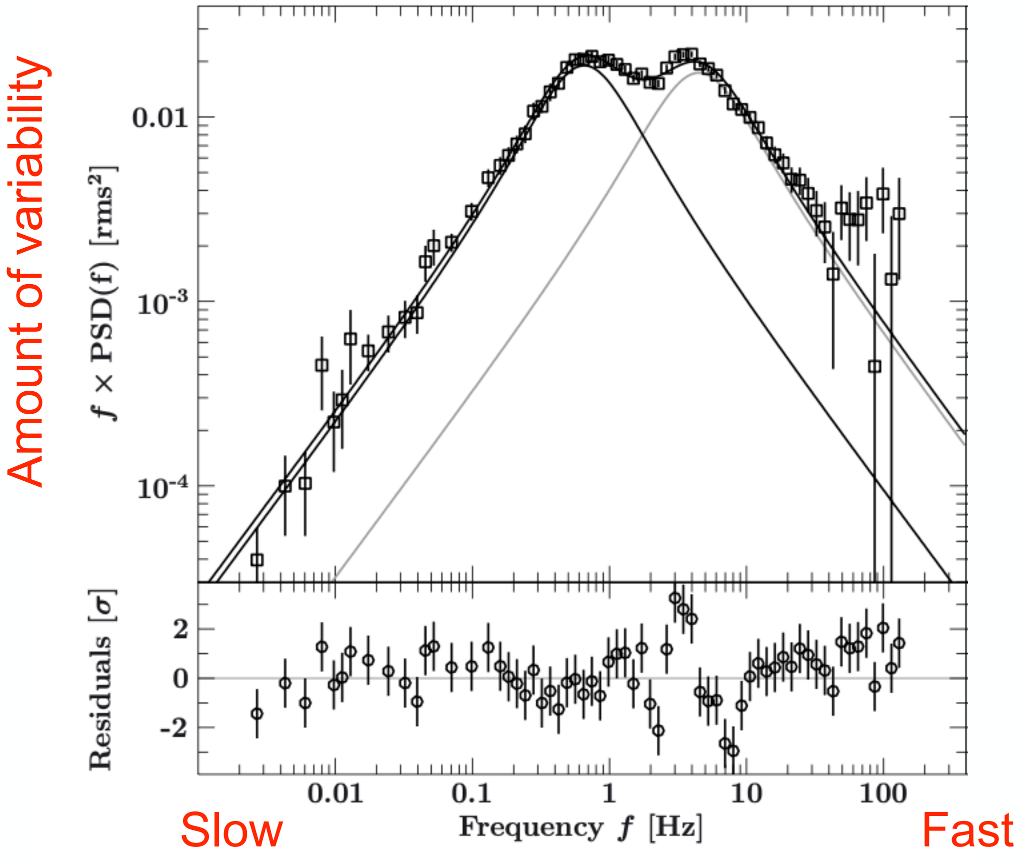


Slow

Fast

Boeck et al. 2011

Black holes: Power spectra



Boeck et al. 2011

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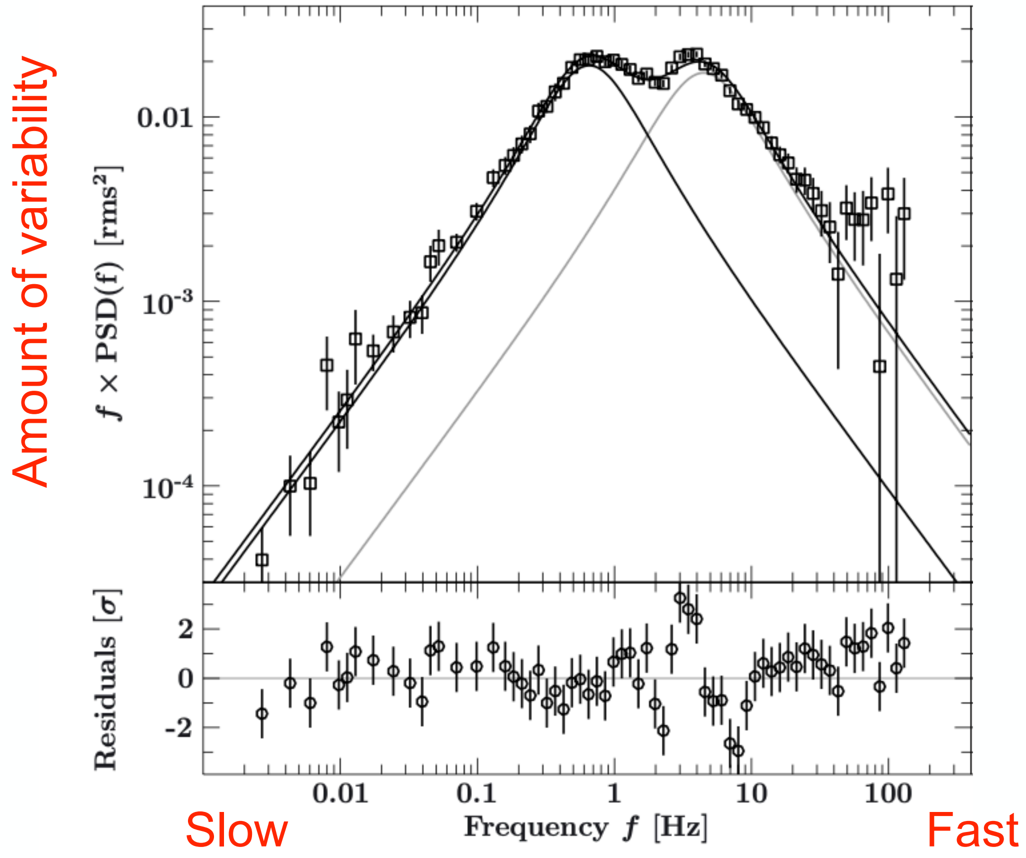


Boeck et al. 2011

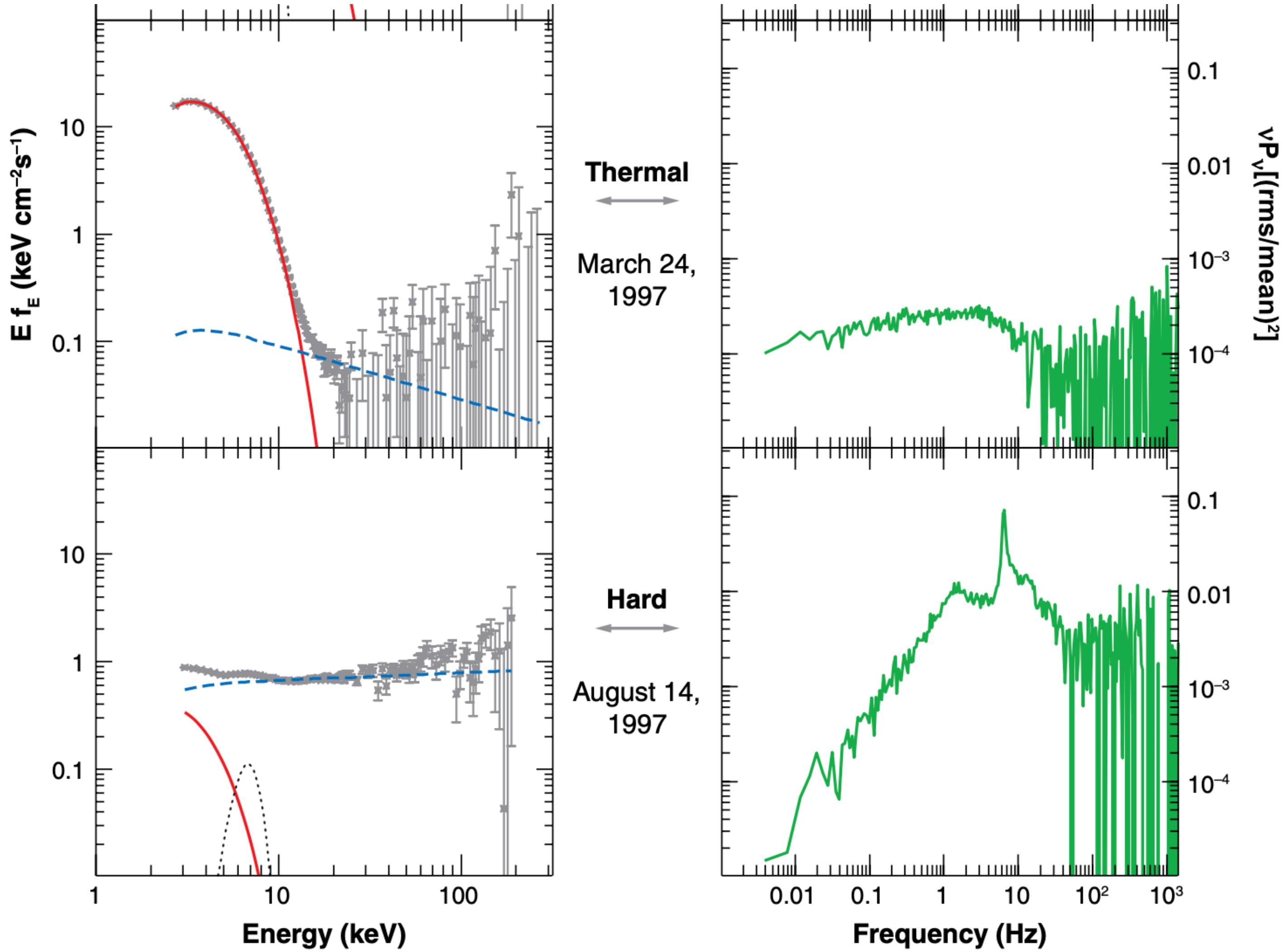
Power density spectrum

- a non-complex quantity obtained by multiplying the discrete Fourier transform and its complex conjugated quantity = the **PDS is the squared magnitude of the complex Fourier transform**
- measure of contribution of different frequencies to total variability
- XRBs: can typically be modelled with multiple broad & narrow Lorentzians

Papers VG finds especially good intros:

- Pottschmidt 2002 (PhD thesis)
- Nowak et al. 1999

Black holes: Power spectra



Remillard & McClintock 2006

Spectral and timing properties are correlated (both in the same source and across sources)!

Black holes: X-ray radio correlation

esa

THE ASTROPHYSICAL JOURNAL, **177**:L5–L10, 1972 October 1

OBSERVATION OF A CORRELATED X-RAY–RADIO TRANSITION IN CYGNUS X-1

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AND

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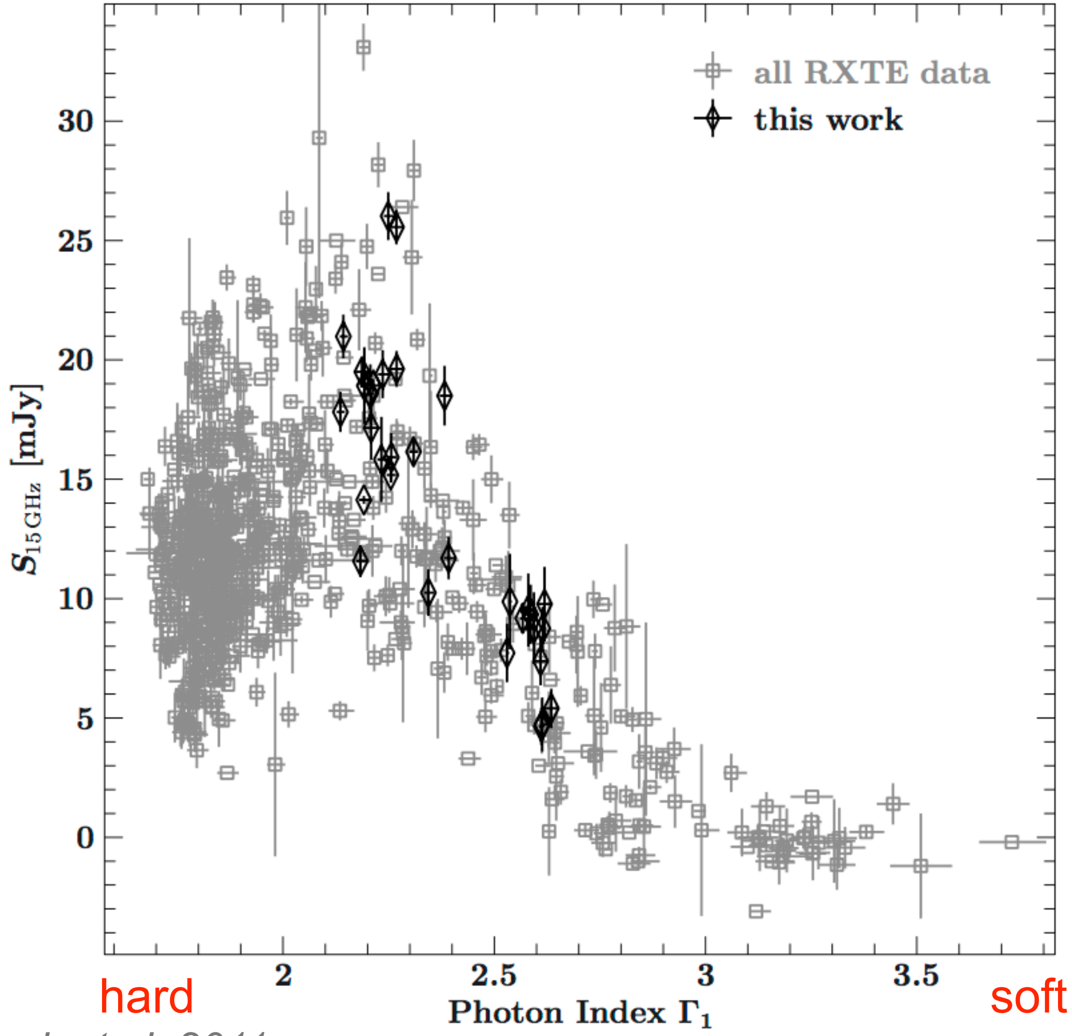
Harvard College Observatory, Cambridge, Massachusetts
Received 1972 July 24

ABSTRACT

Analysis of 16 months of *Uhuru* data on Cyg X-1 has shown a remarkable transition in the source which occurred during 1971 March and April. The average X-ray intensity in the 2–6-keV energy range decreased by about a factor of 4, the average X-ray intensity in the 10–20-keV band increased by a factor of 2, and a weak radio source suddenly appeared. This simultaneous X-ray and radio behavior provides strong evidence for the identification of the radio source with Cyg X-1. *Uhuru* also monitored Cyg X-1 for 35 consecutive days during 1971 December and 1972 January. The data were analyzed for an effect due to a binary system. Although large-scale fluctuations were present, no periodicity was found.

- The very first detection official detection of a state transition

Black holes: X-ray radio correlation



Boeck et al. 2011

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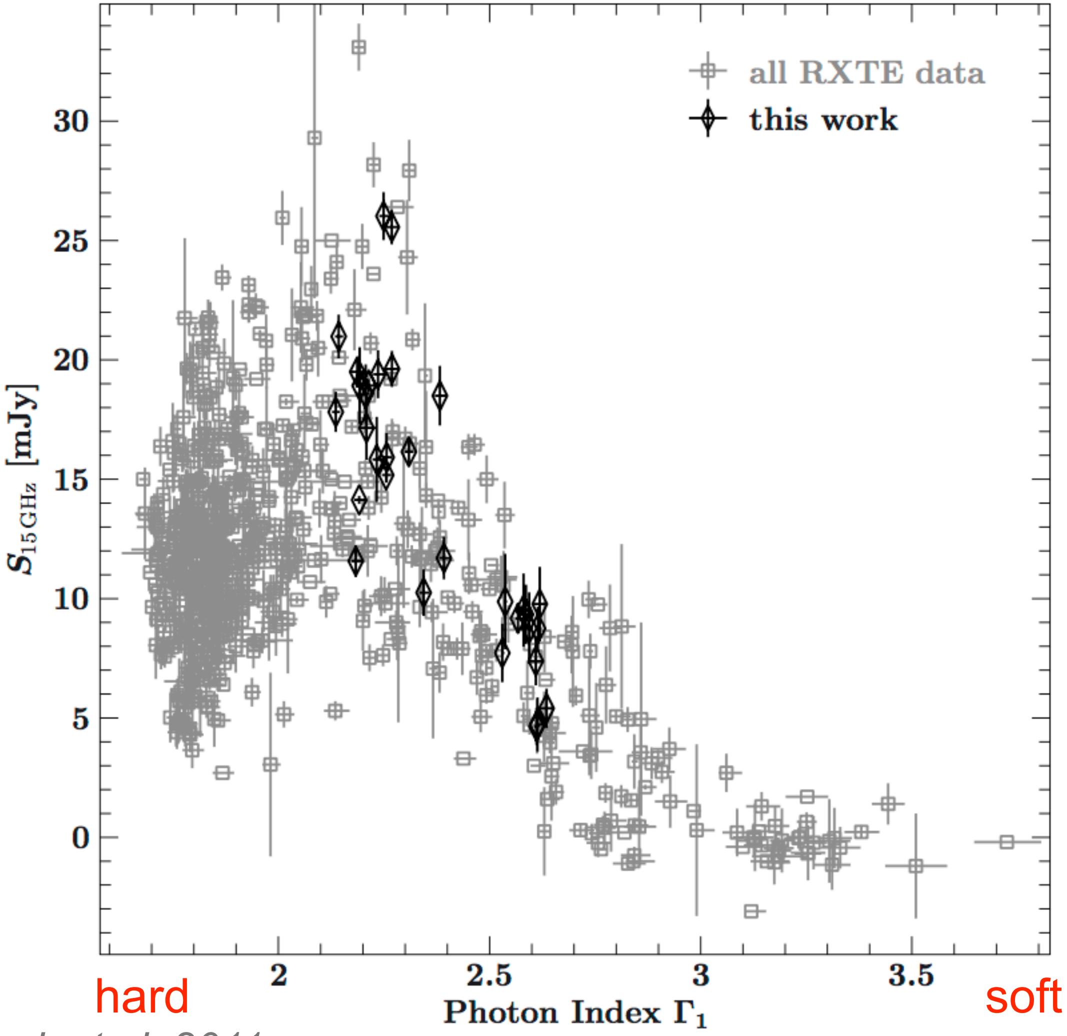


Boeck et al. 2011

For a given black hole X-ray binary, the radio emission is correlated with X-ray emission:

- ➤ radio detected in hard state
- ➤ (mostly) no radio in soft state
- ➤ radio flares most often during transition
- ➤ hints of simultaneous radio & X-ray flares for several sources such as Cyg X-1 and GRS 1915-105
- ➤ detections of extended radio emission in hard state

Black holes:q-track / turtlehead-diagram

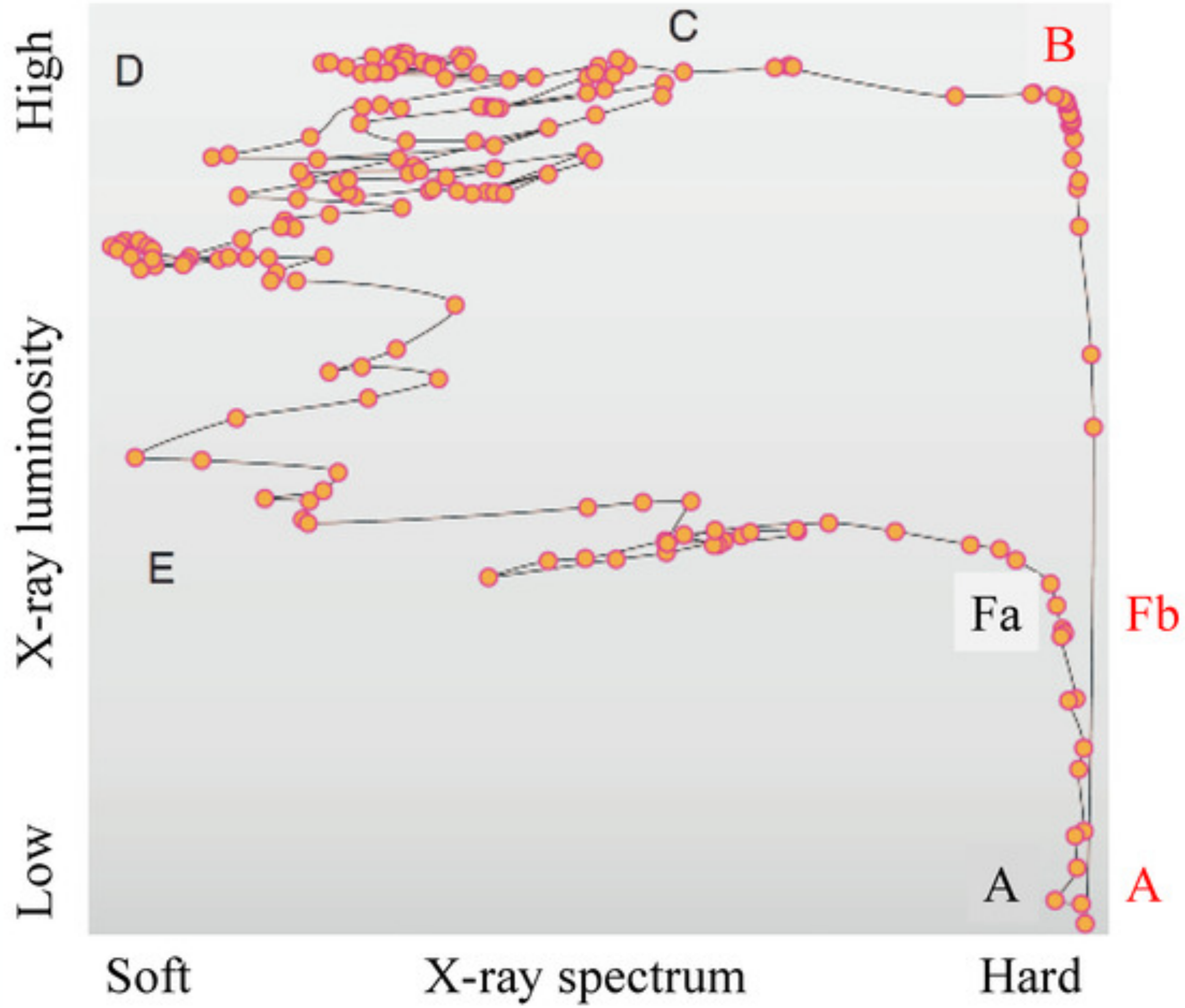
HID: hardness luminosity diagram

$$\text{hardness} = \frac{CR_{\text{hard band}}}{CR_{\text{soft band}}}$$

or

$$\text{hardness} = \frac{CR_{\text{hard band}} - CR_{\text{soft band}}}{CR_{\text{soft band}} + CR_{\text{soft band}}}$$

Black holes:q-track / turtlehead-diagram



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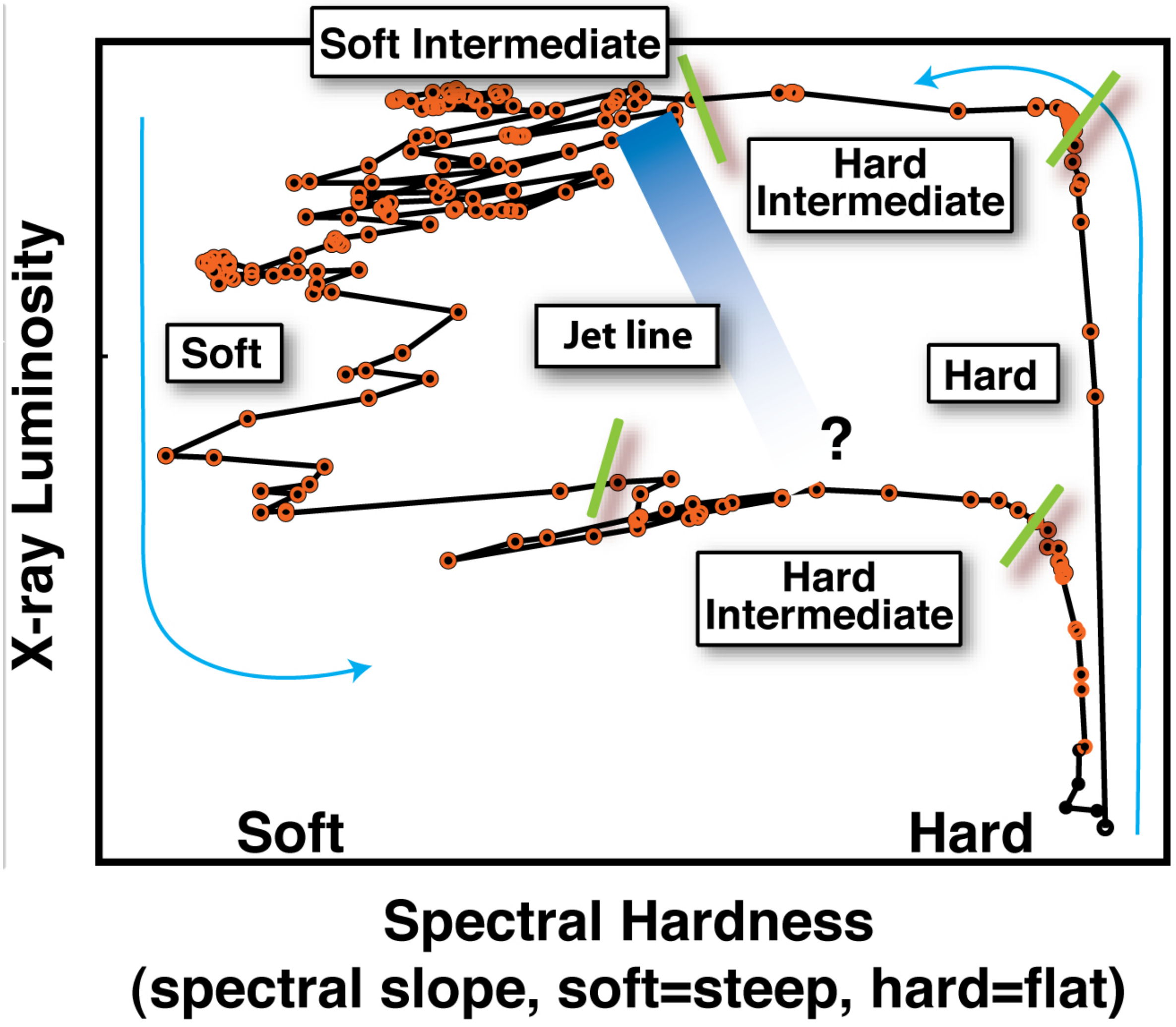

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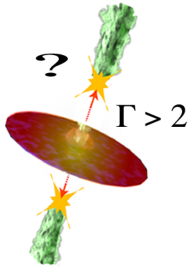
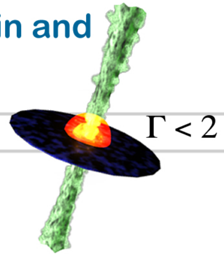
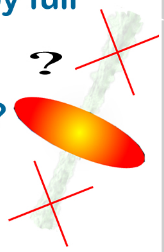
JET LINE AREA:
- 2 - 50% L_{Edd}.
- High-frequency QPOs (after) .
- Type A & B QPOs (after).
- See radio ejecta (fast) each "crossing" of jet line.
- RMS drop ("The Zone") associated with ~0.2 Hz lowest freqency Lorentzian, close to ejecta time.



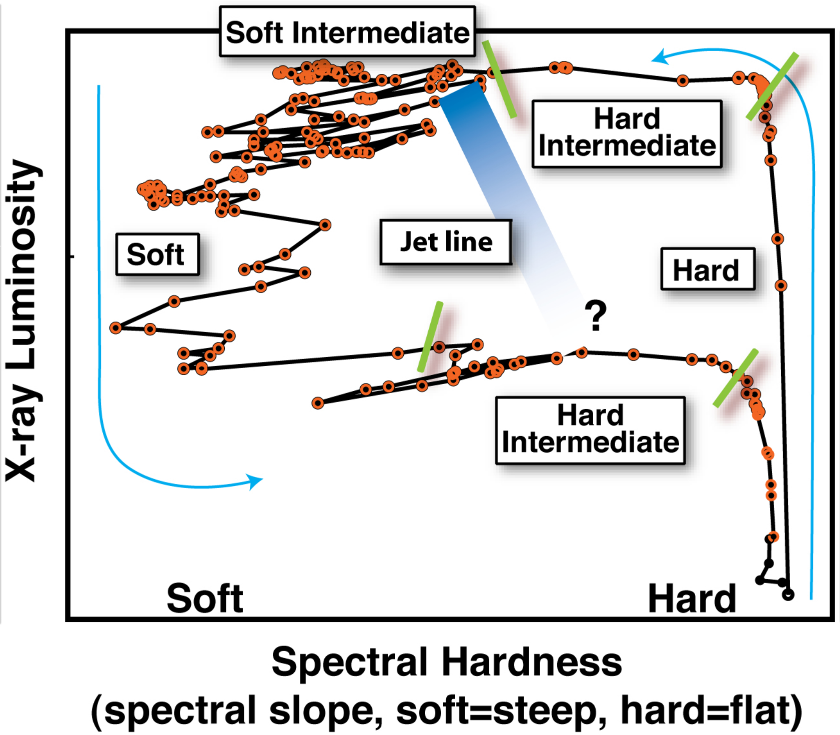
HIMS:
- Disk starts near ISCO.
- Transition starts around 2 - 50% L_{Edd}.
- Type C QPOs.
- IR drops.
- Radio starts going optically thin and variable (new ejecta?).



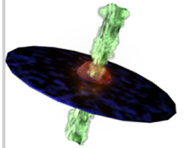
SOFT STATE:
- Optically nuclear thin jet radio emission observed initially, but quenched by at least 20-50x by full transition. Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to ~MeV .
- Thin disk ~0.1-1.0 L_{Edd} at ISCO.



+ Disk winds



HARD STATE:
- Disk moves in to ~ few R_g by 10% L_{Edd}.
- Lorentzian/broad noise components.
- High RMS variability.
  - Flat spectrum jet up to IR/opt.
  - Compact jet sometimes resolved.
  - Radio/IR/X-ray correlations.
  - Reflection "bump".

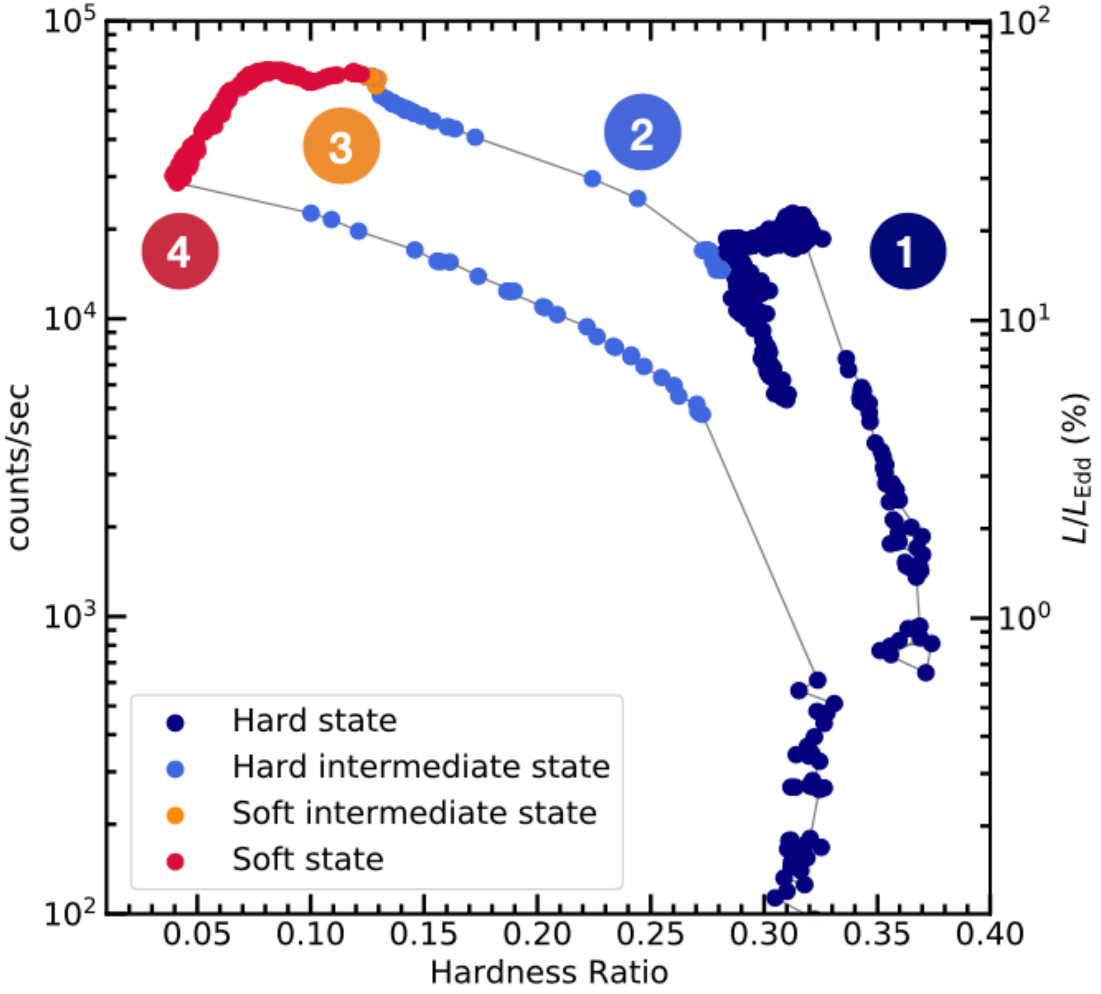


T. Belloni
A. Celotti
S. Corbel
R. Fender
E. Gallo
M. Hanke
E. Kalemci
D. Maitra
S. Markoff
I. McHardy
M. Nowak
P.-O. Petrucci
K. Pottschmidt
J. Wilms

HIMS:
Same as upper branch but:
- No optically thin radio flare.
- Radio recovers close to hard state.
- Lower flux level (hysteresis).

QUIESCENCE:
- Thin disk recessed to > 10^2 R_g
- BB component seen in UV/Optical.
- Disk 10-100x more luminous than LX. By ~10^{-4} L_{Edd}.
- No iron lines?

Q-track shapes:



Kalemci et al. 2023

1 Hard State

- Hardest corona, weak disk
- Compact radio jet
- Iron line and Compton hump
- Highest RMS: Type C QPOs, Reverberation lags

2 Hard Intermediate State (HIMS)

- Softening corona, stronger disk
- Compact radio jet shuts down
- Iron line and Compton hump
- High RMS: Type C QPOs, Reverberation lags

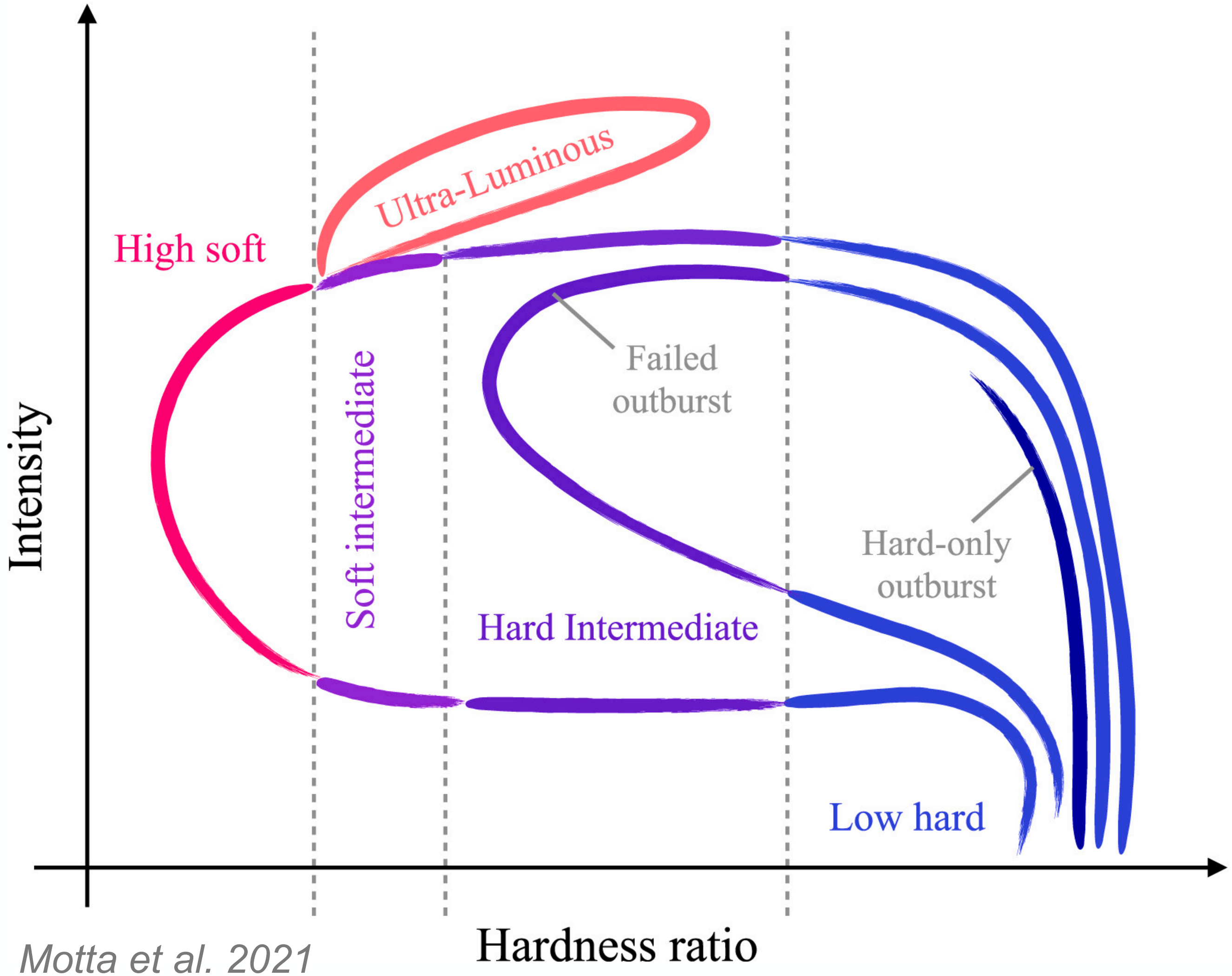
3 Soft Intermediate State (SIMS)

- Still softer corona, stronger disk
- Ballistic radio jet
- Iron line and Compton hump
- Low RMS: Transition from Type C to B QPOs

4 Soft State

- Weak corona, strong disk
- No radio jet, equatorial winds
- Less prominent iron line and Compton hump
- Low RMS: Rarely Type A QPOs, no lags

Black holes:q-track / turtlehead-diagram



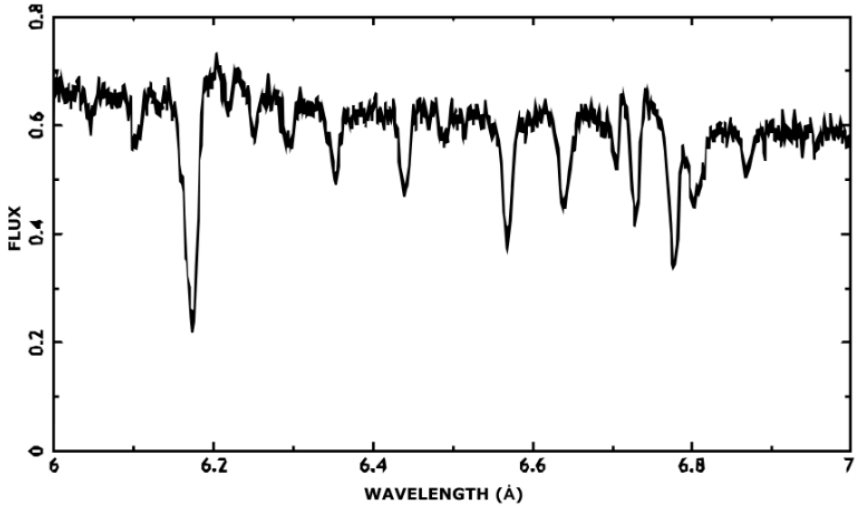
Motta et al. 2021

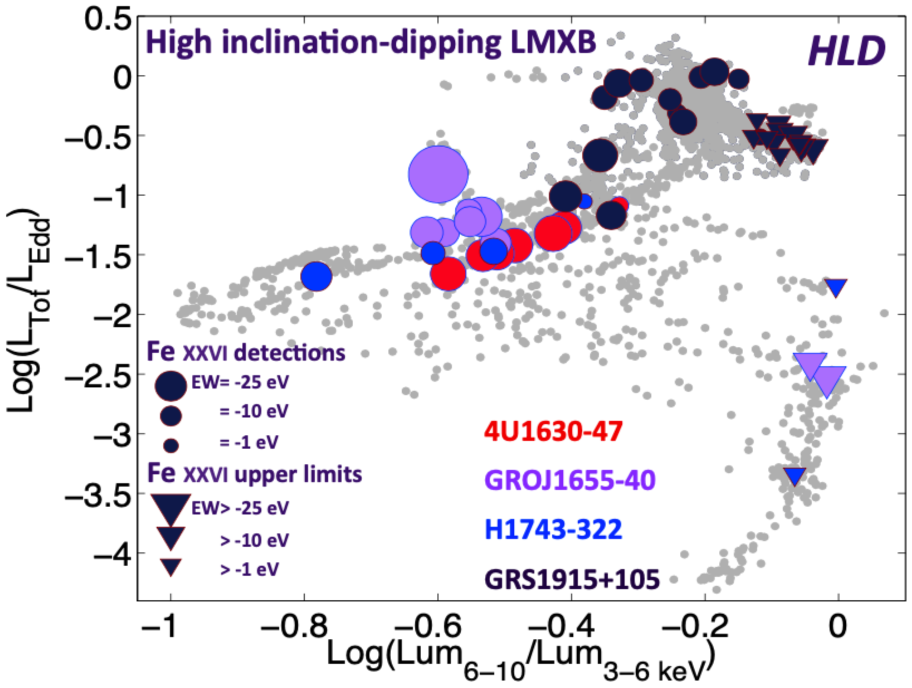
Outbursts even from the same source show a variety of behaviors so the q-track in not always q-shaped:

- full outburst (at different maximum intensities!)
- failed outbursts
- high only outbursts
- …

Disk winds

Kalemci+ 2023 after (NASA/CXC/U.Michigan/ J.Miller+ 2006 (left) & Ponti+ 2012 (right)



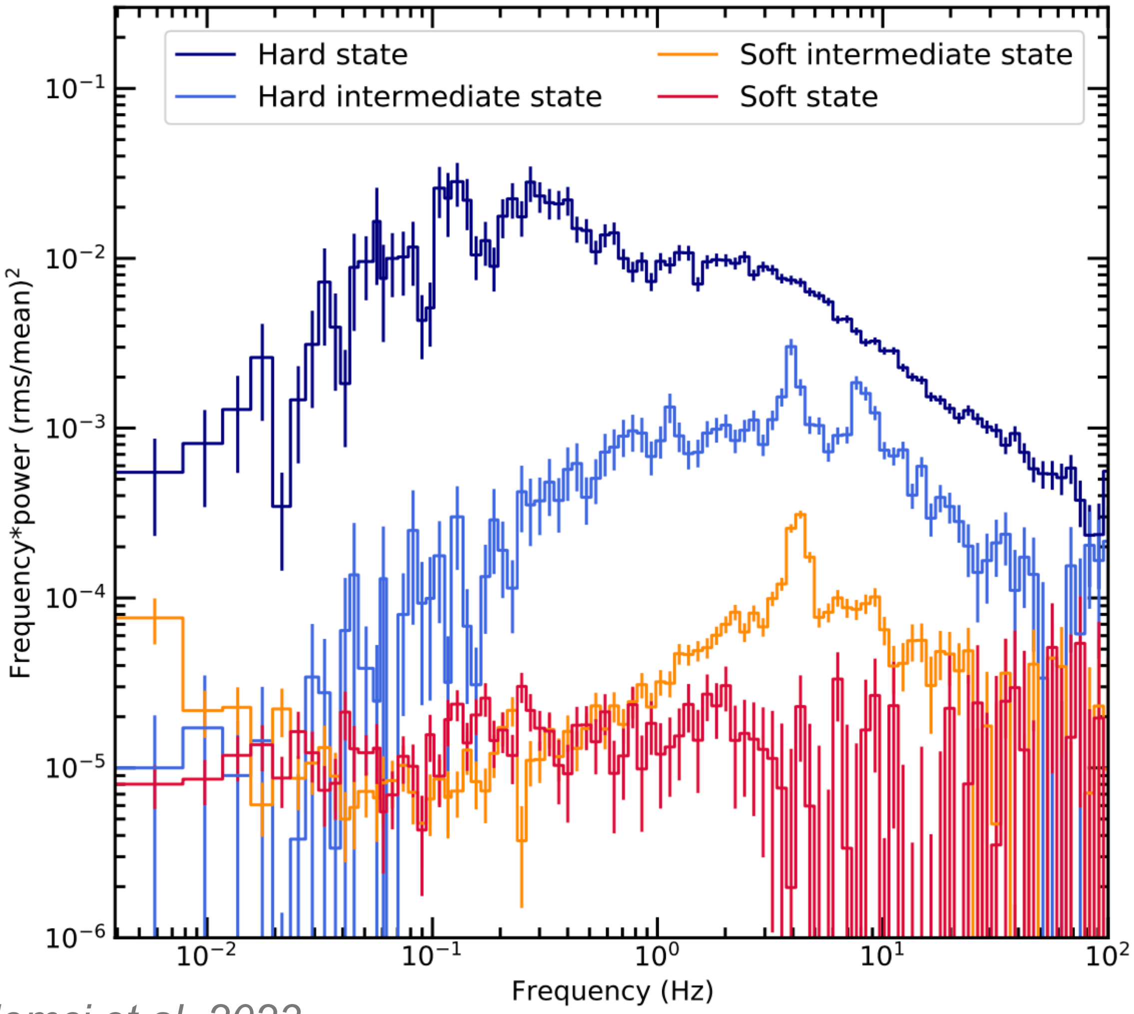


➤ soft state: blue-shifted absorption lines in high inclination sources $\Longrightarrow$ ionized, equatorial outflows

➤ mass outflow rate can exceed the mass accretion rate through disks

➤ hard state: detection of “cold” winds in optical/IR observations

Low-frequency quasi-periodic oscillations (QPOs)



Kalemci et al. 2023

- hard state: broad noise components
- bright hard: variability shifts & often becomes more concentrated $\Longrightarrow$ type C QPOs
  - likely geometric origin due to inclination dependence (Heil et al. 2015; Motta et al. 2015)
  - often accompanied by harmonics
- hard intermediate state: broad band noise drops, but QPOs increases, until suddenly drops
- replaced by type B QPOs: 1-6 Hz, typically lower amplitude than type C, short-lived (smtimes a few hundred seconds), also inclination dependent
- soft state: usually no QPOs, handful type A detections (possible subset of Bs?)

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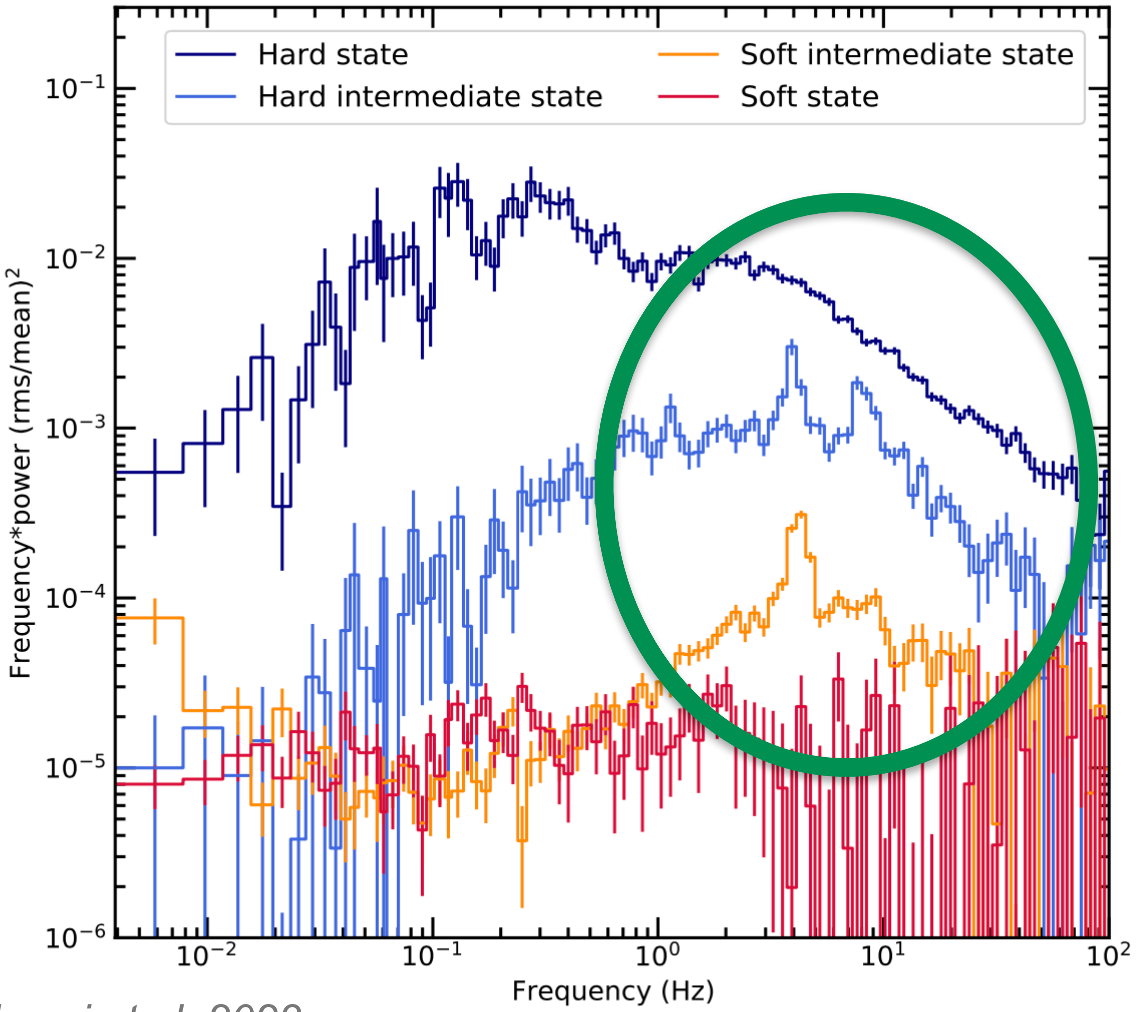

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Terminology & a few words of caution

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Low/high vs. hard/soft vs. powerlaw/thermal

- low/high: emission in soft X-rays (oldest state definition, driven by soft X-ray instruments)
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Clear defined states vs. a continuum

- “jumps” in some properties (esp. timing properties)
- radio ejections
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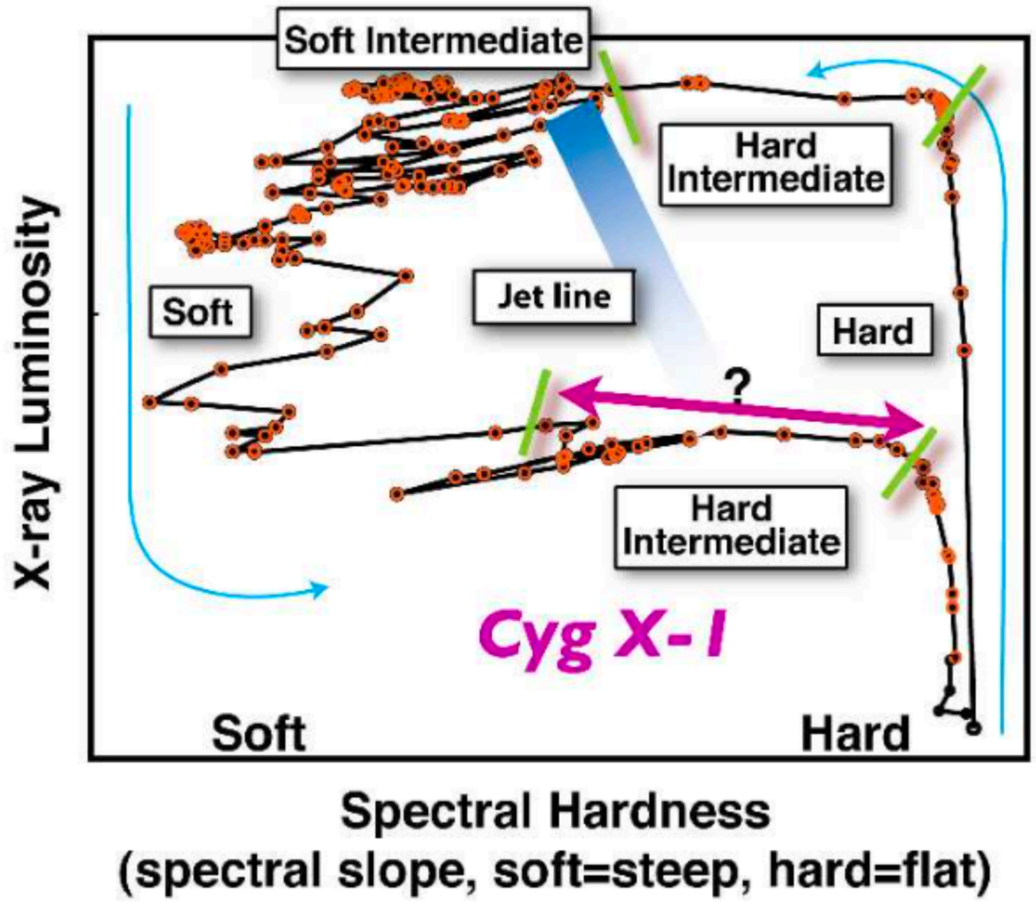
q-track / turtlehead diagram

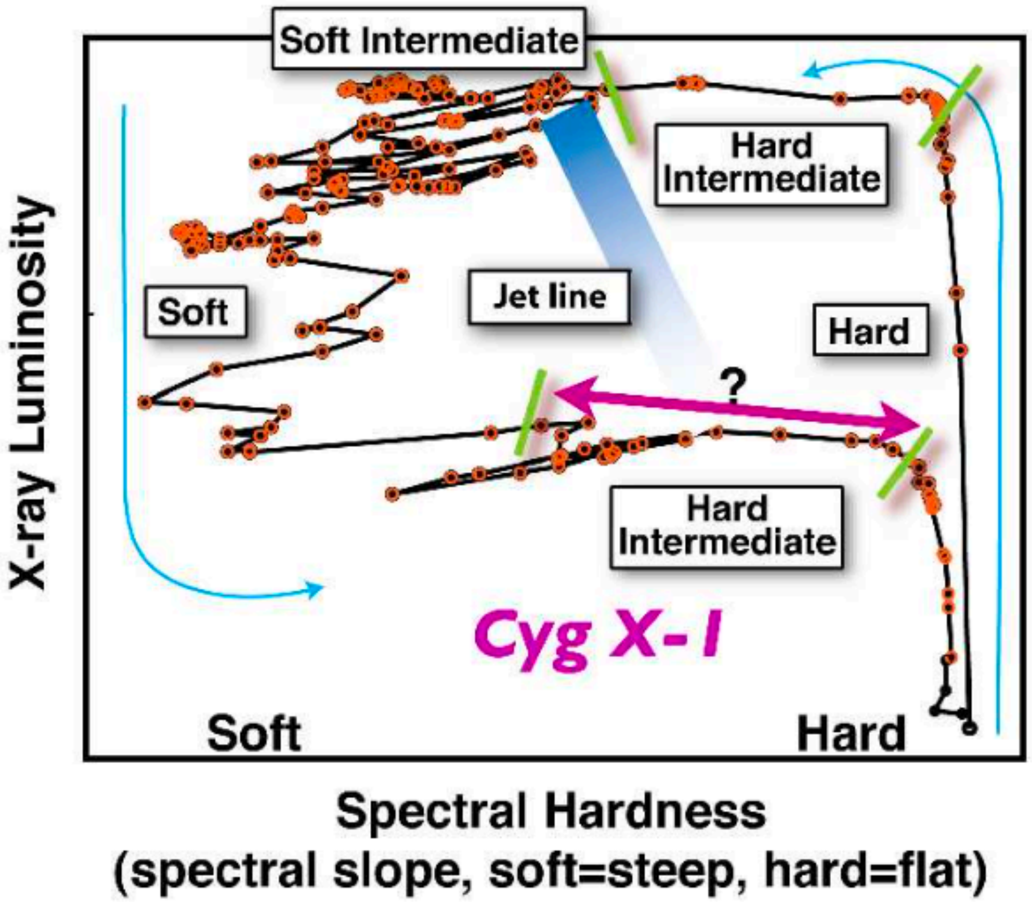
- many outburst are "failed", never reading the soft state
- shape of q-track depends on: source, incl. inclination; instrument used; units used

q-track outliers

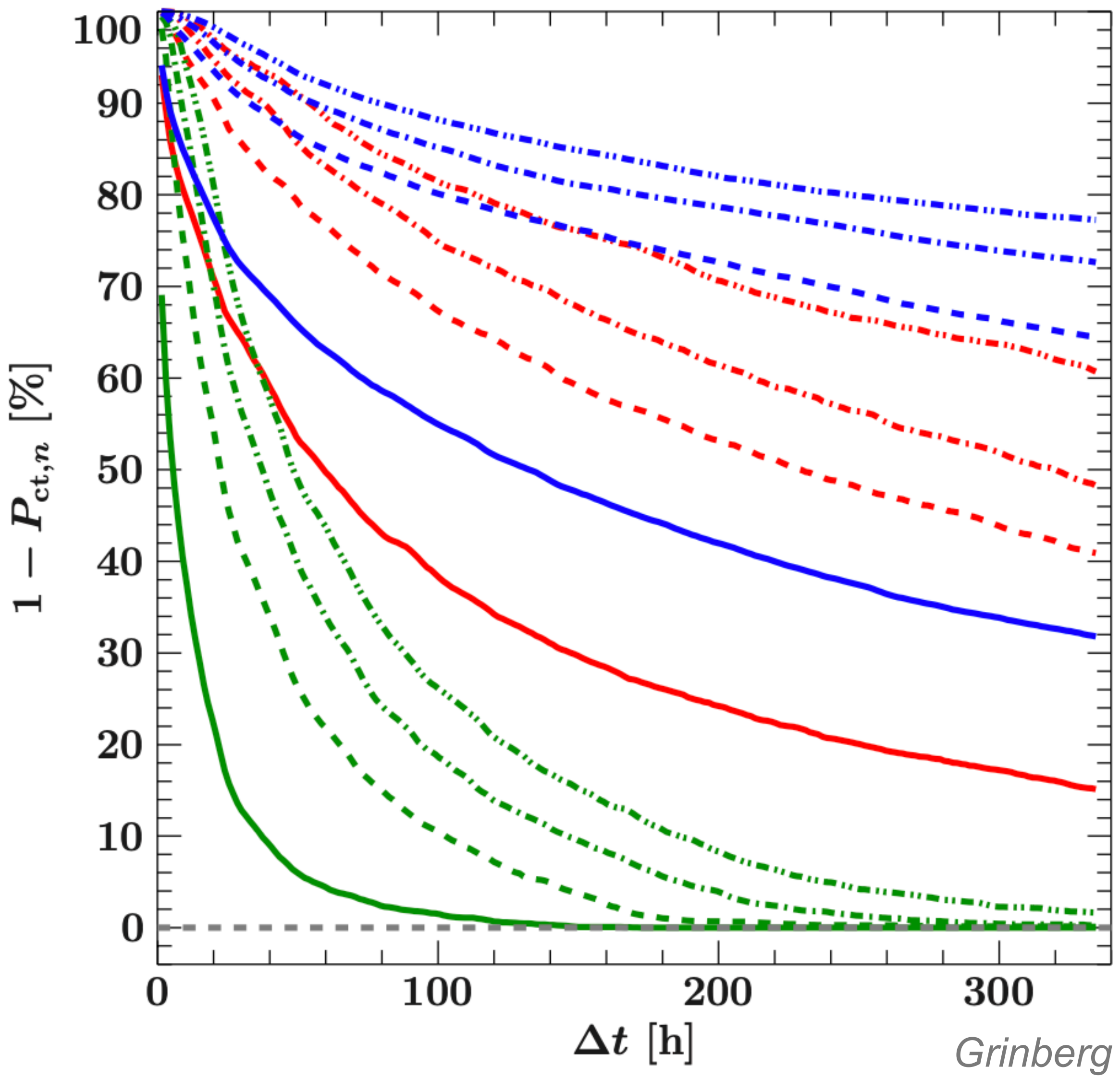


q-track outliers

- Cygnus X-1: not a transient, likely occupies only a narrow range on HID
- GRS 1915+105: distinct, repeating variability patterns; recently - possibly a highly obscured state
- 1E 1740.7–2942 and GRS 1758–258: most of the time in a hard state, but will sometimes descrease in luminosity to enter soft state
- 4U 1630–47 : changes the direction of movement through outburst
- …



Stability of states



Grinberg 2013

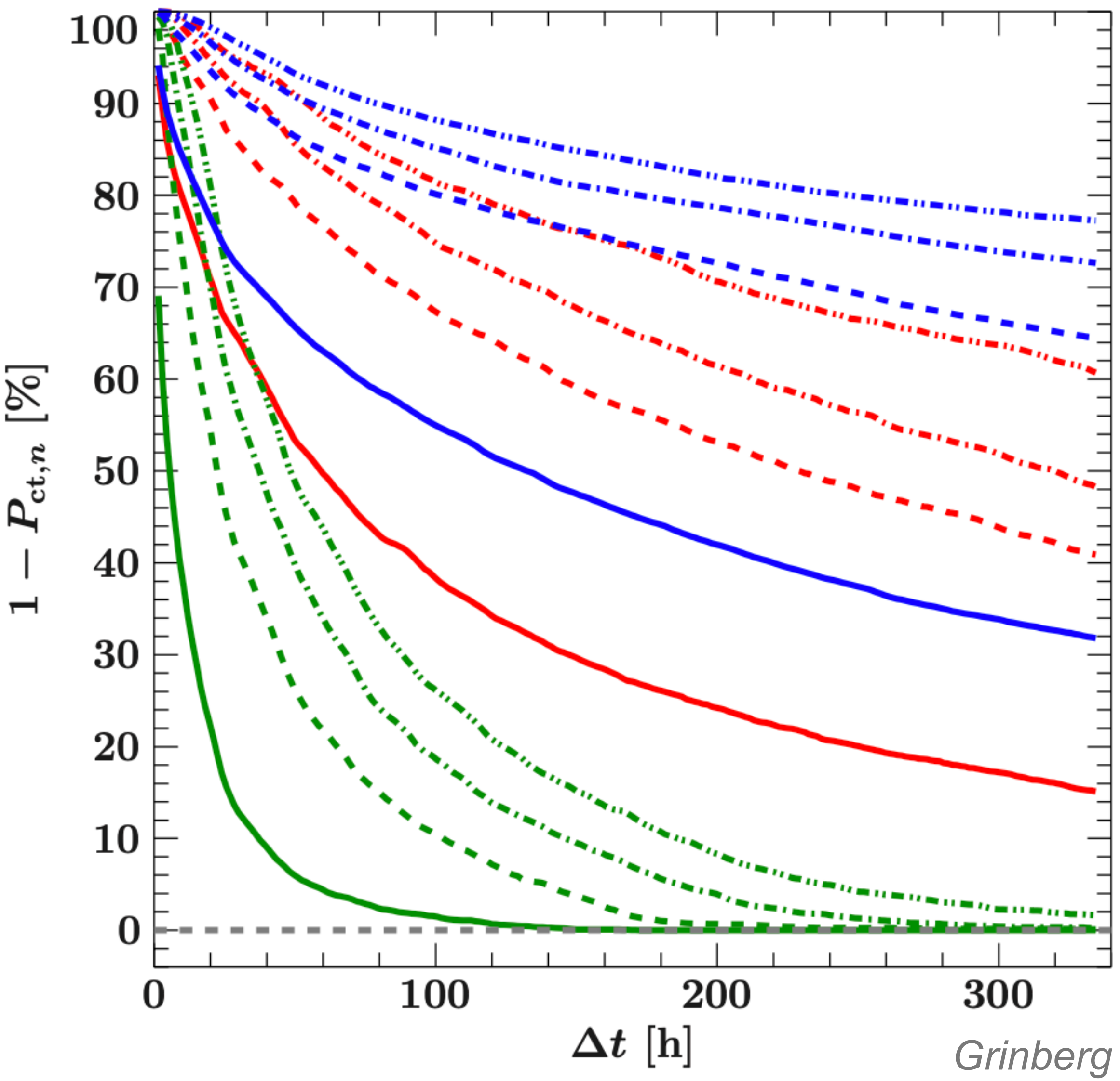
Stability of states

Q-tracks provide no information on the overall timing of an outburst:

- how much time does the source spend in a given state, i.e. how “stable” is a given state?
- how fast are state transitions?

typically: fast transitions, hard & soft relatively stable; e.g. Böck et al for a state transition within a few hours

Right: the probability of Cygnus X-1 to remain in the same state for hard, intermediate and soft states

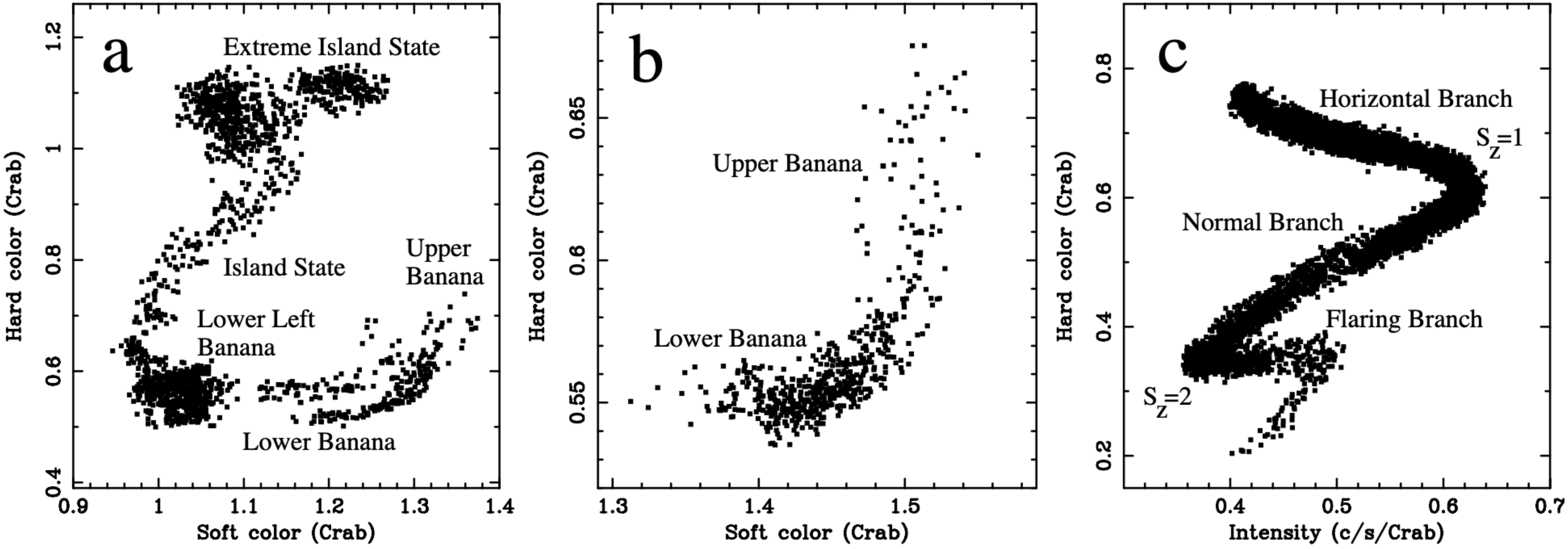


Grinberg 2013

Neutron star LXMBs

Atoll source

Z source



Van der Klis et al. 2006
(on ArXiv: 2004)

Neutron star LXMBs

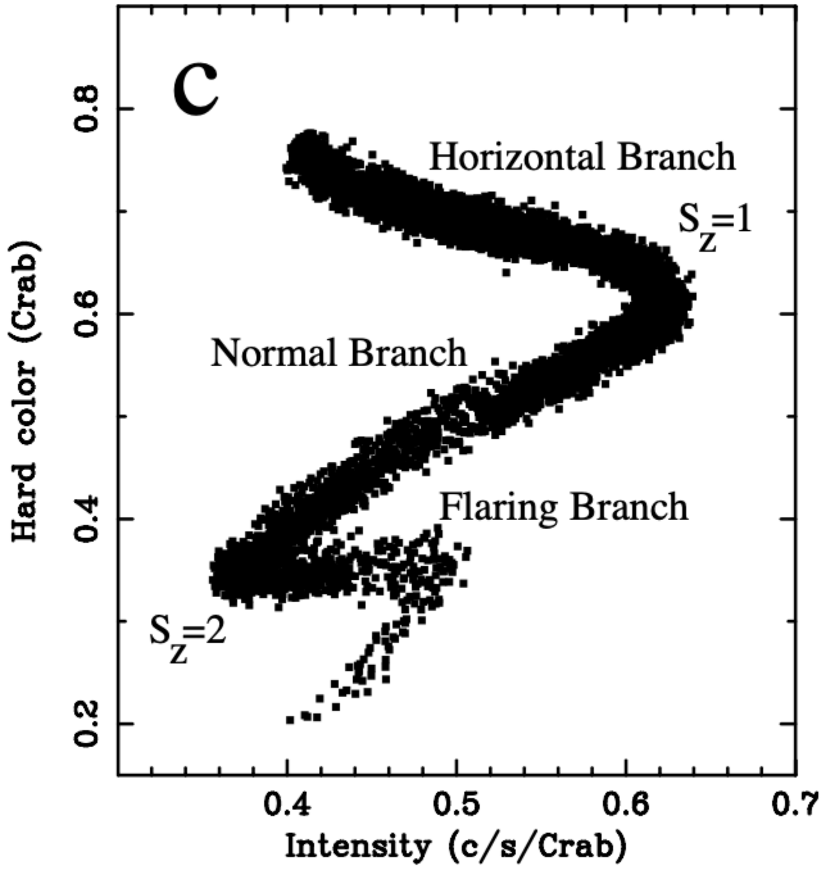
Z-sources

High luminosity LMXBs, close to Eddington luminosity

horizontal branch: strong variability, Horizontal branch oscillations (~50 Hz)

normal branch: weaker variability

flaring branch: mostly thermal spectrum



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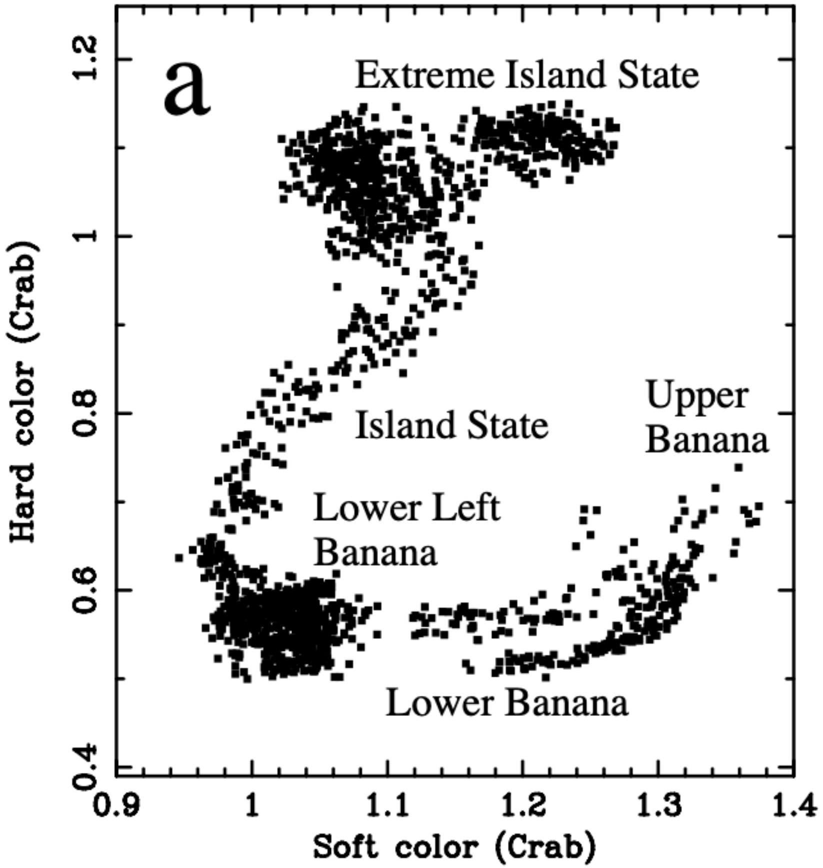

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Atoll sources

usually lower luminosity than X-sources

banana state: higher luminosity, low frequency noise dominates variability

island state: lower luminosity, high frequency noise dominates variability

rough correspondence to soft+hard states

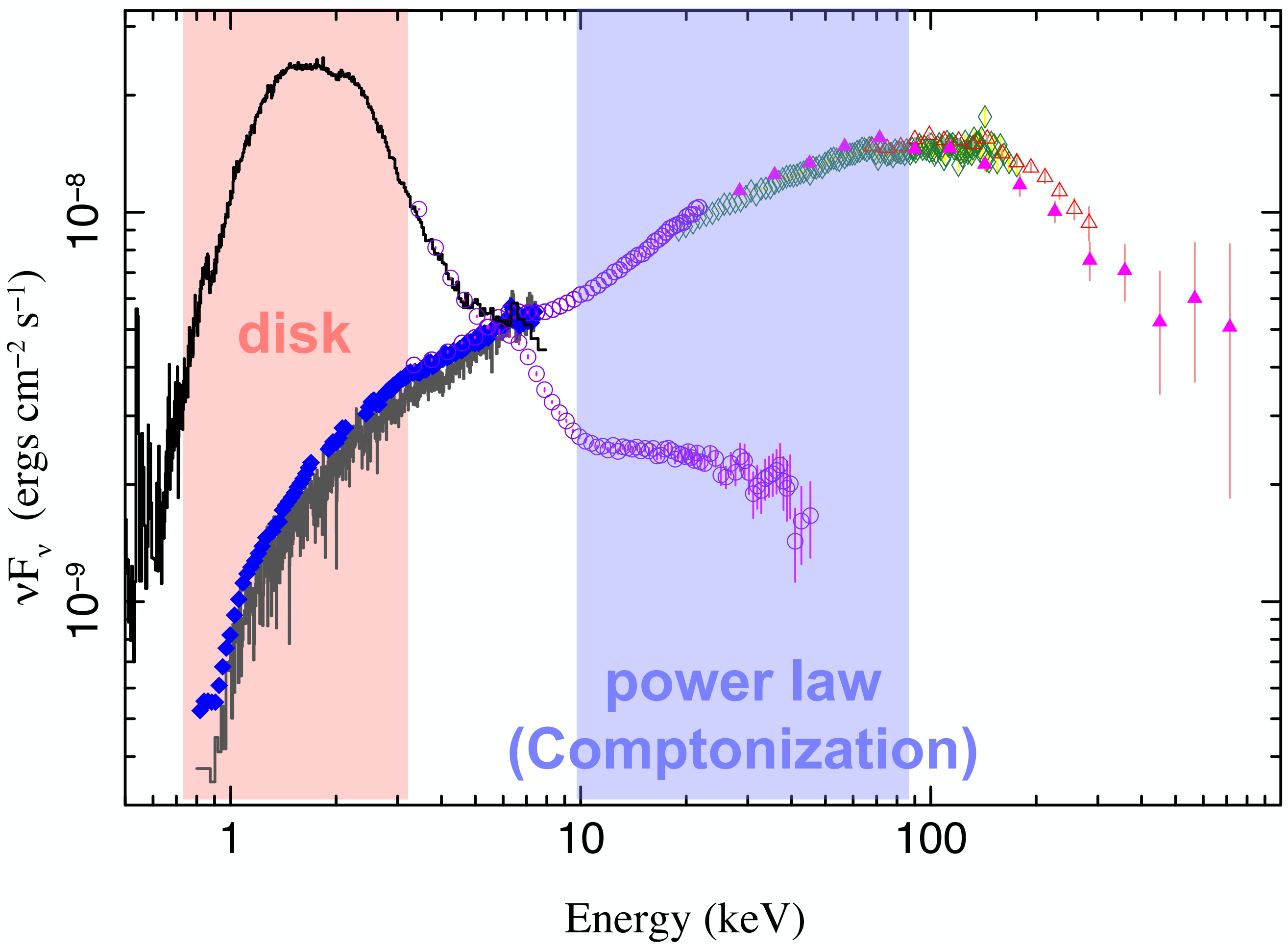
source movement: timescales of days-weeks, faster in banana state

Questions?

Questions?

Next: physics & open questions

Continuum formation



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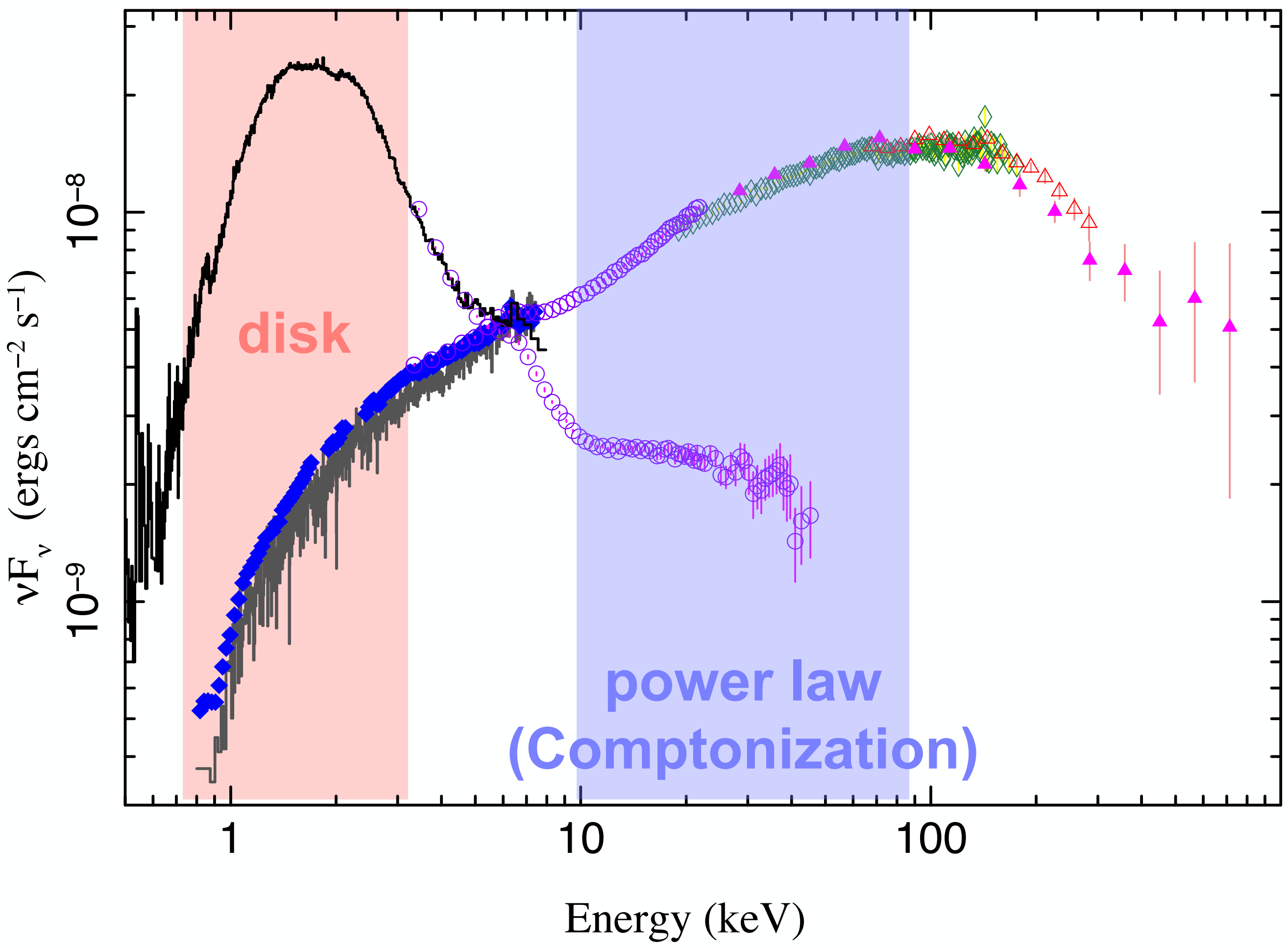
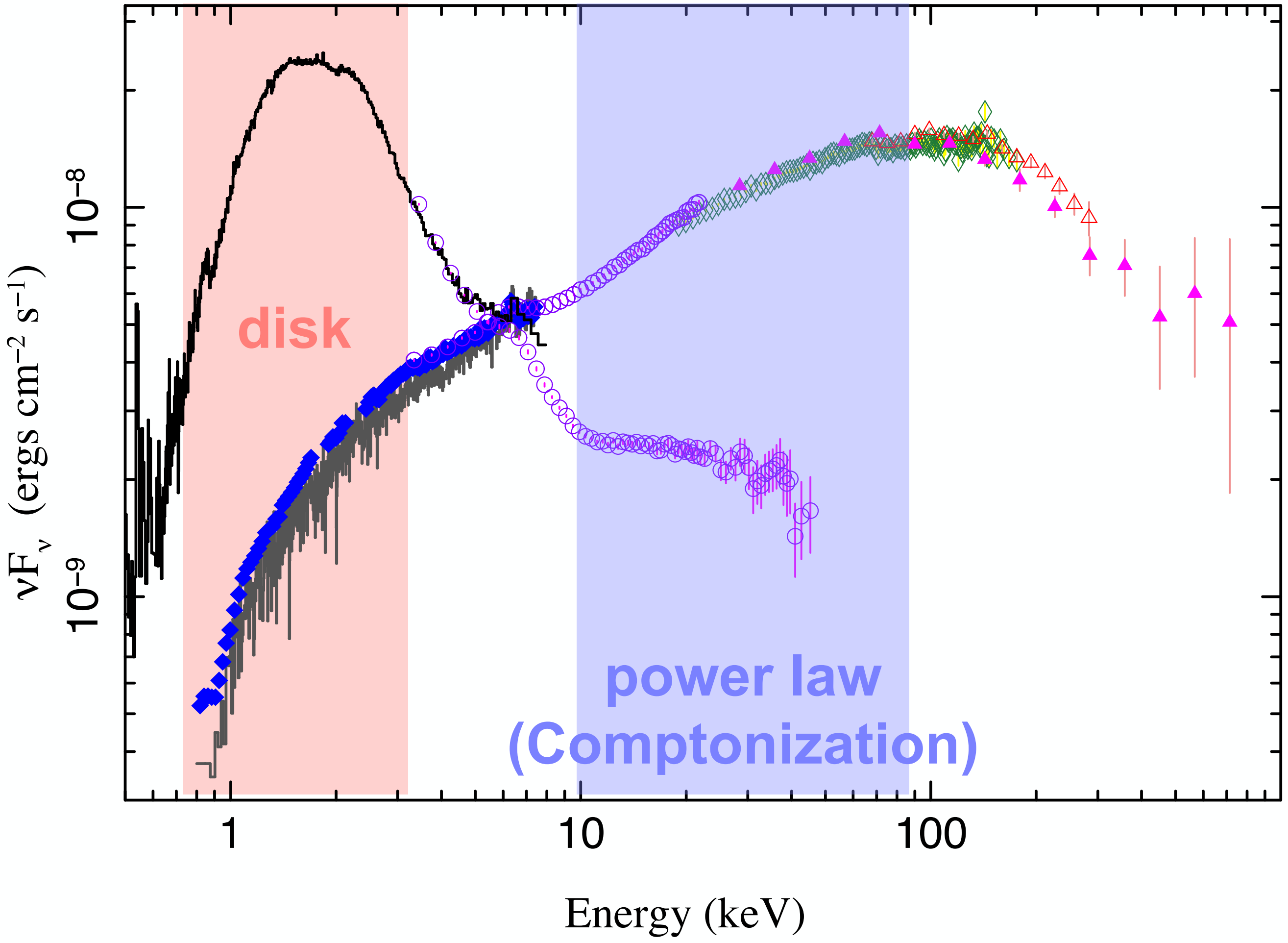


above 10 keV:

- ➤ exponentially cutoff power law
- ➤ cutoff: 50-300 keV for black holes, less for neutron stars
- ➤ non-thermal hard tails in some sources

Continuum formation



above 10 keV:

- exponentially cutoff power law
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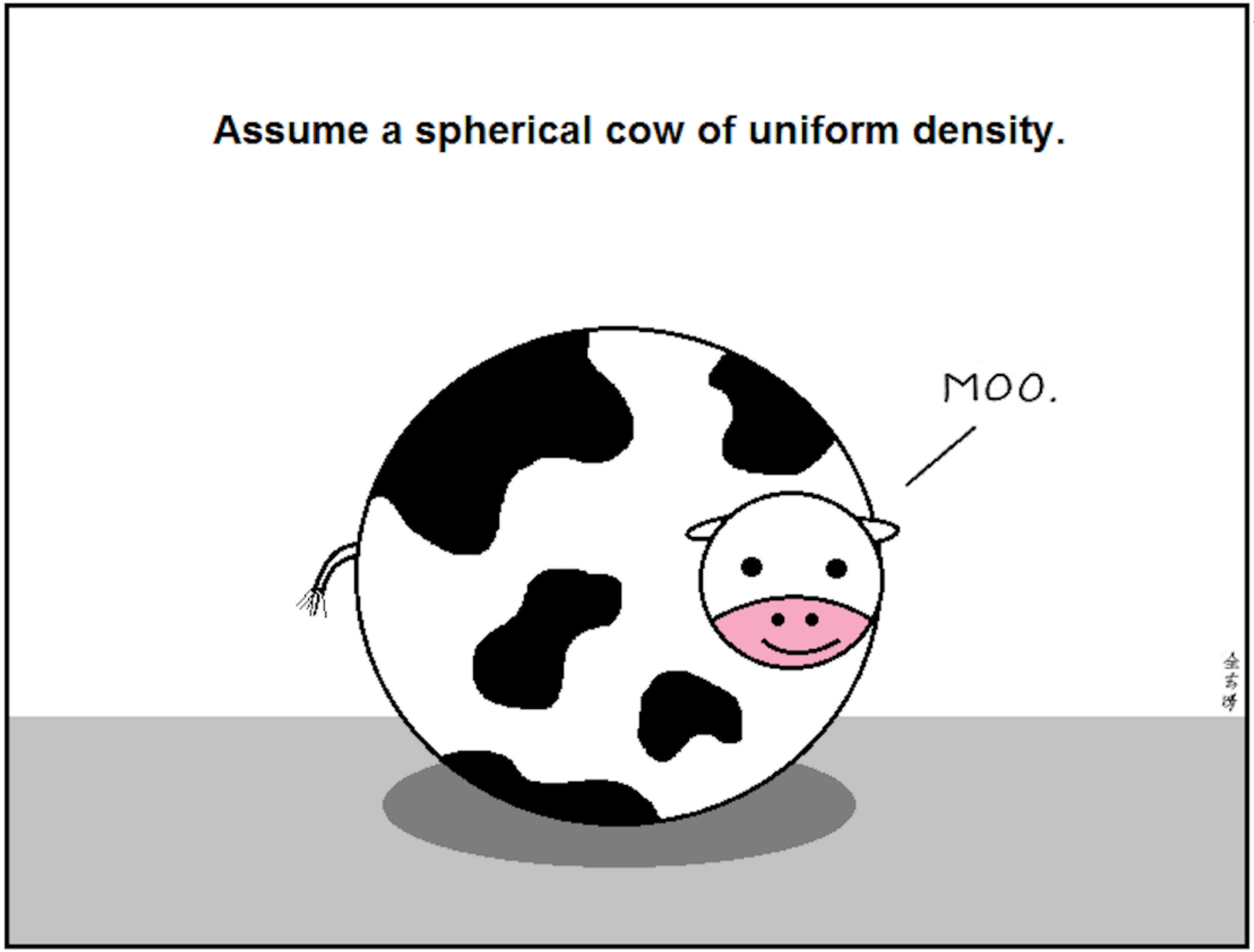
below 10 keV:

- sum of power law + disk contribution
- emission lines (esp. iron line)
- absorption

Continuum formation



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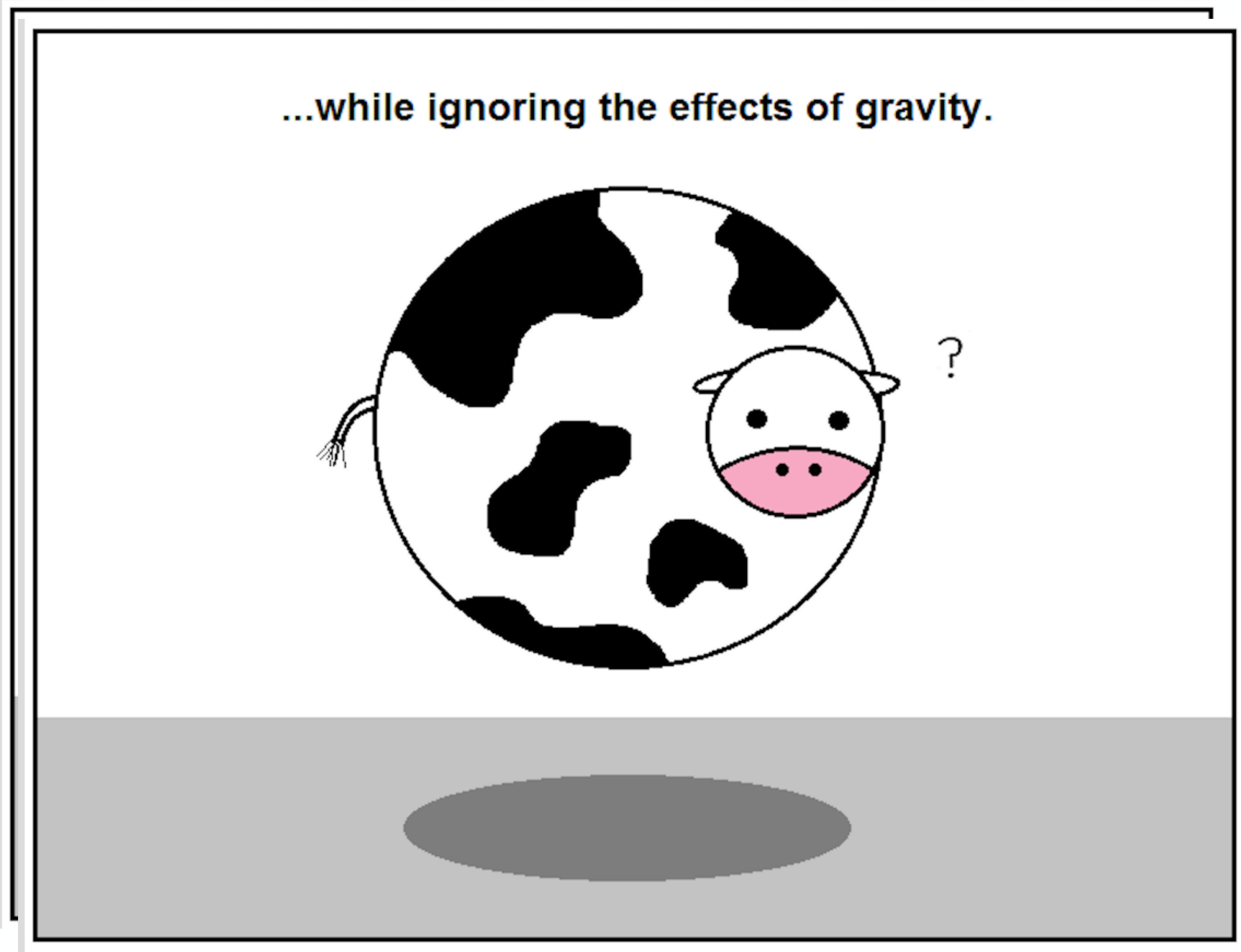

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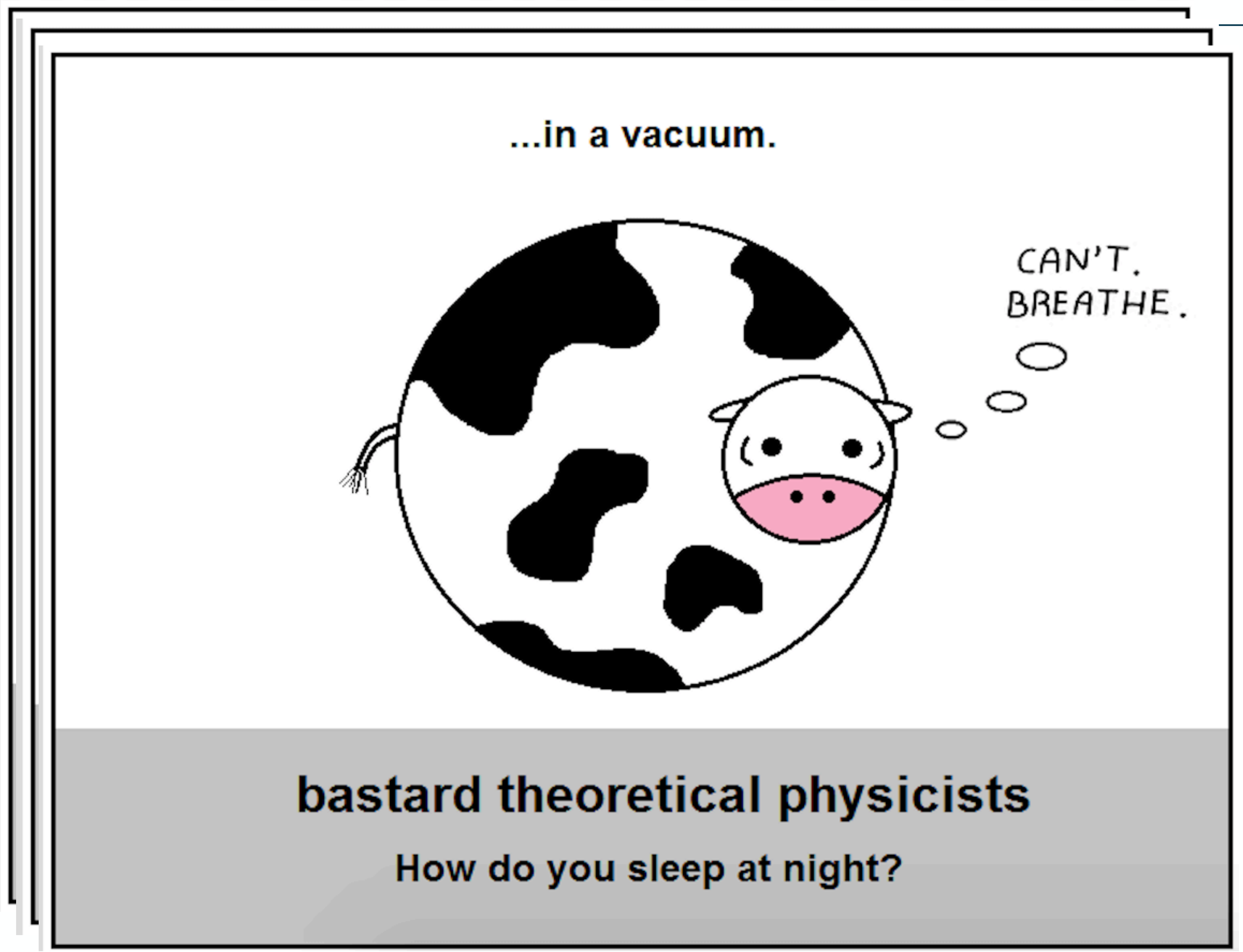

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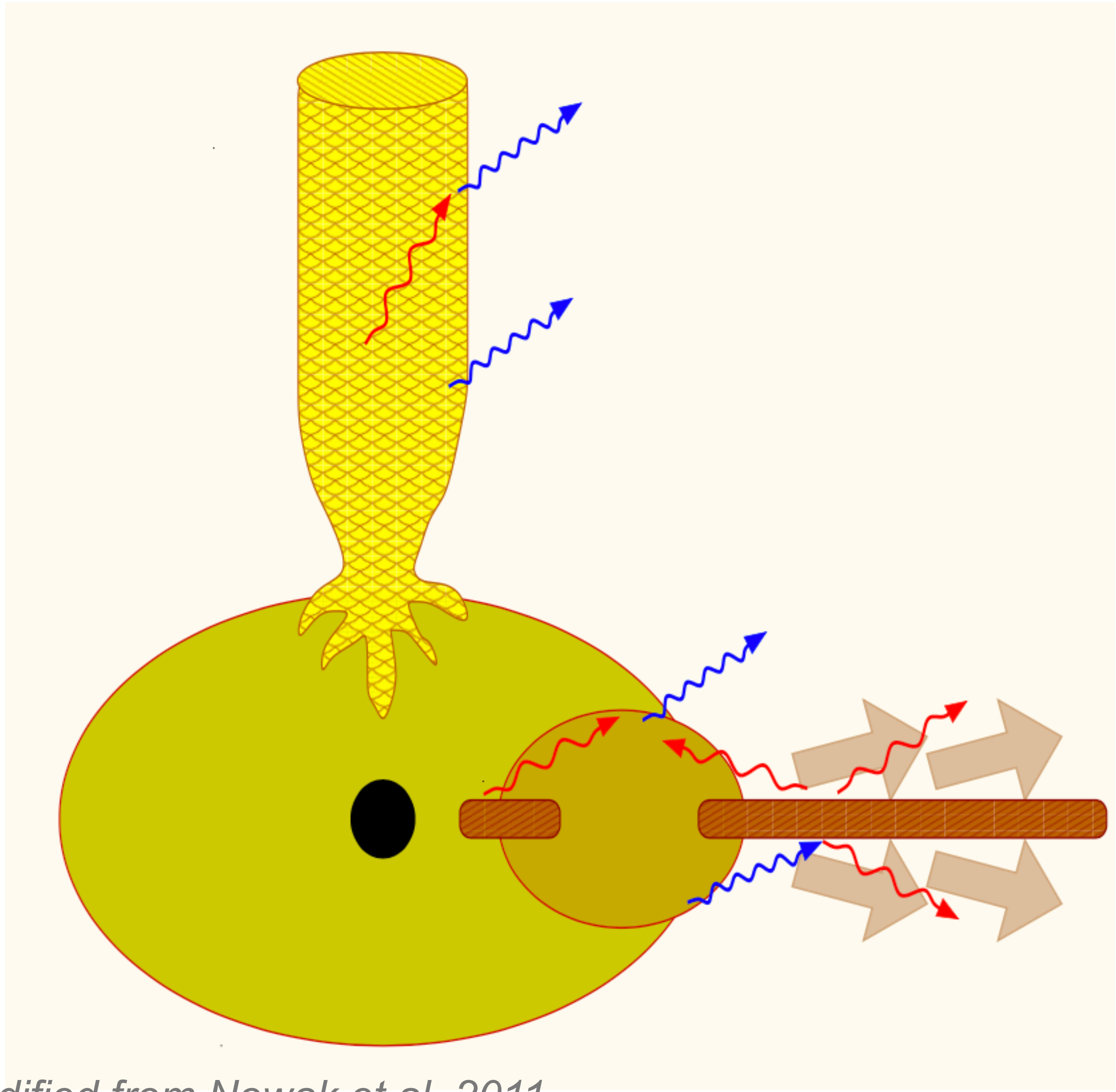


Modified from Nowak et al. 2011

corona models:

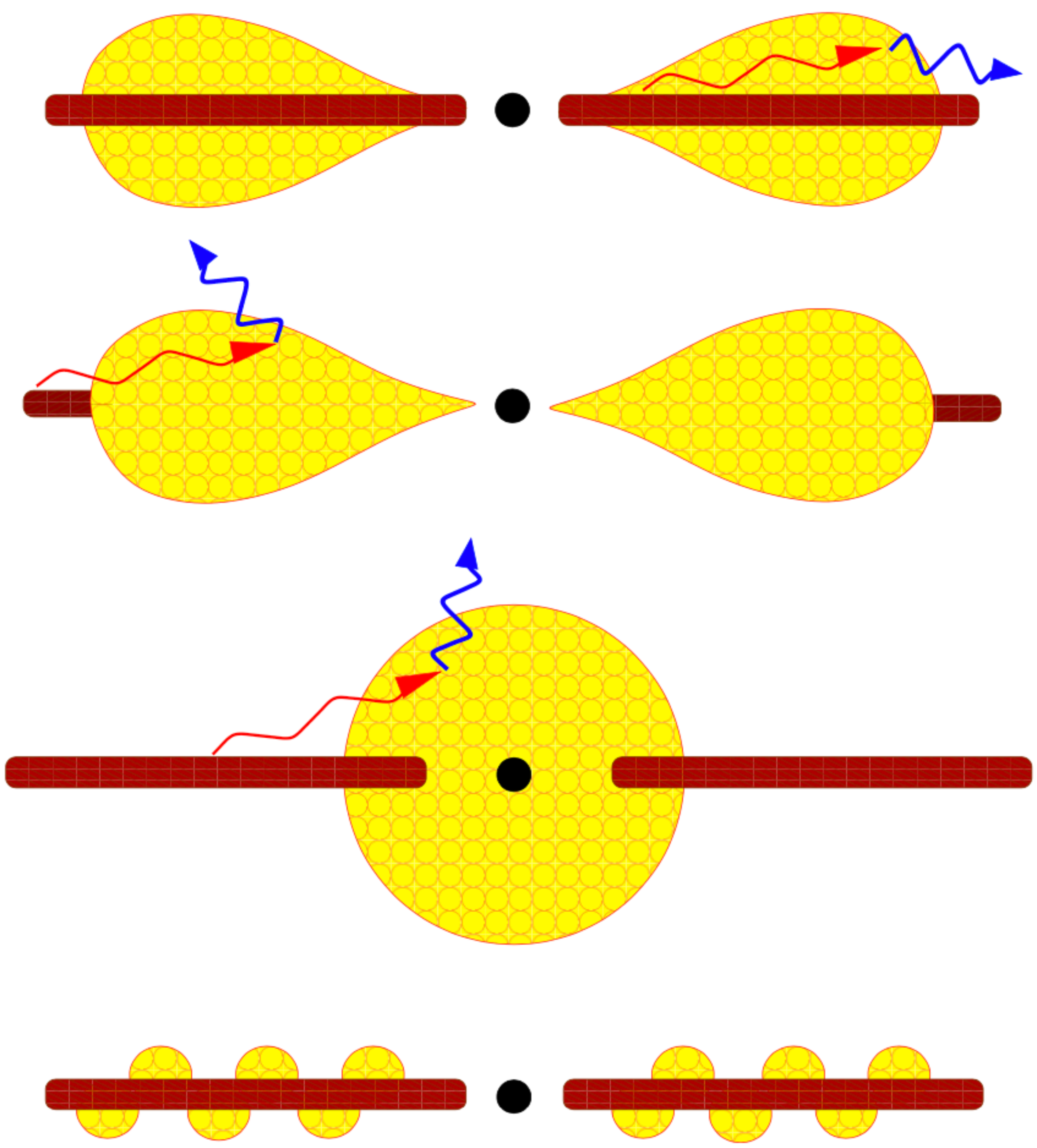
➤ Comptonization from a hot electron plasma surrounding the disk (Haardt & Maraschi (1991), Dove+ (1998), ….)

lamppost models:

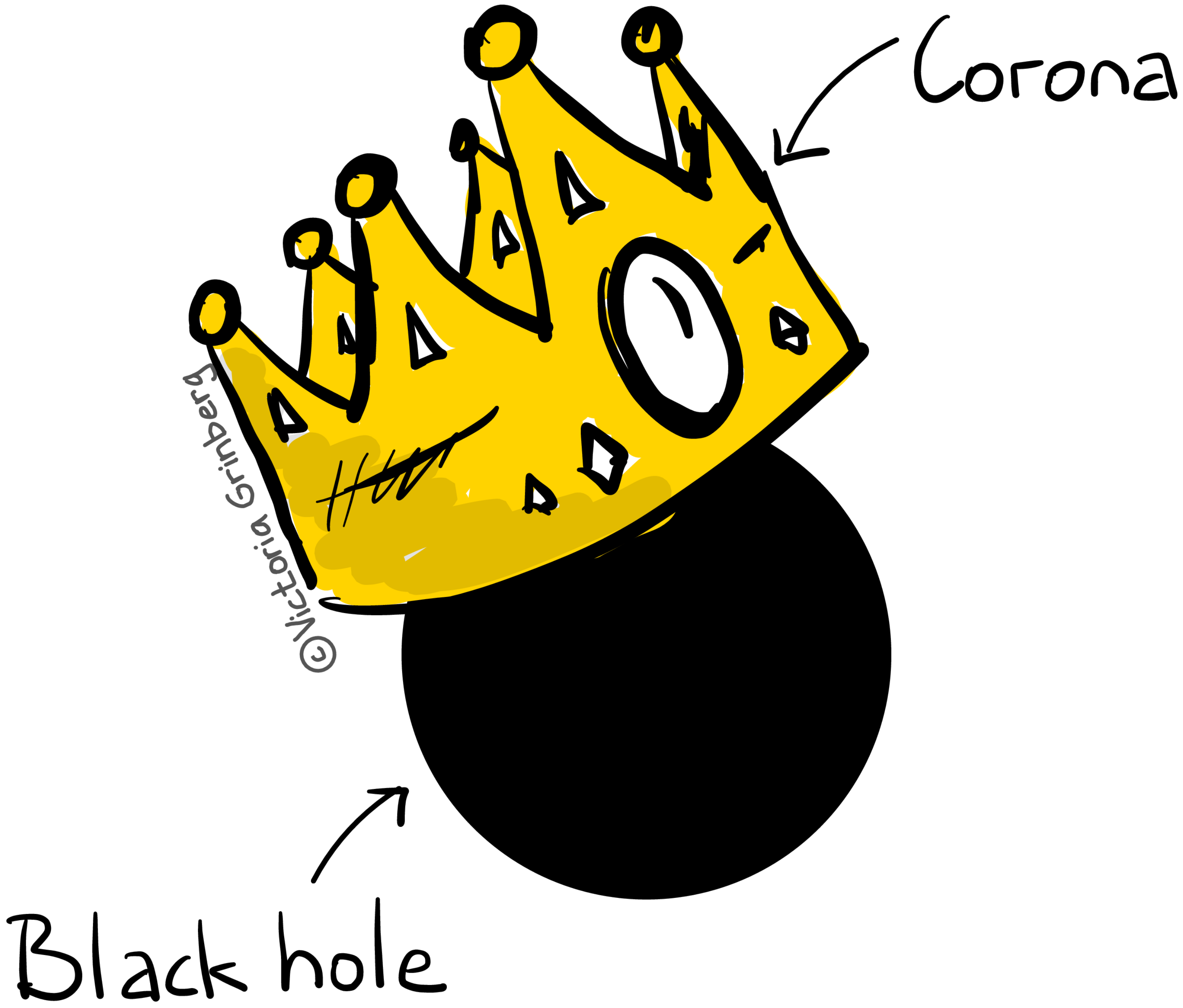
➤ Comptonization from the base of a jet (Matt+ (1992), Markoff+ (2005), ….)

… or is the base of the jet the corona?

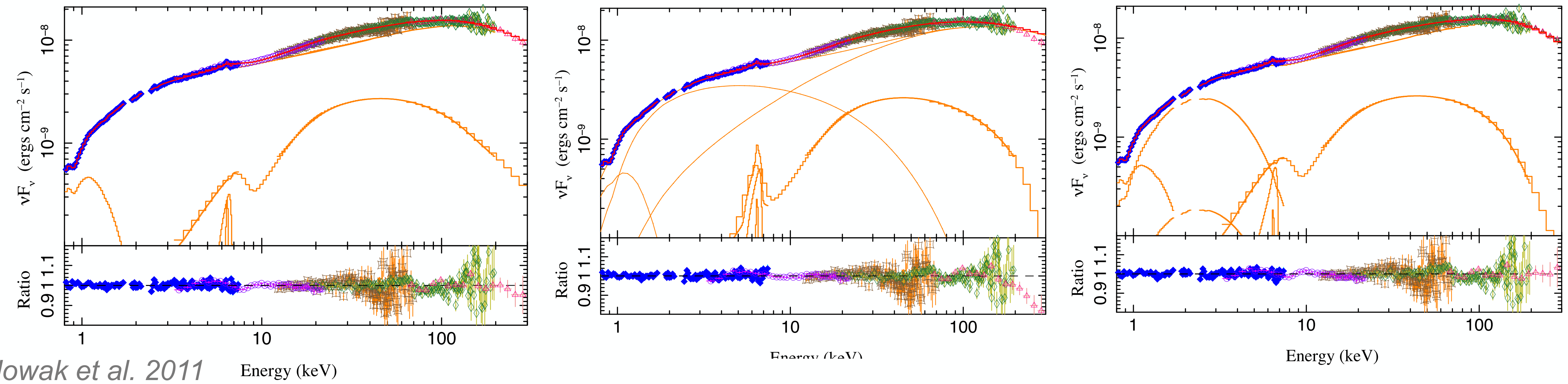
Coronal geometry is still one of the (THE?) big questions!



Reynolds & Nowak 2003


Corona
Black hole
©Victoria Grinberg

Continuum formation



Nowak et al. 2011

- ➤ Different spectral models result in similar statistical significance -> pure (continuum) unlikely to solve the problem
- ➤ multiple high end models (comptonization models, JED - Petrucci & al., agnjet - Markoff & al.)
- ➤ other approaches: multi-method approaches (spectro-timing, polarization), reflection features (iron lines), …

Relativistically broadened iron lines

Most black holes & many neutron star X-ray binaries show reflection components and relativistically broadened iron lines (and so do AGN!); sometimes (detectable) only in certain states

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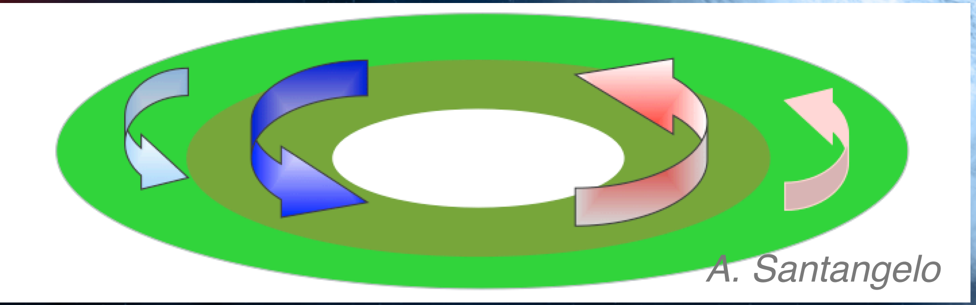

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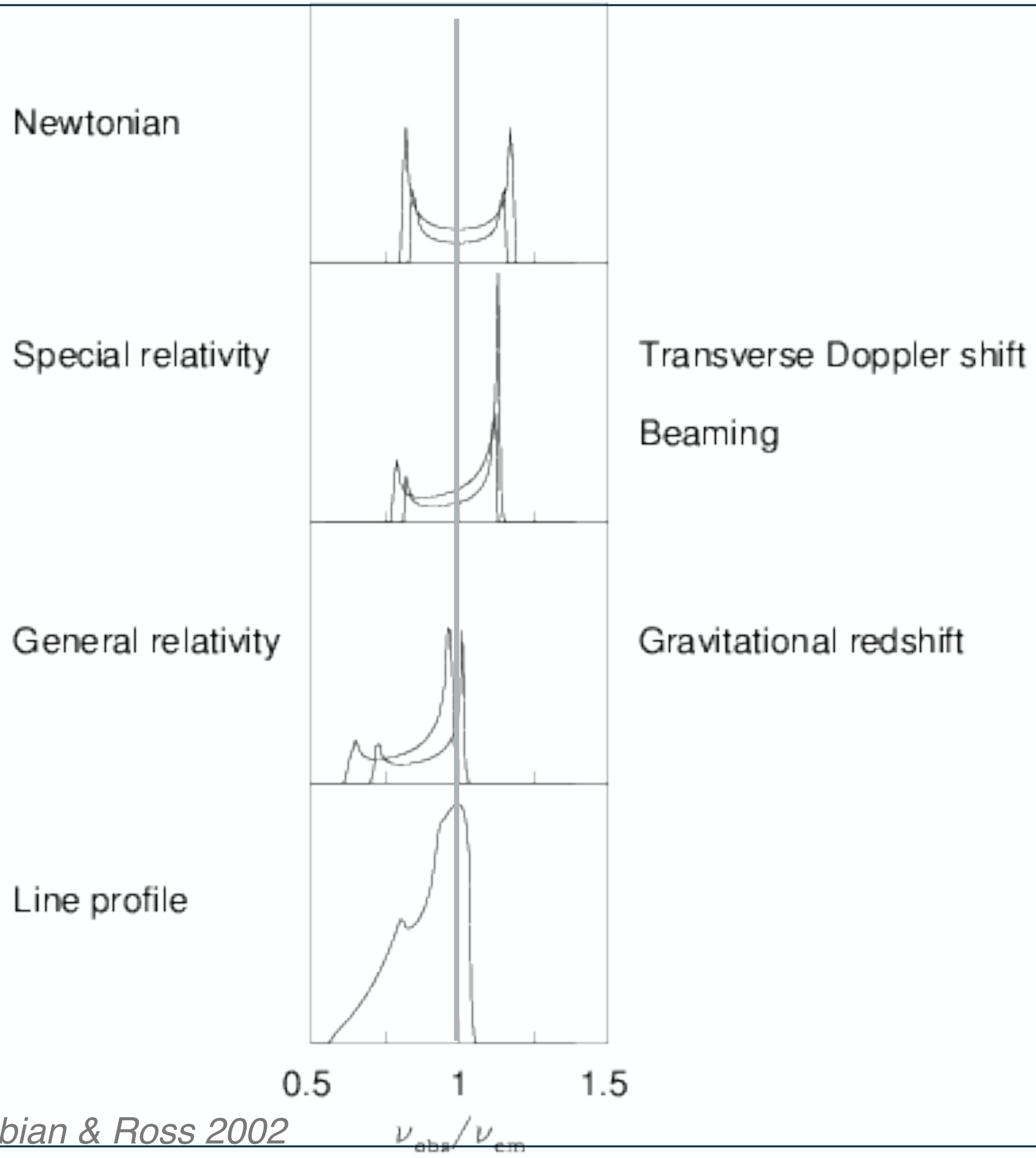
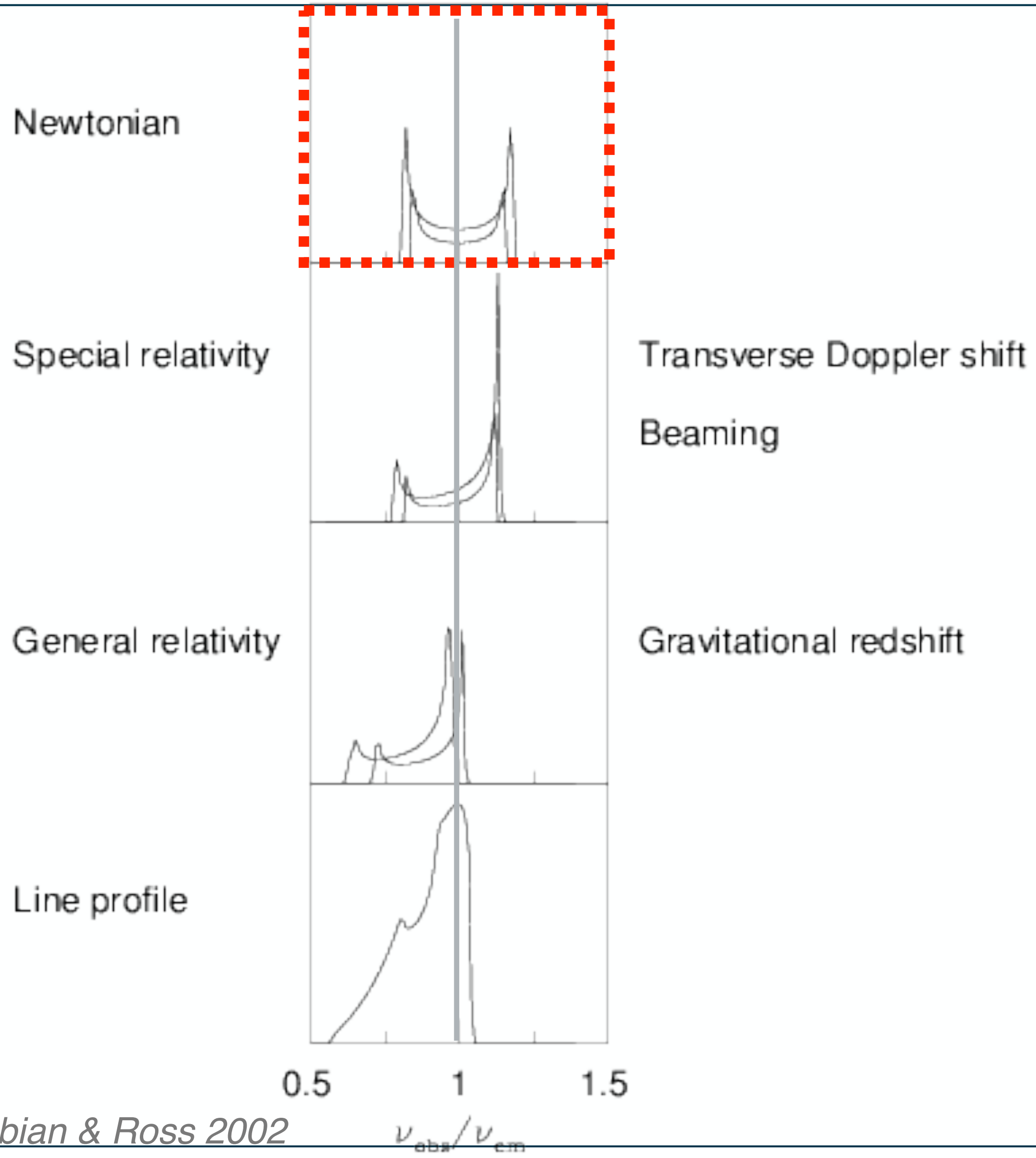


Fabian & Ross 2002

A. Santangelo

Relativistically broadened iron lines



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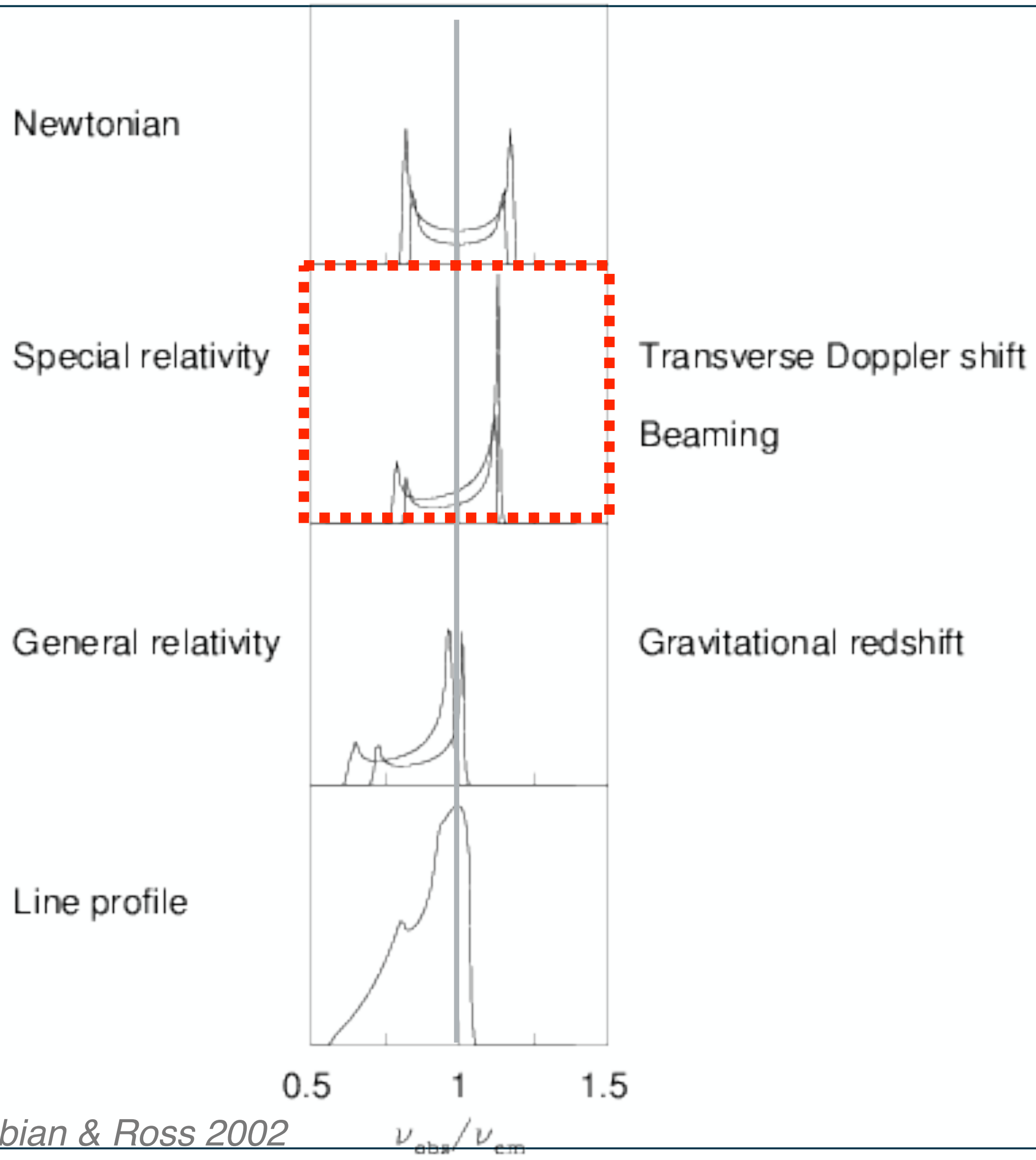

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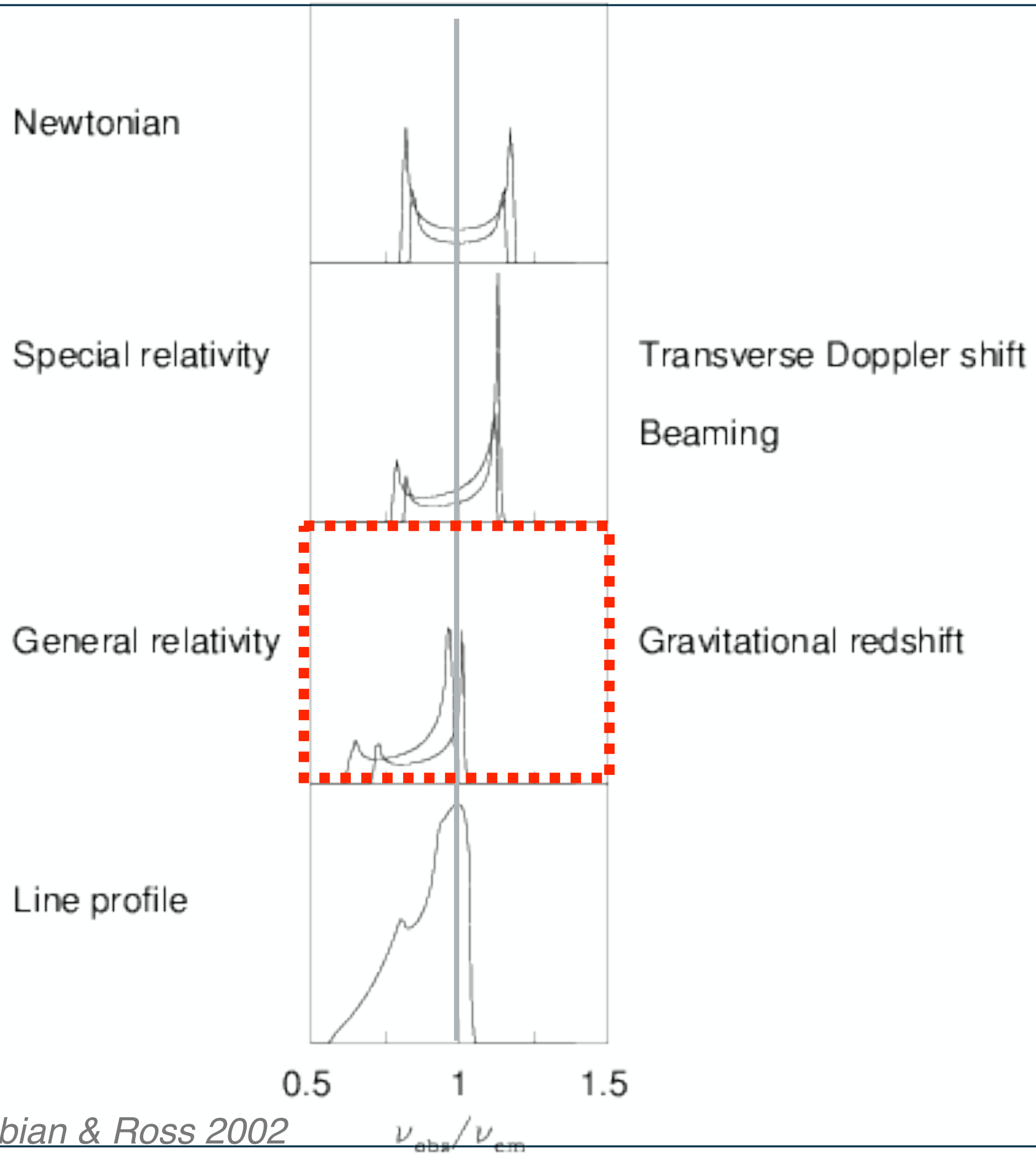

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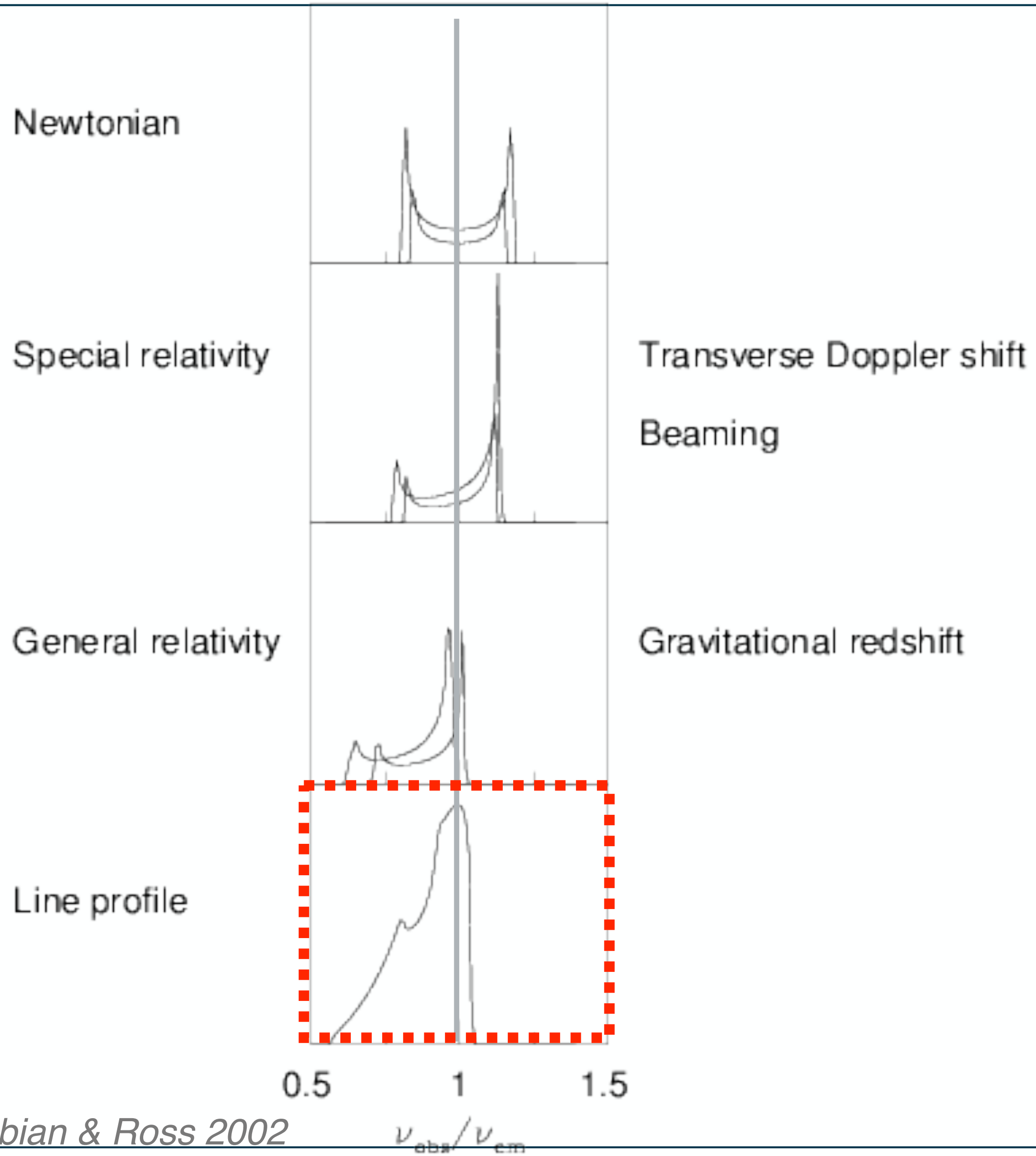

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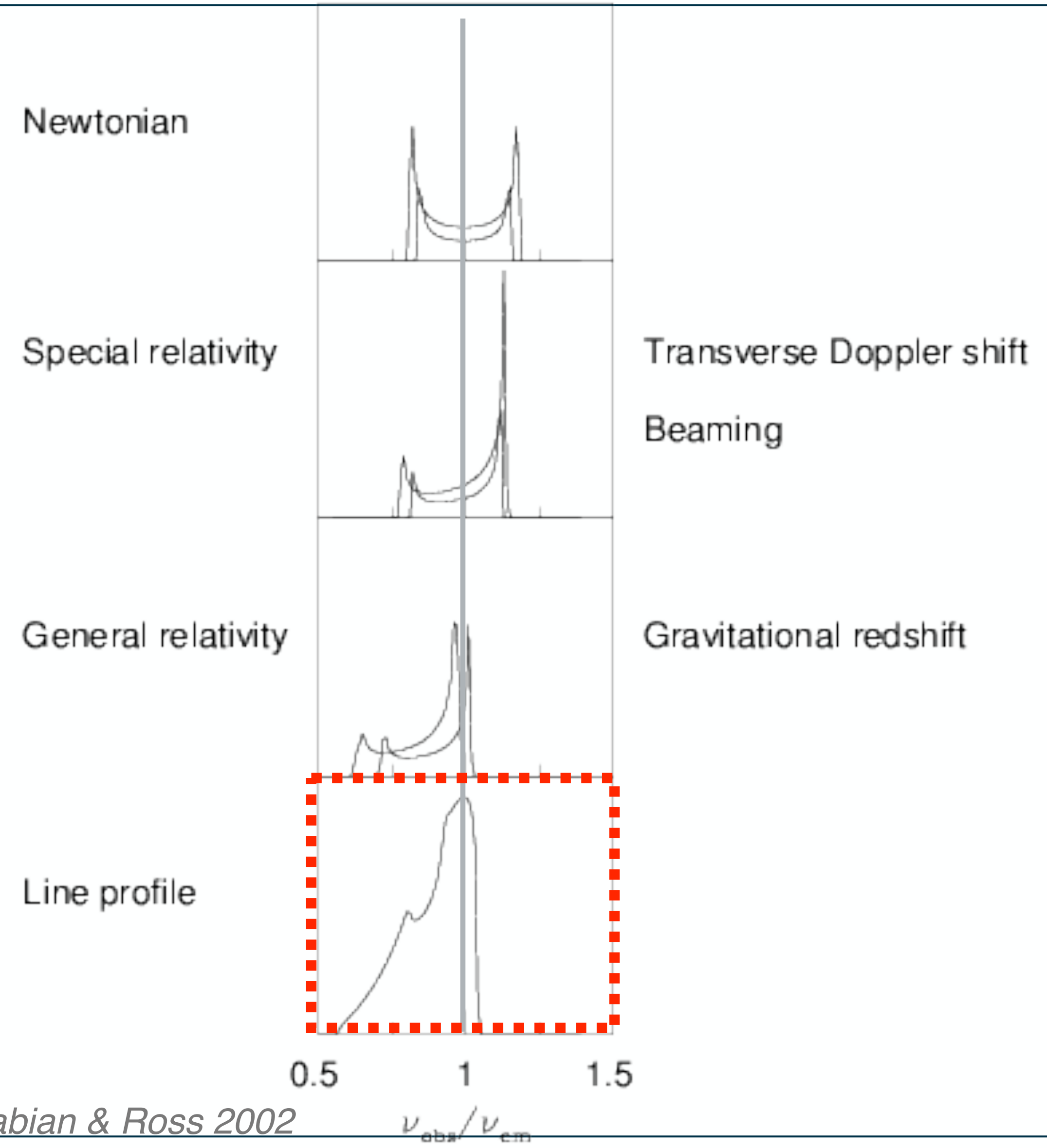

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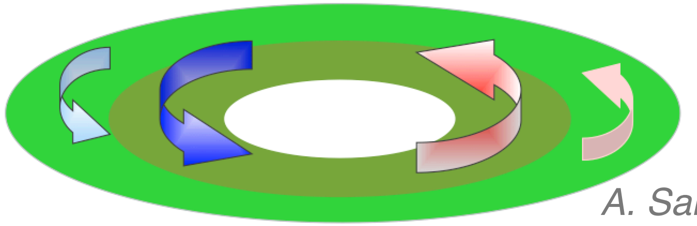

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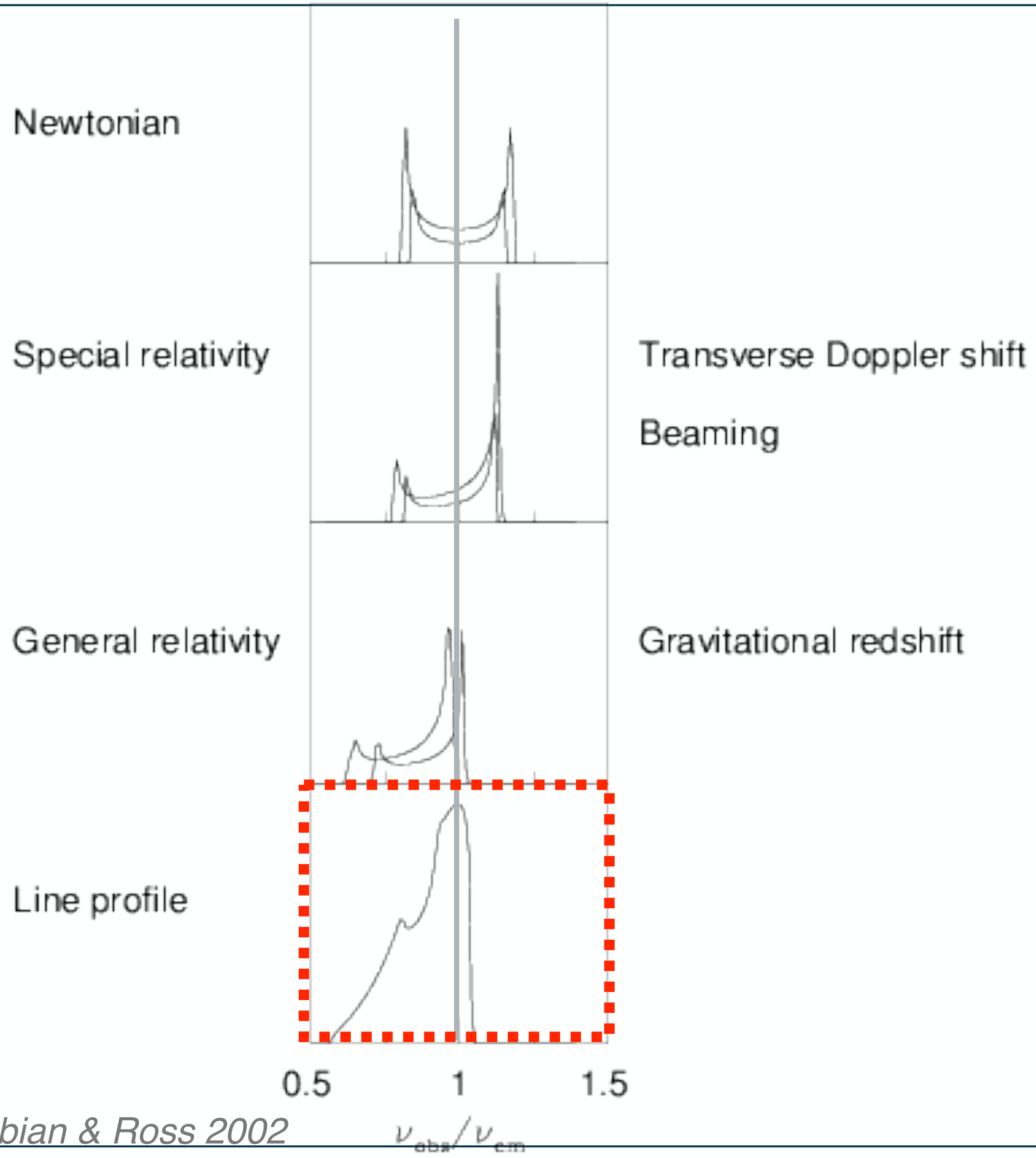

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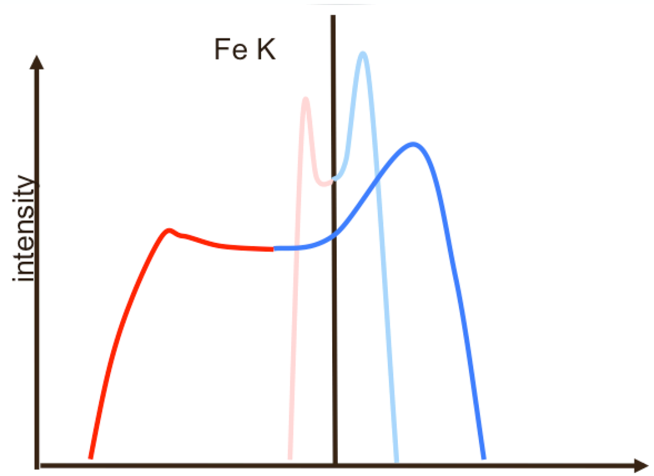

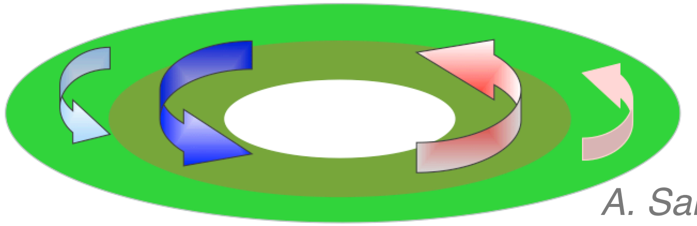

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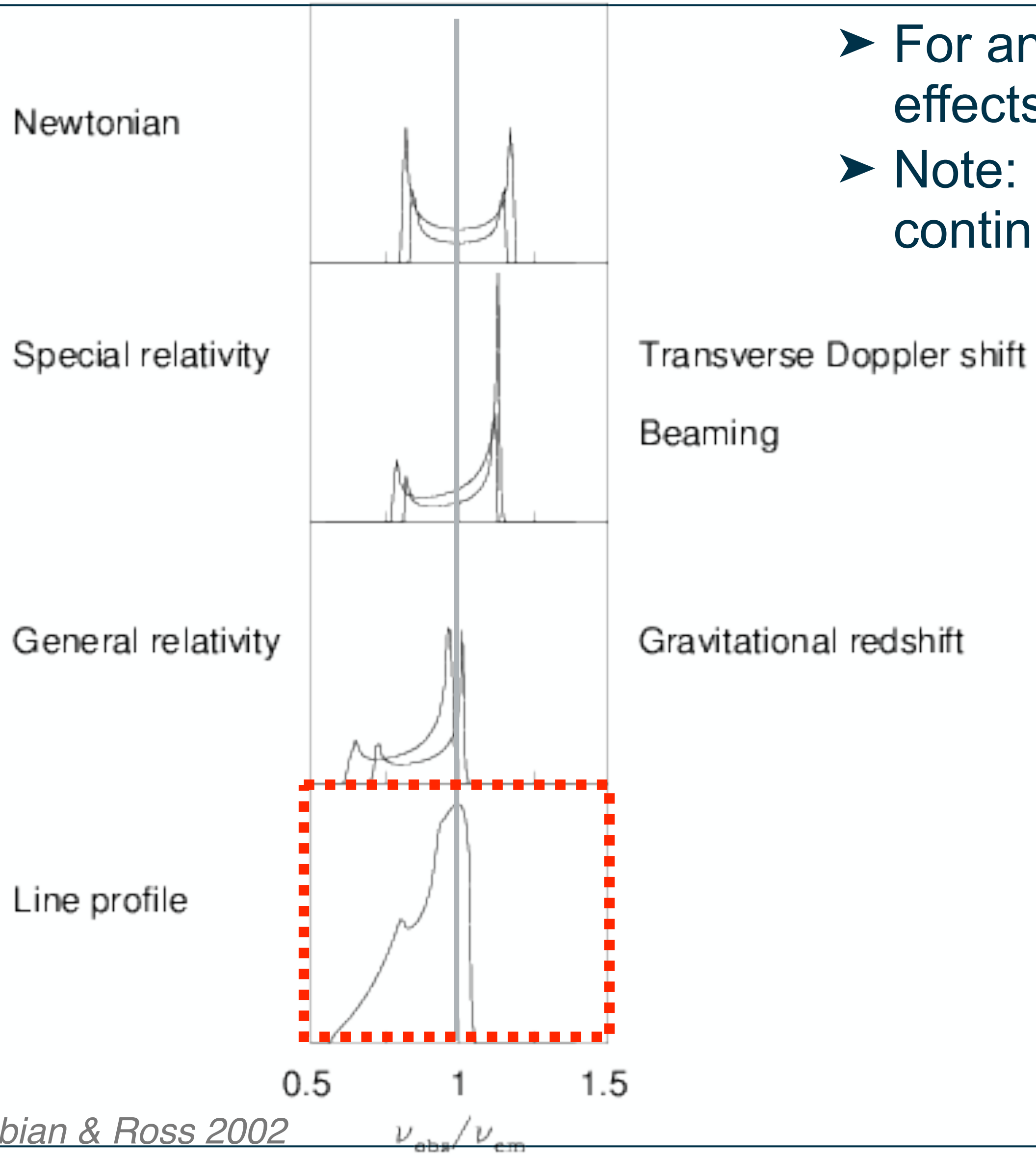
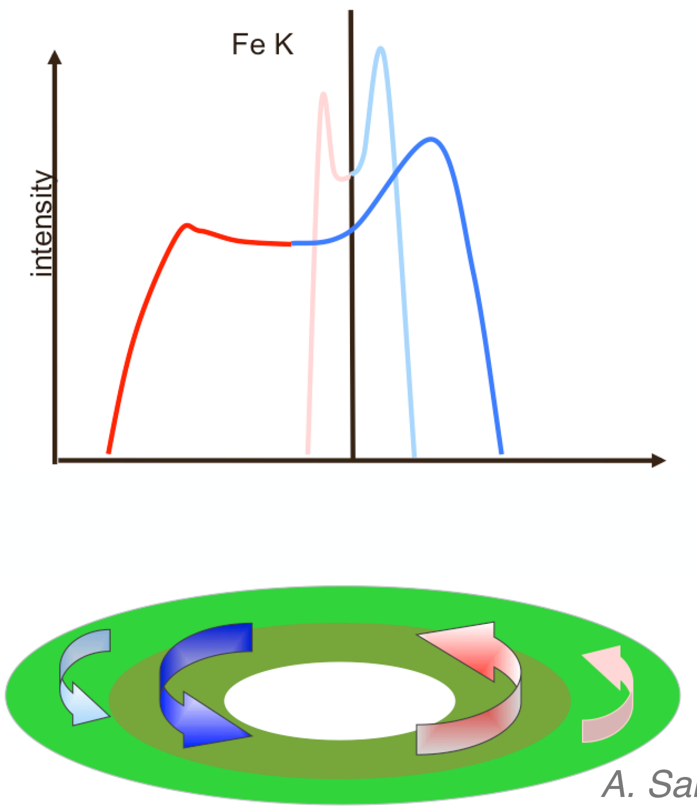


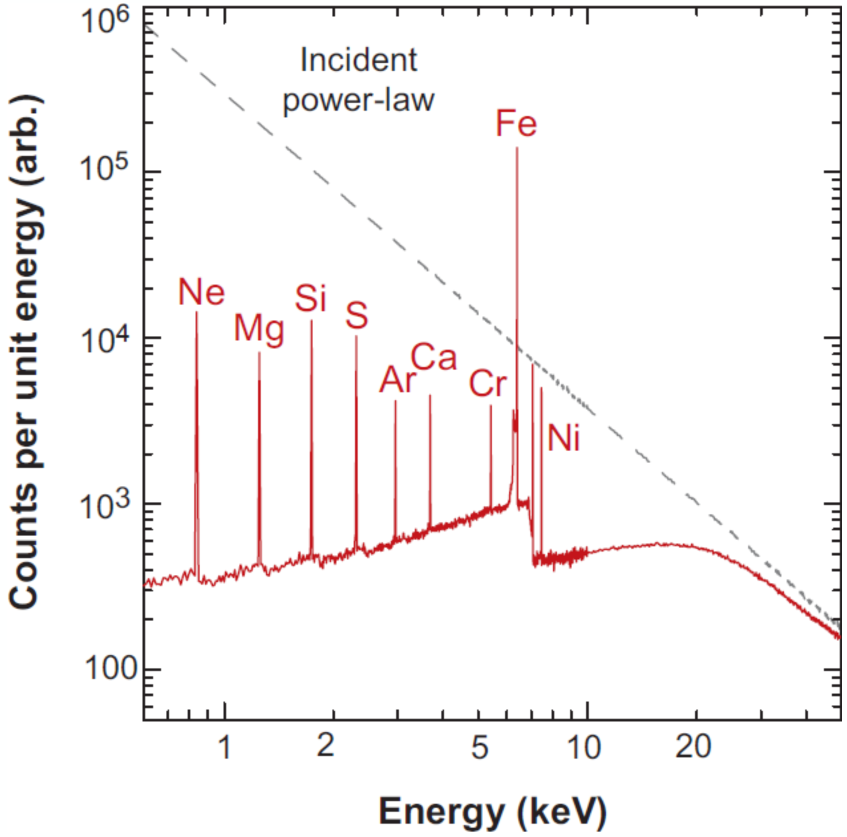
Fabian & Ross 2002

- ➤ For an emission line close to the compact object, relativistic effects will lead to changes in its shape
- ➤ Note: relativistic effect affect all emission, not just lines! -> continuum fitting method for spin measurements



A. Santangelo

X-ray Reflection



Miller 2007 after Reynolds 1996

neutral disk irradiated by power law

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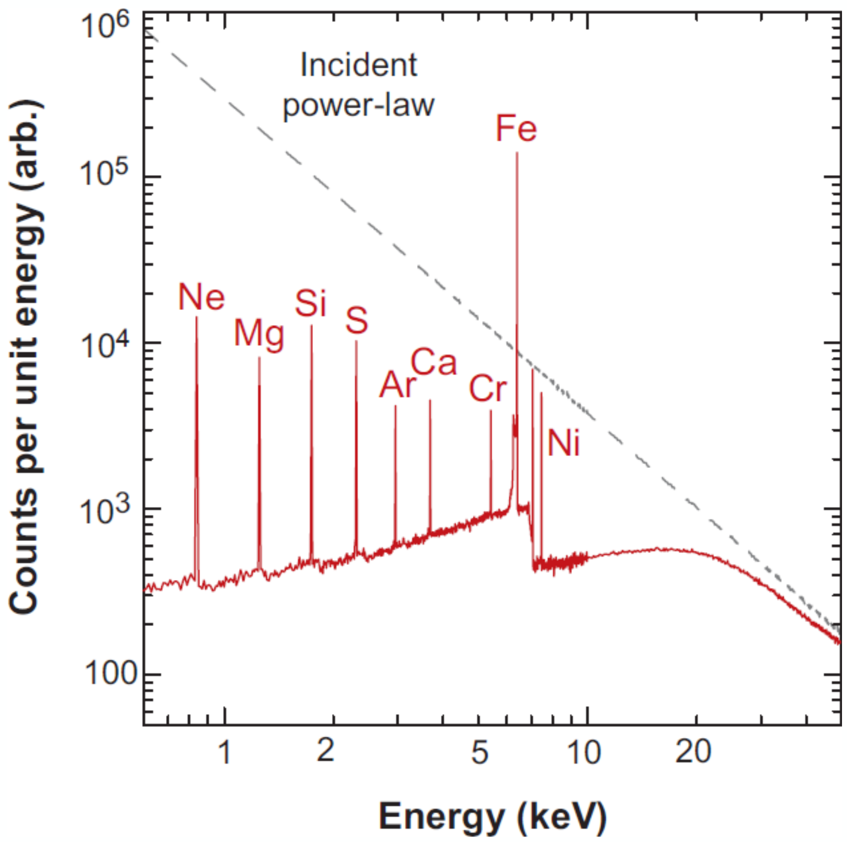

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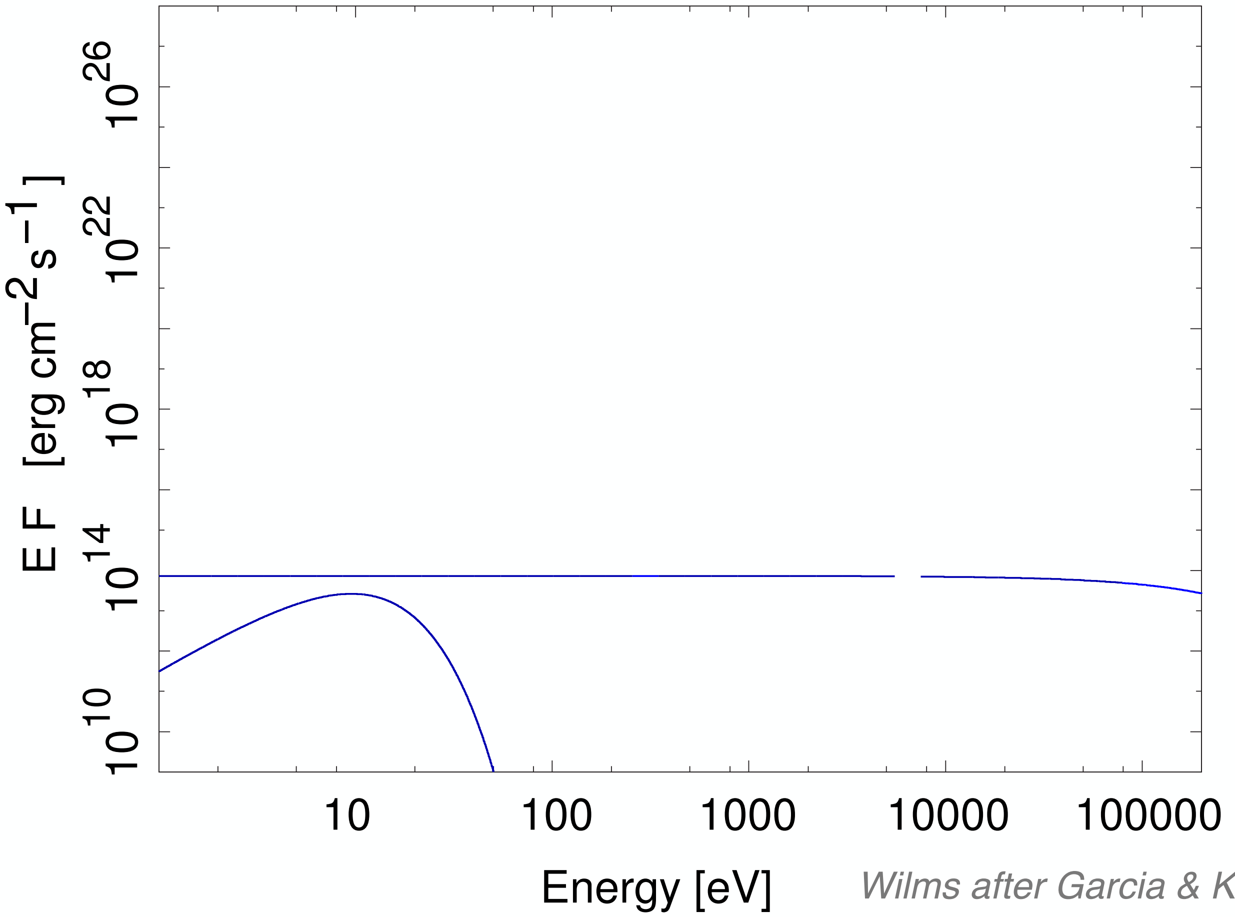

Wilms after Garcia & Kallman, 2010

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ionization parameter $\xi = 4\pi F_{\mathrm{x}}/n_e$

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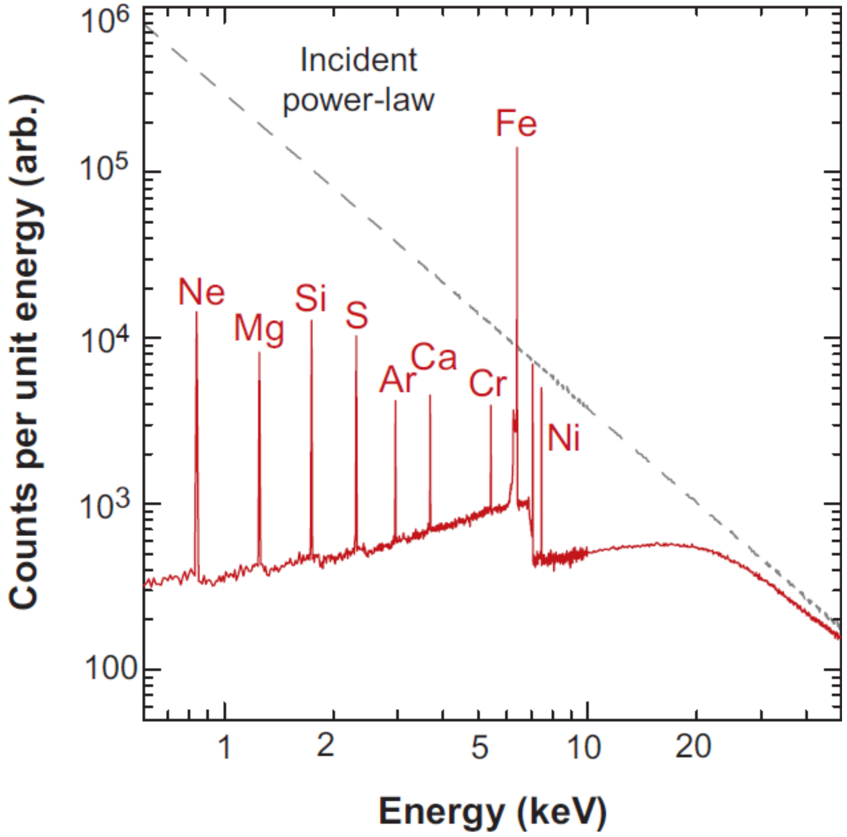

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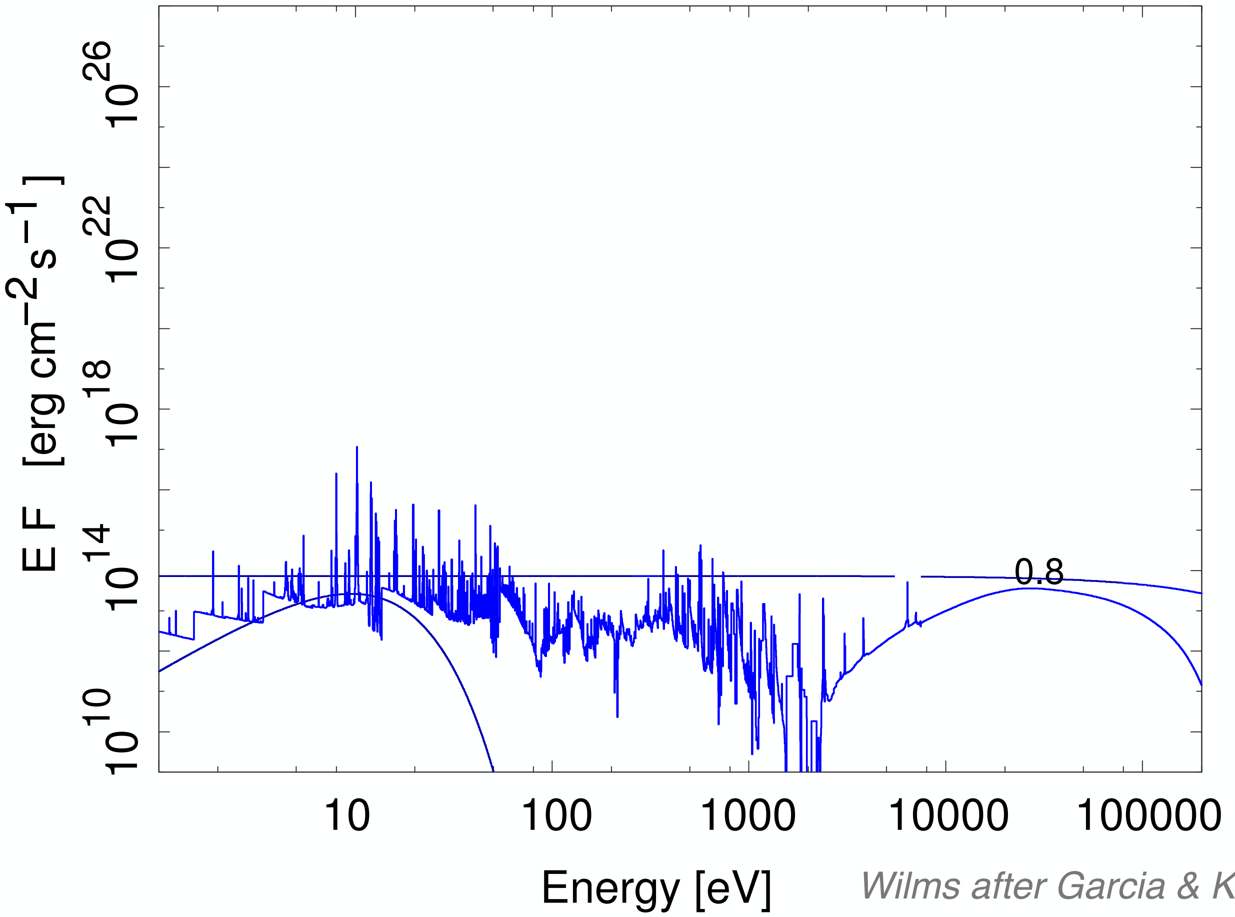

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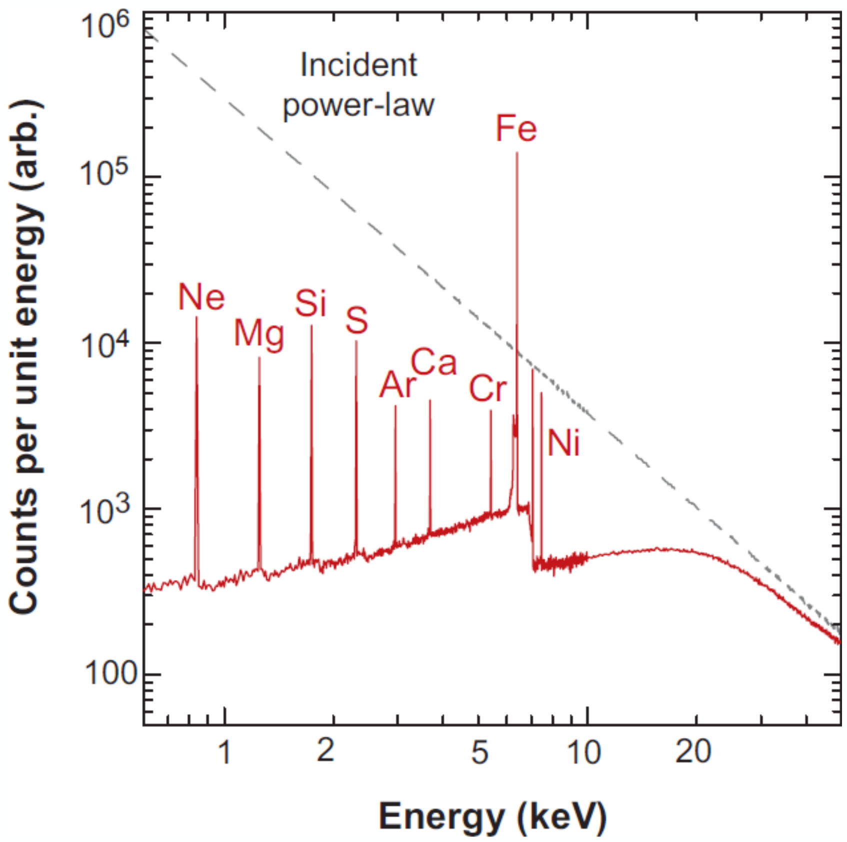

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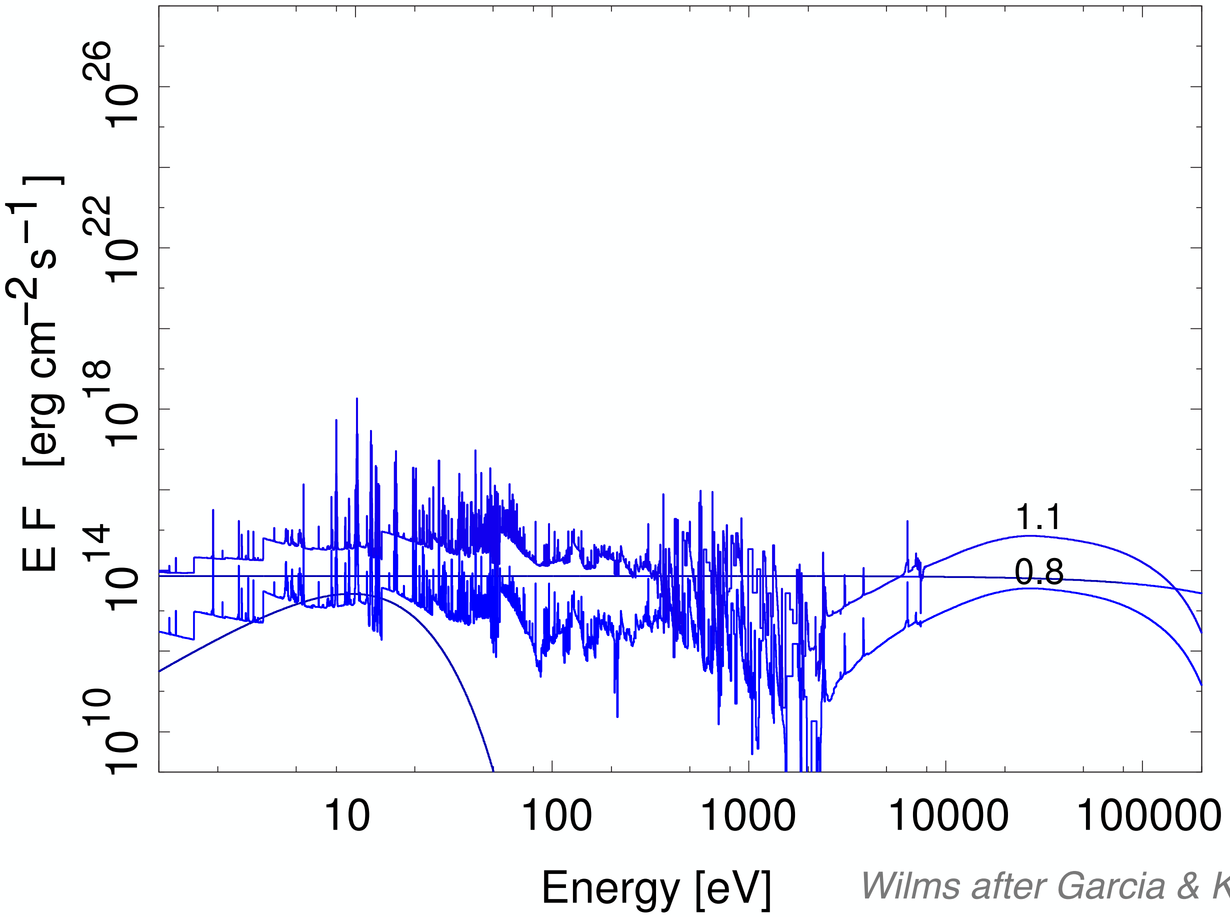

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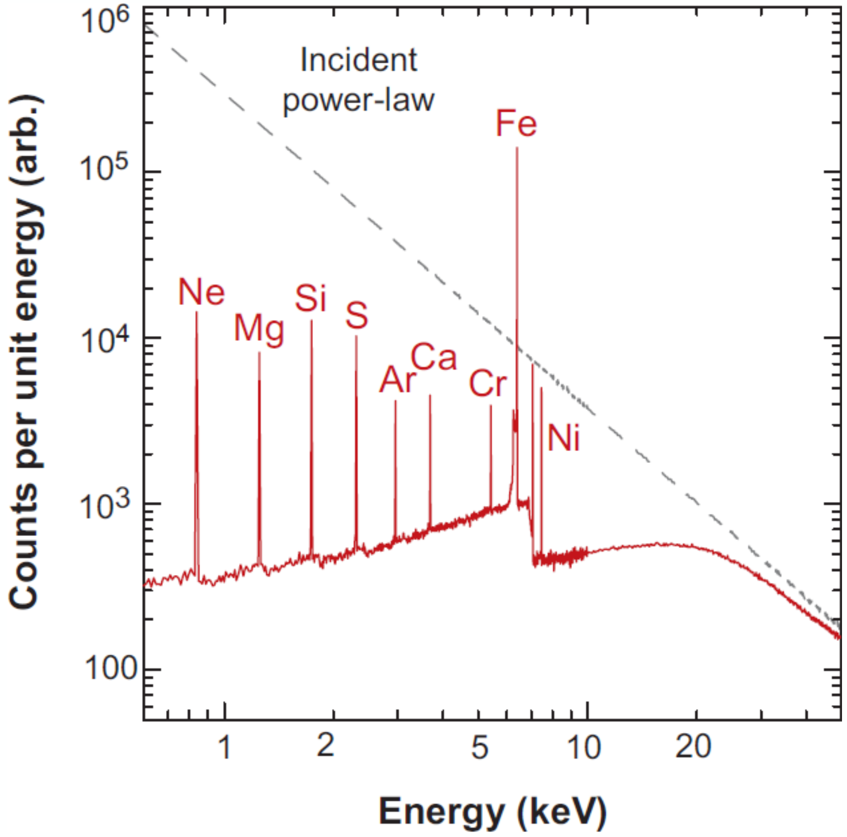

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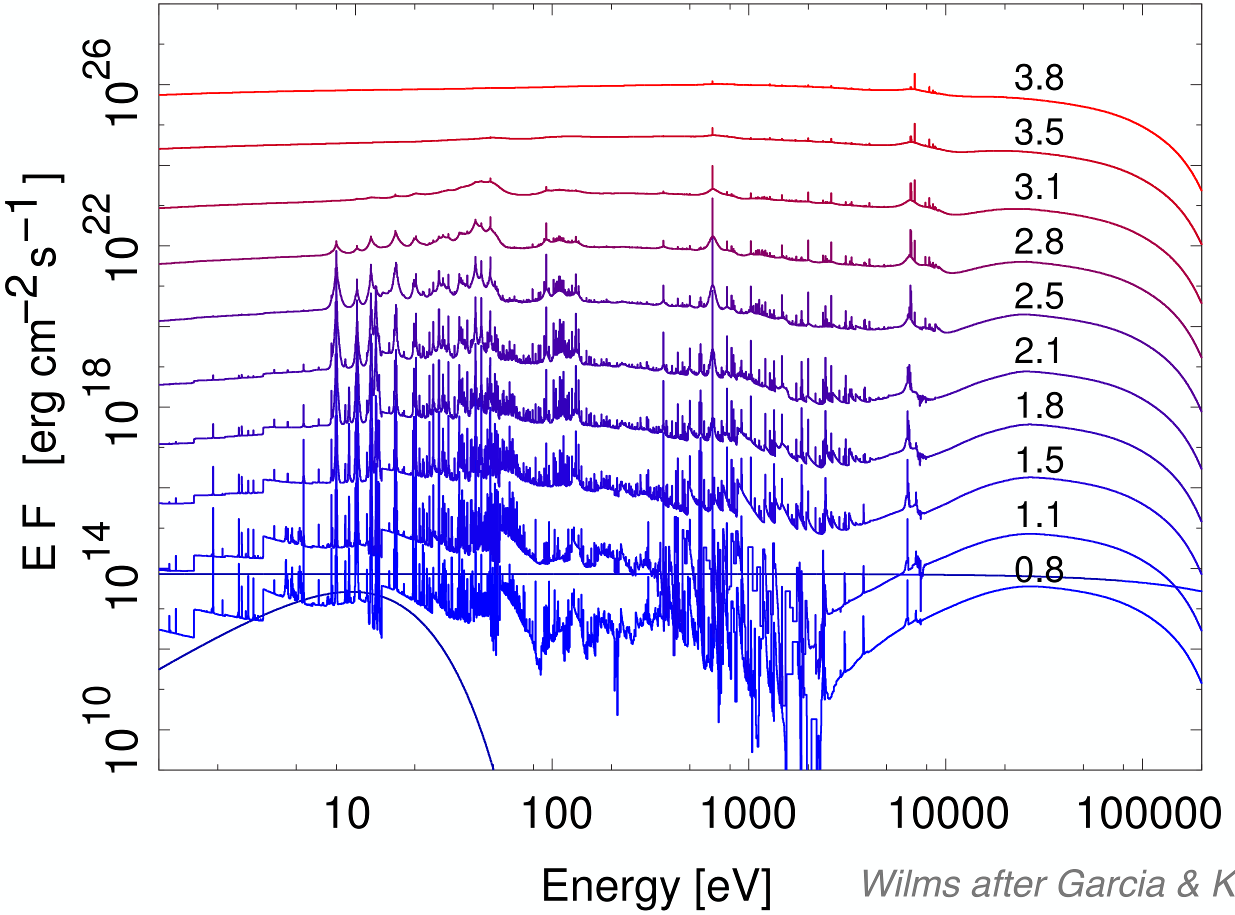

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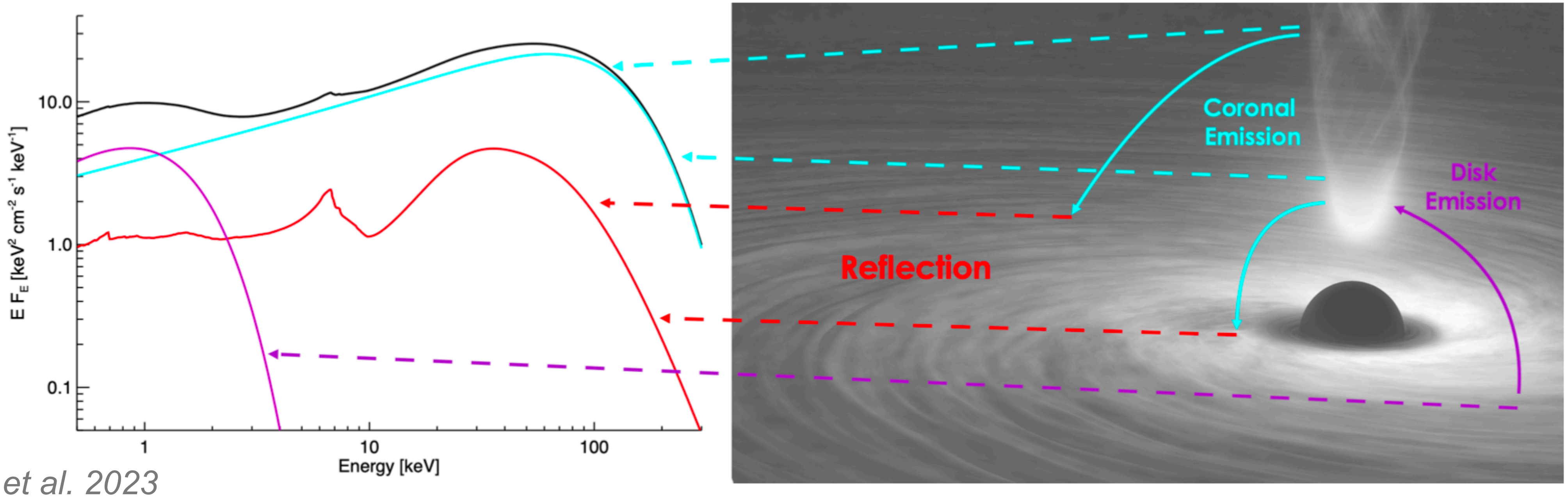
Relativistically broadened iron lines



Kalemci et al. 2023

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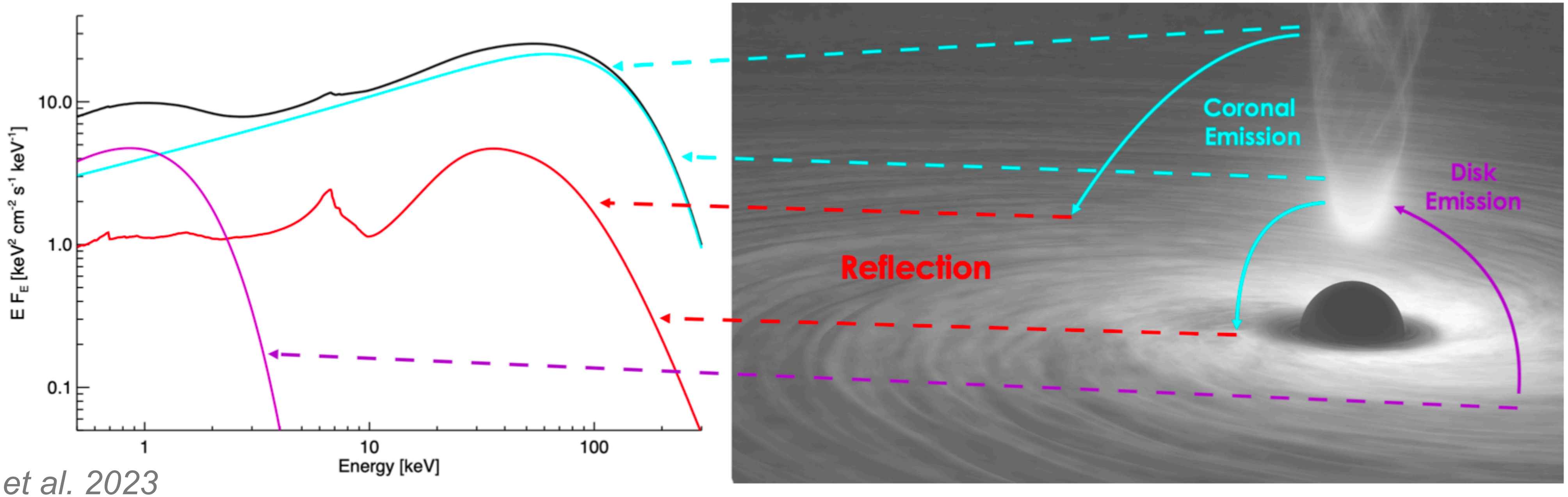
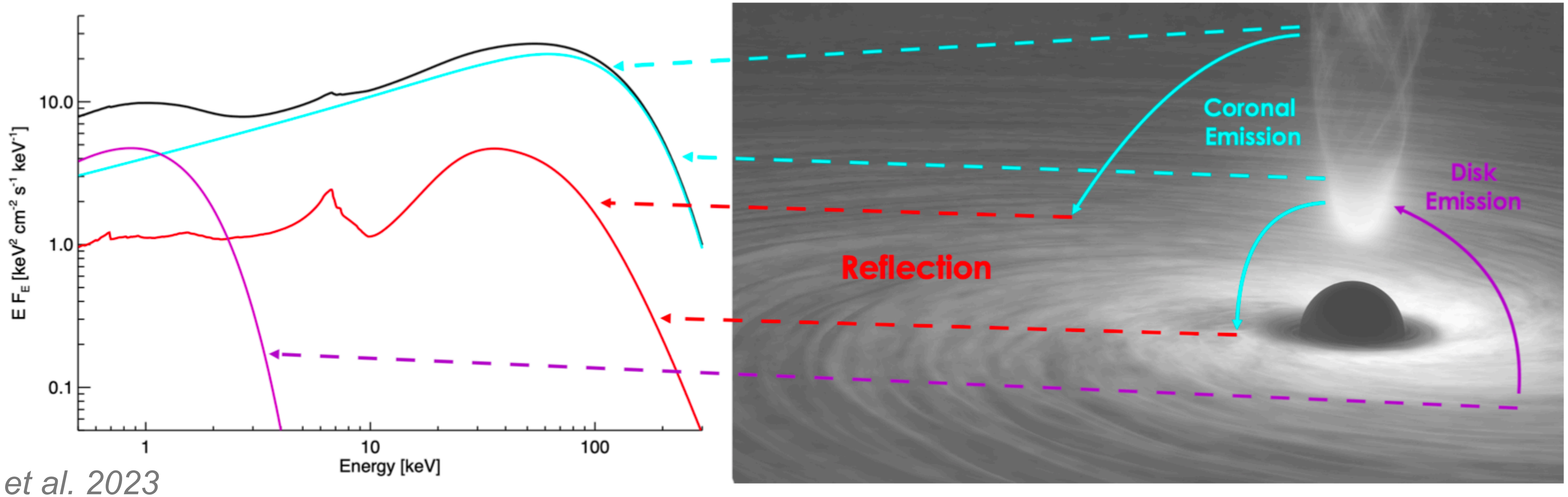


Kalemci et al. 2023

➤ Comptonization of soft X-ray photos in hot corona with T ~ 10^8K: power law

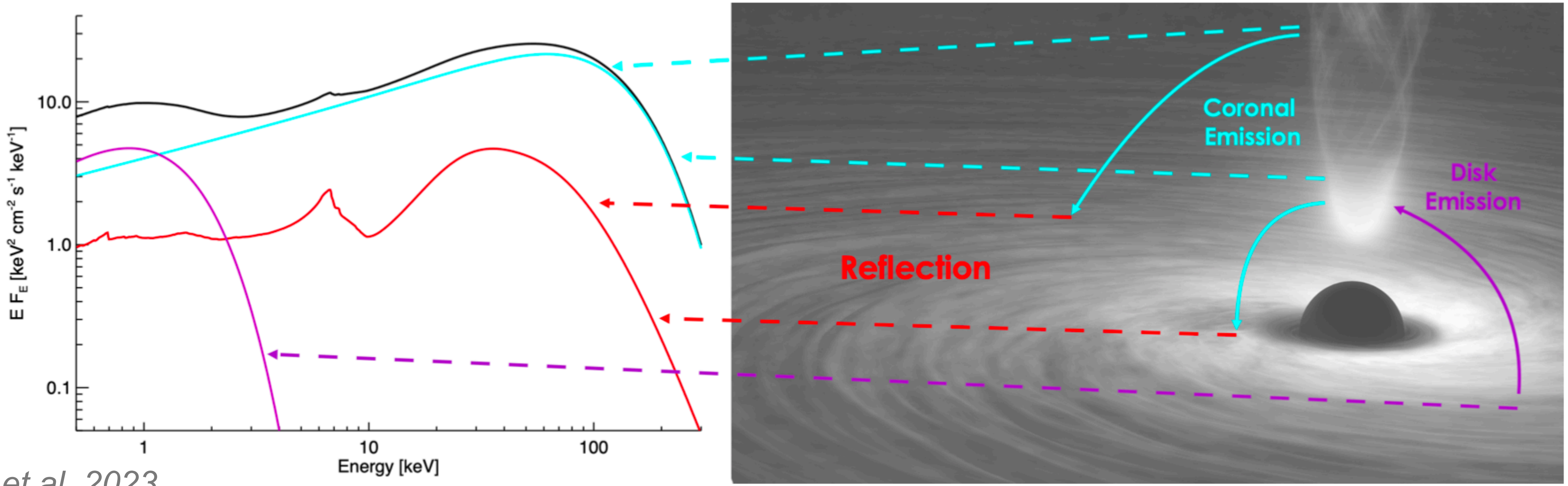
Relativistically broadened iron lines



Kalemci et al. 2023

- ➤ Comptonization of soft X-ray photos in hot corona with T ~ 10^8K: power law
- ➤ scattering of power law photos on the disk: reflection hump / Compton hump

Relativistically broadened iron lines



Kalemci et al. 2023

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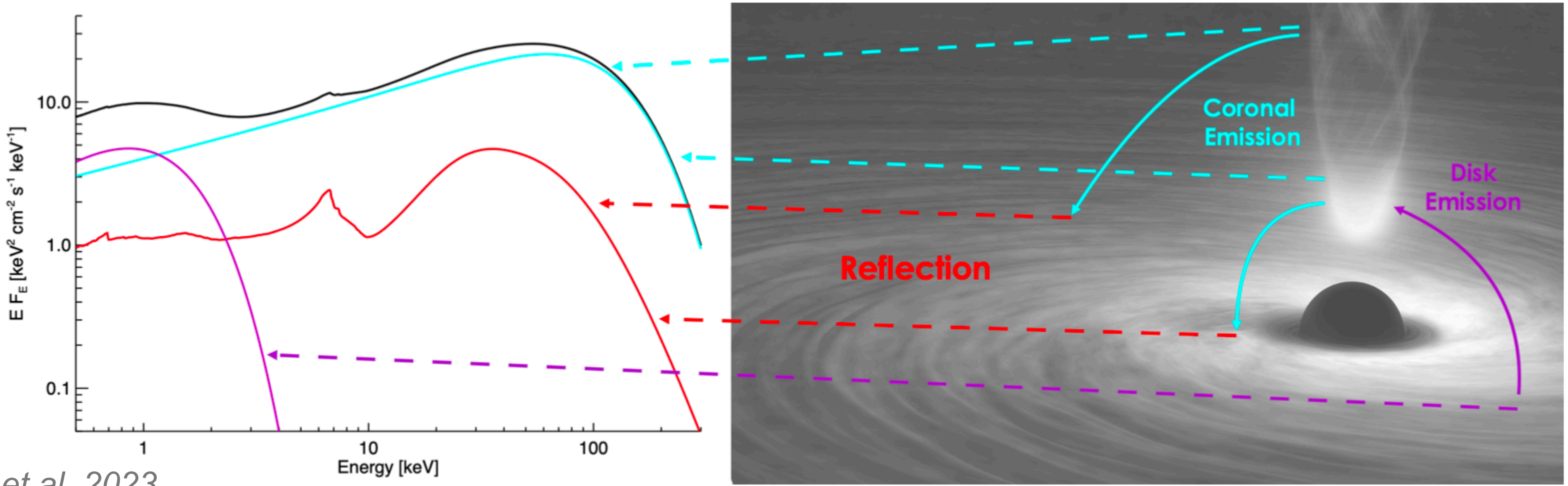
Relativistically broadened iron lines



Kalemci et al. 2023

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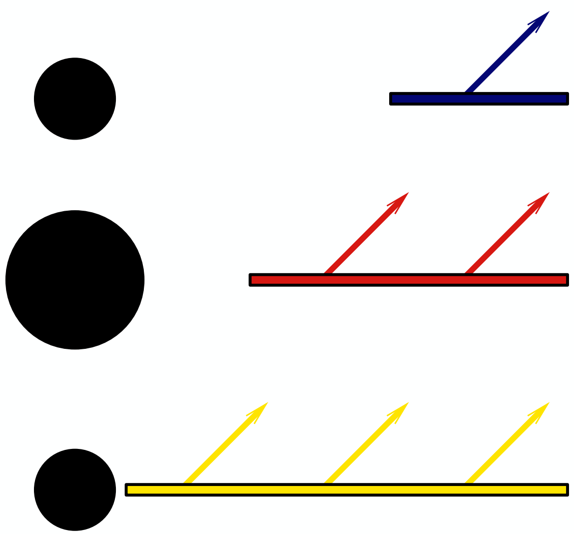
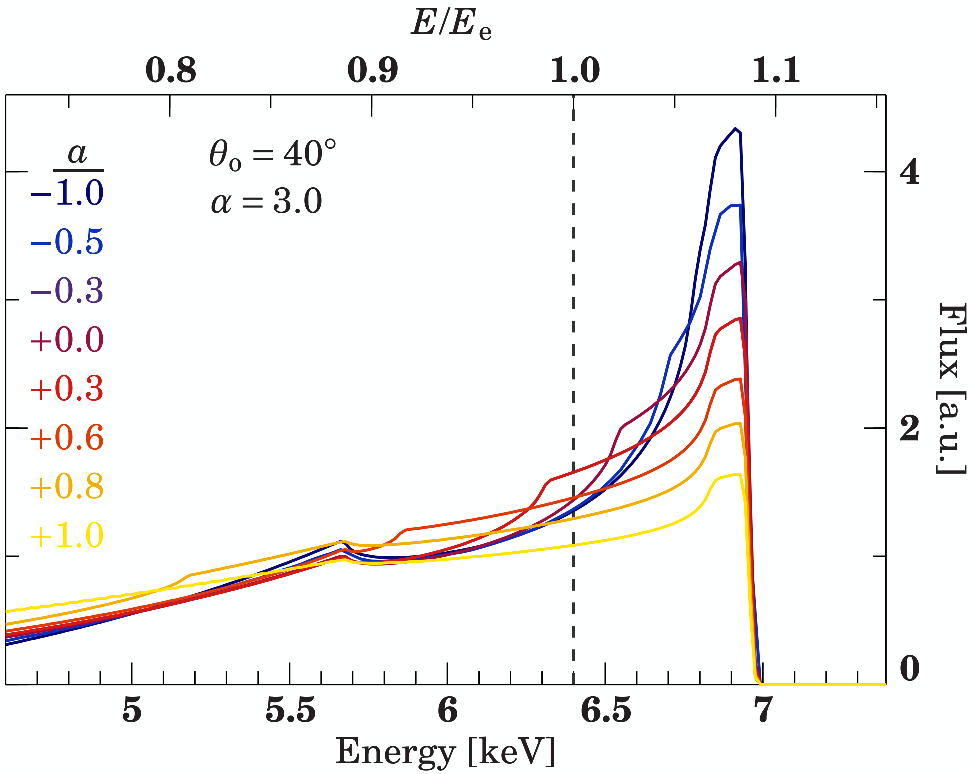
- ➤ scattering of power law photos on the disk: reflection hump / Compton hump
- ➤ photoabsorption of power law photos in disk: fluorescent lines, esp. Fe Kα at 6.4 keV
- ➤ realistic disks: ionized, NOT neutral - complex physics with a side of atomic physics & atomic data (see also lecture on high res spectroscopy)

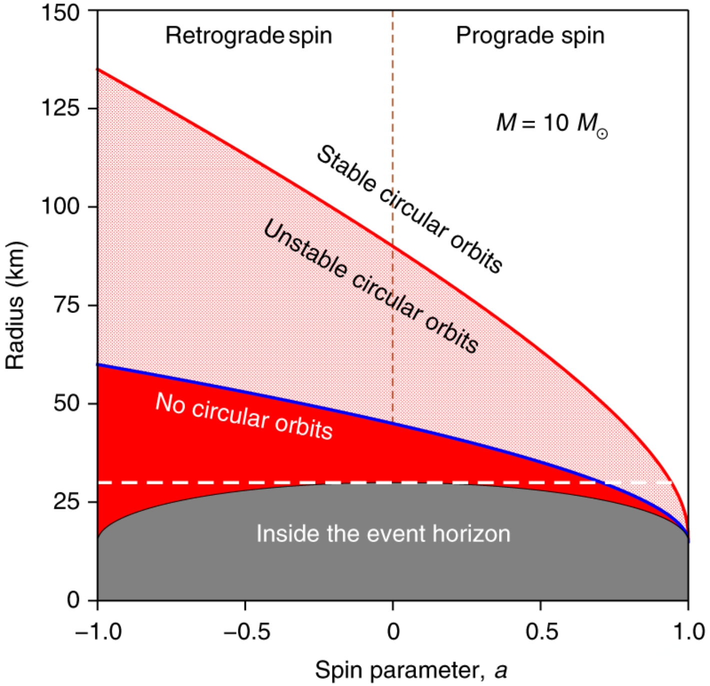
Diagnostic potential

c) spin a



Dauser 2010

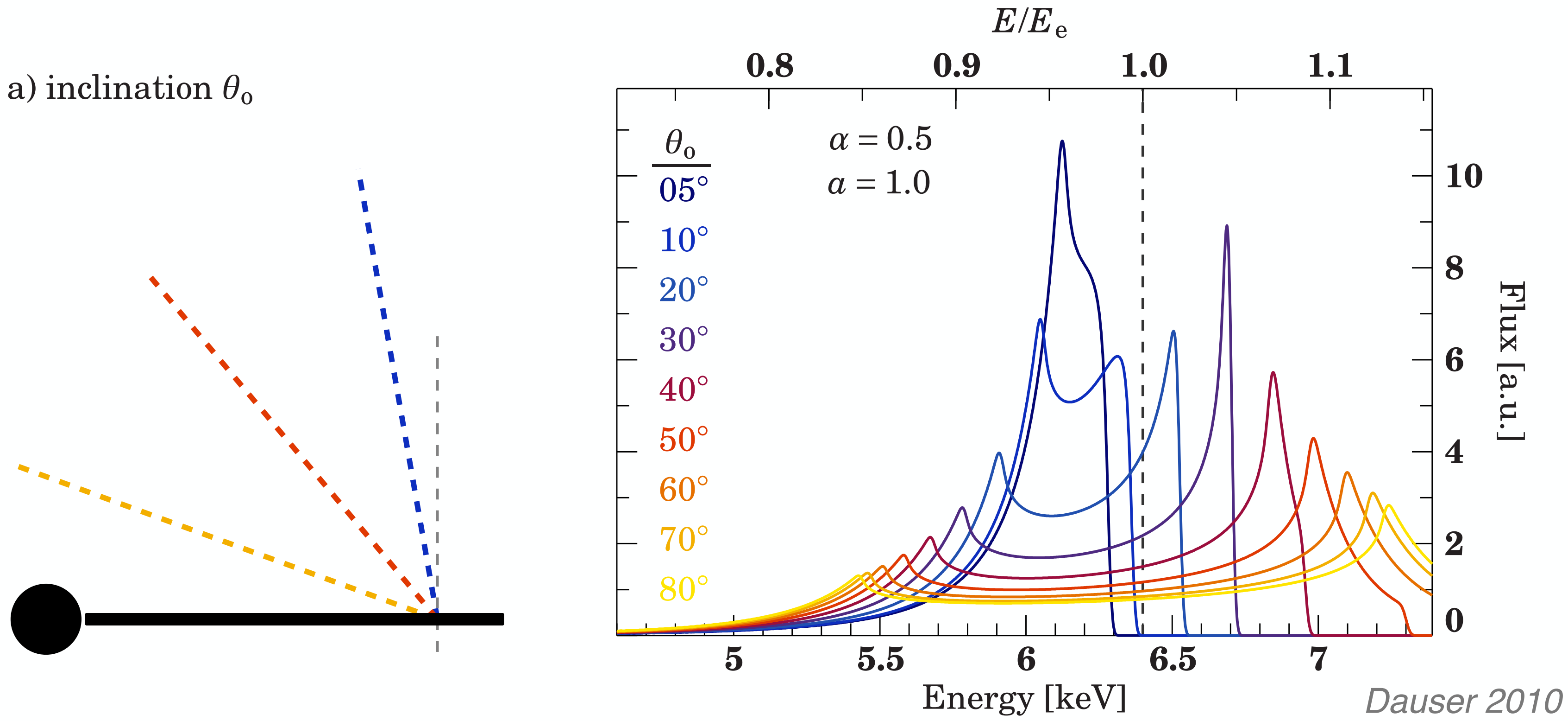




Reynolds 2020

➤ higher spin $\Longrightarrow$ smaller ISCO $\Longrightarrow$ more distortion

Diagnostic potential: inner disk inclination

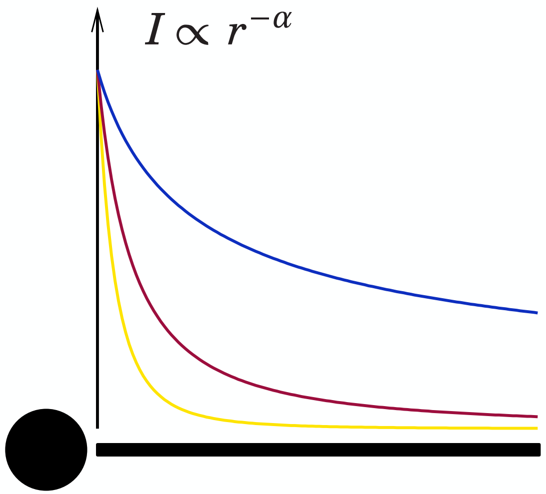


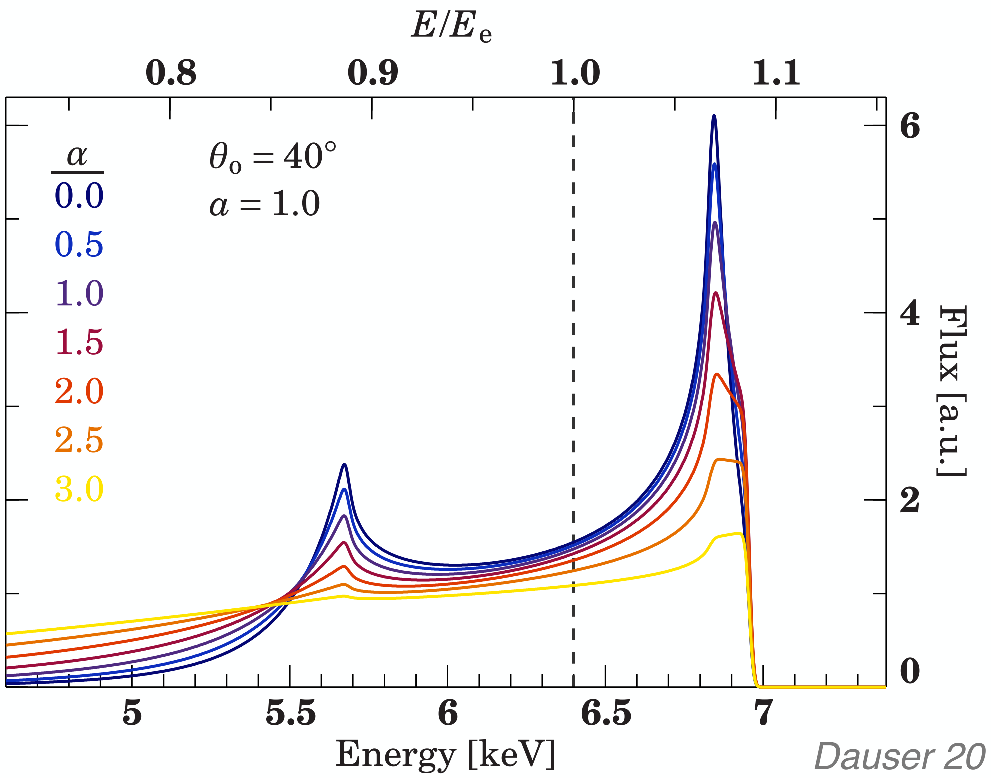
Dauser 2010

➤ higher inclination $\Longrightarrow$ more line distortion, including stronger blue-shift (higher projected velocity!)

Diagnostic potential: emissivity

b) emissivity α

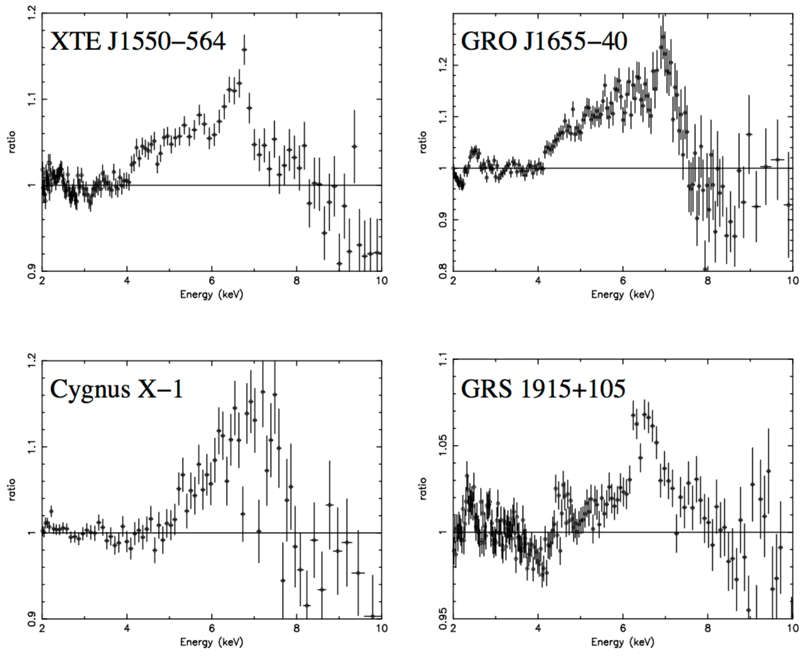




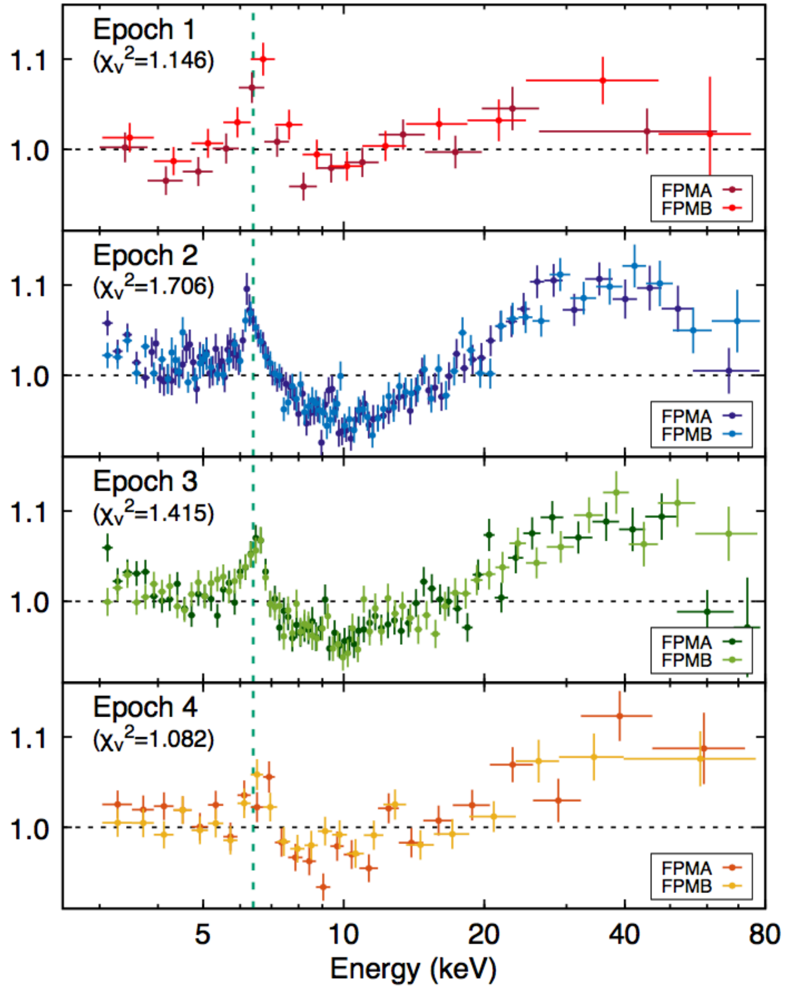
Dauser 2010

➤ emissivity = energy release per unit area
➤ for a "classical" accretion disk: α = 3

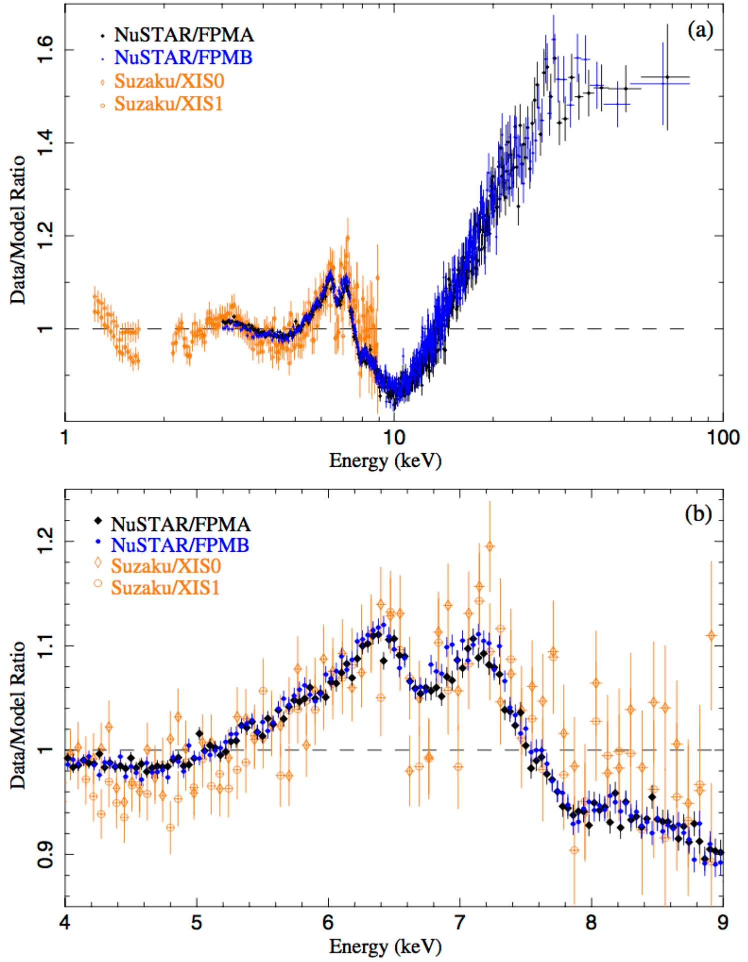
Relativistic iron line: real data



Miller 2007

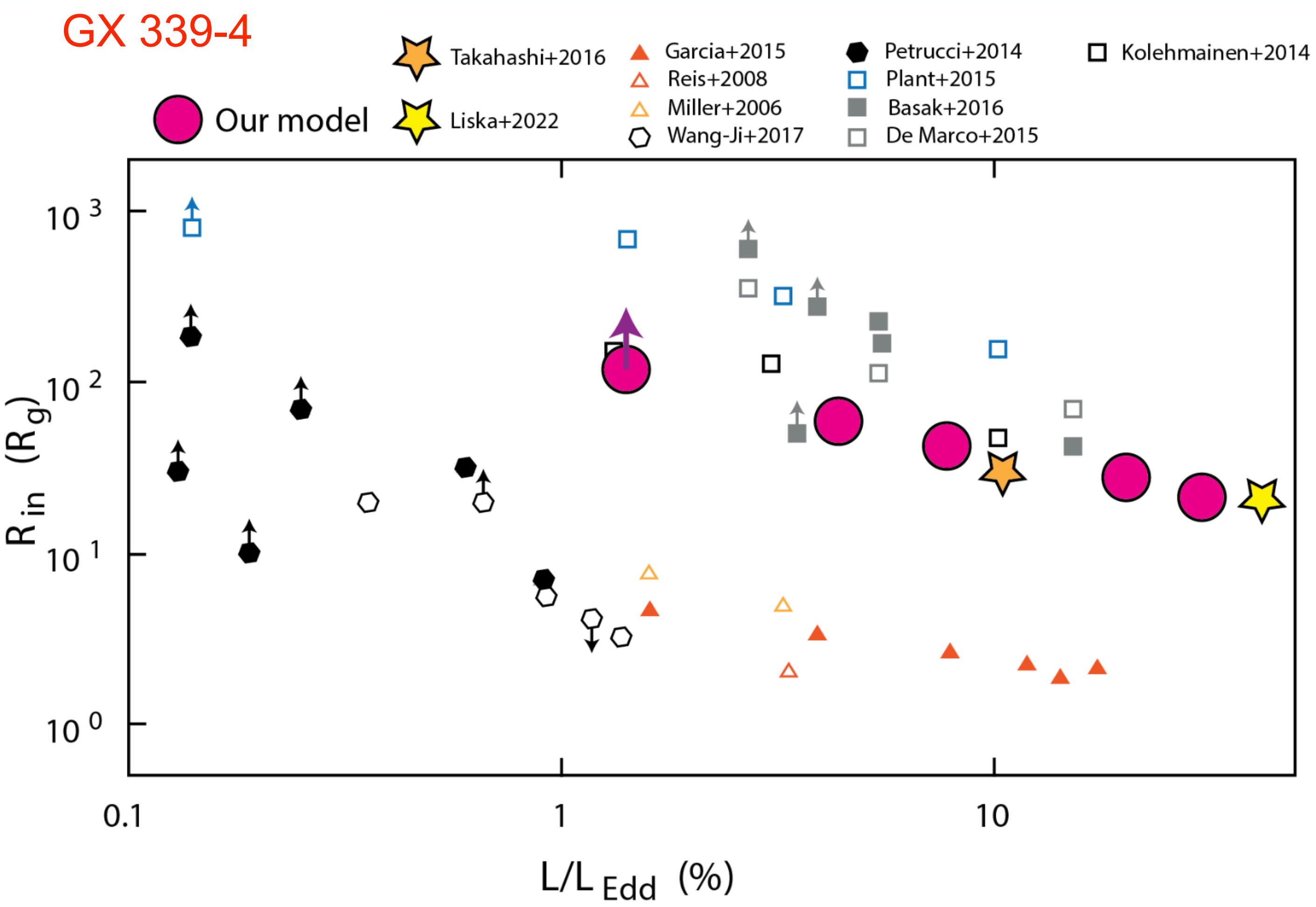


Garcia+ 2019



Tomsick+ 2014

Inner disk radius in hard state

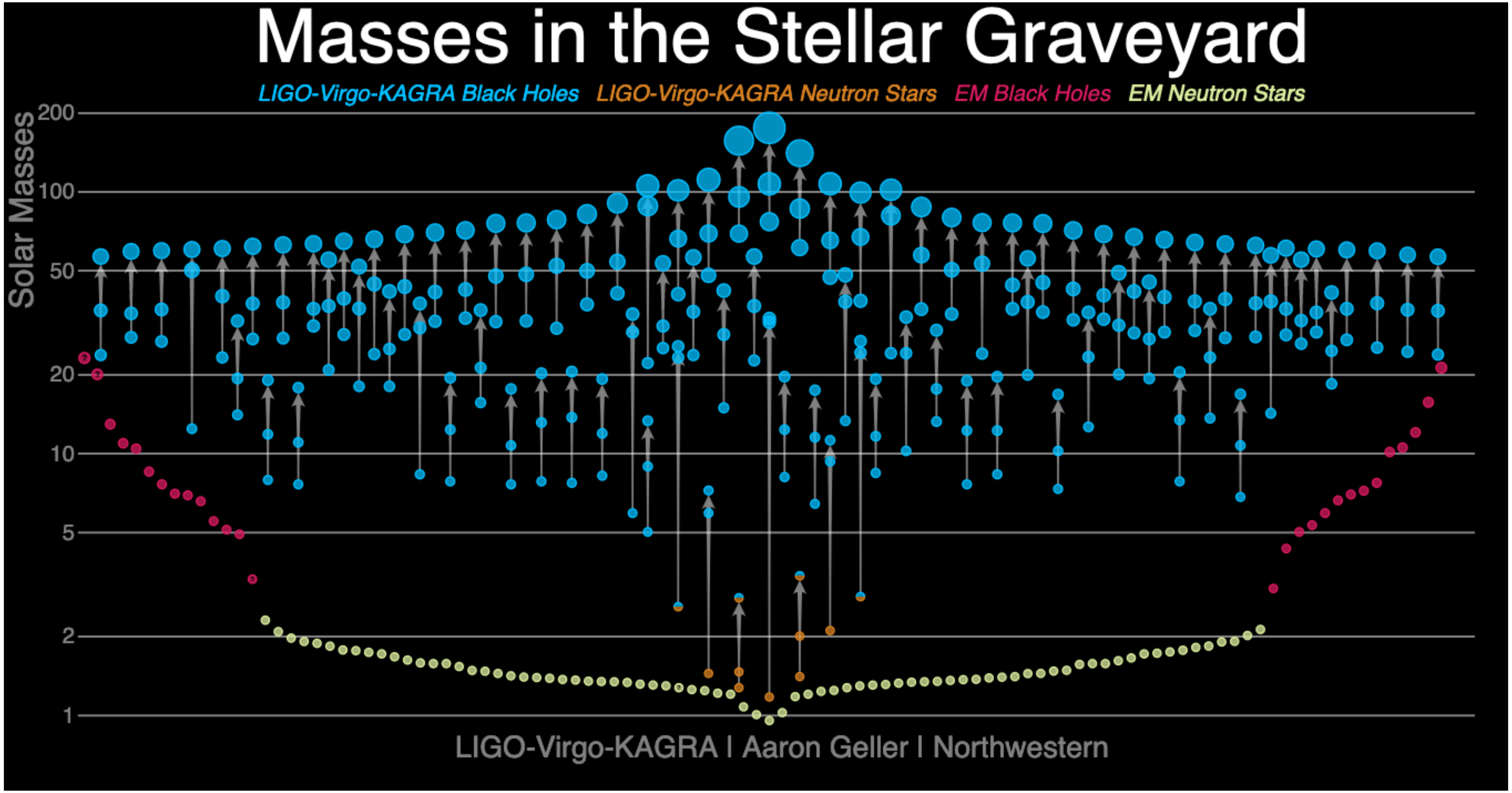


Nemmen+ 2023

Basic idea (e.g. Esin 1997, Done 2007): thin cold accretion disk is truncated at certain radius & gives space to hot corona

- Measurements of inner disk radius differ by order of magnitude - partly with the same data
- Different "tracks" with different methods (reflection vs. continuum fitting & lags), but different results even with similar methods
- Generally: increasing inner risk radius at lower luminosities

Comparison to BH population from GWs



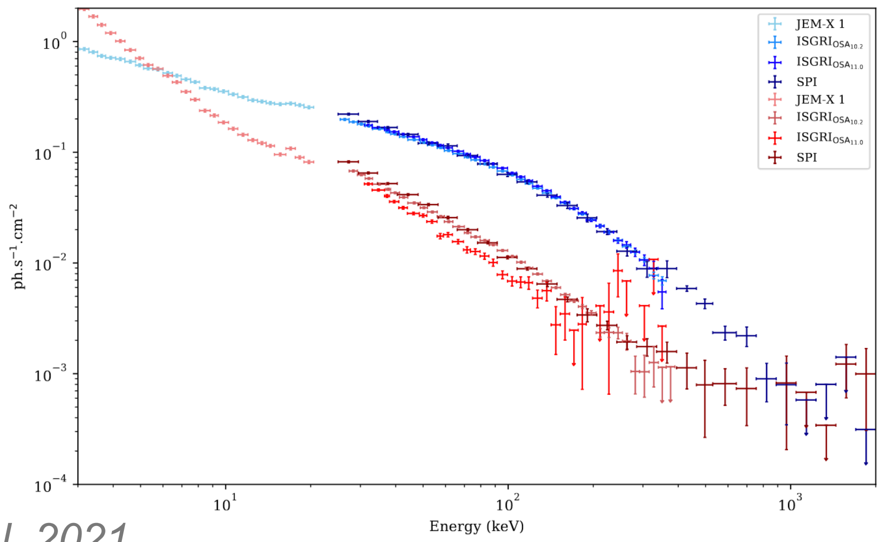
different mass & spin distributions

- spins from X-ray measurements typically higher
- different populations? (Fishbach+2021, Belczynski+ 2021, etc.)

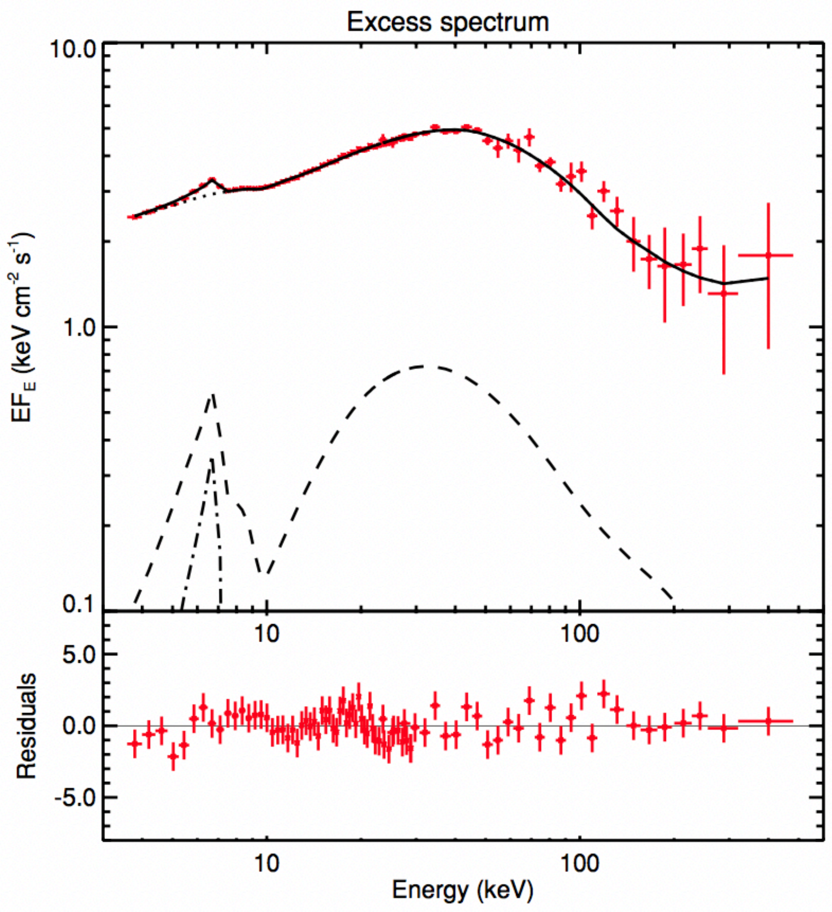
Hard tails & soft gamma-ray polarization

Excess emission about the “normal” Comptonization models at high energies (> 100-200 keV), only accessible with direct measurements above cut-off! INTEGRAL crucial

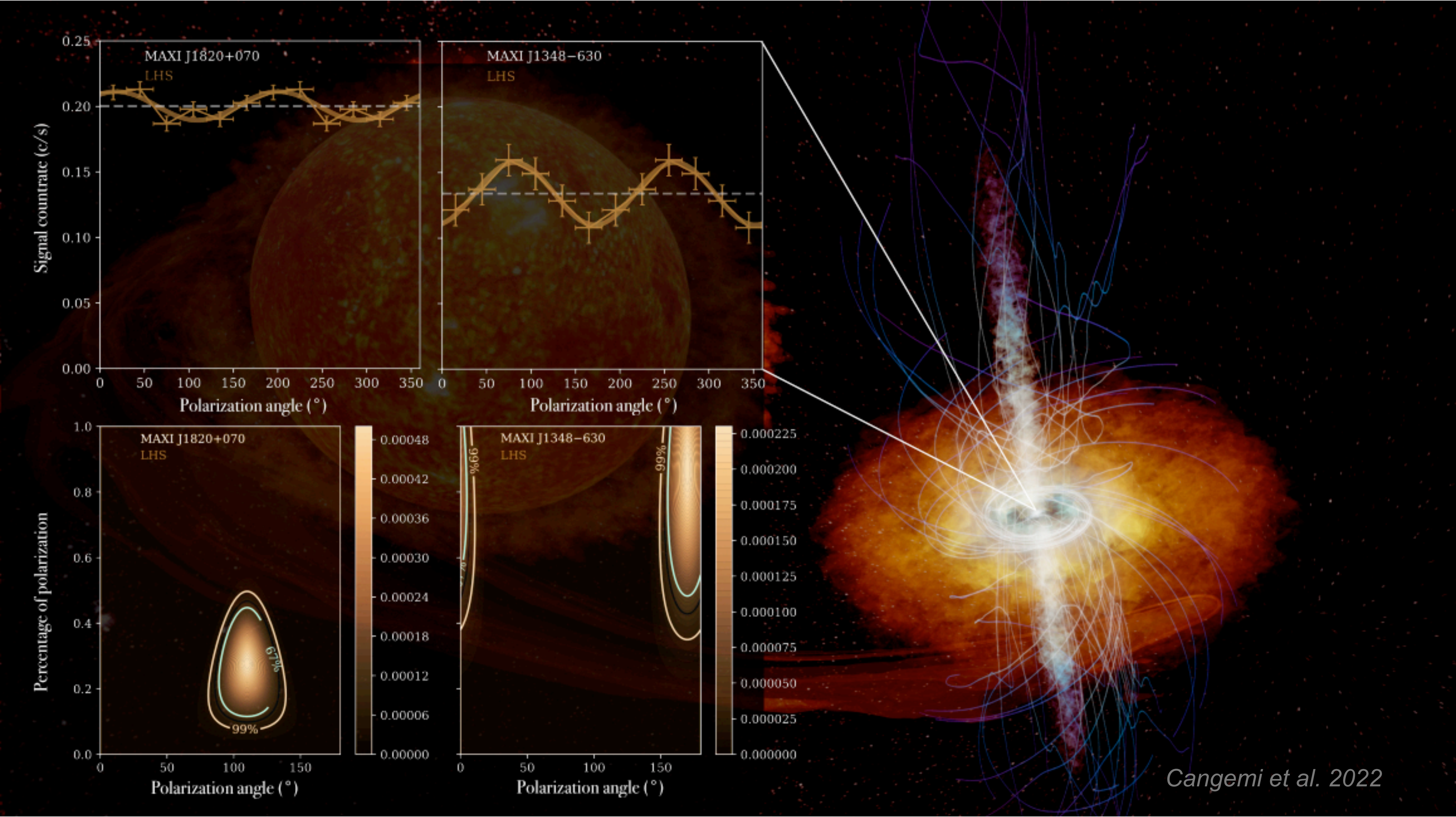
- ➤ different models
- ➤ possible state dependency
- ➤ intrinsic variability



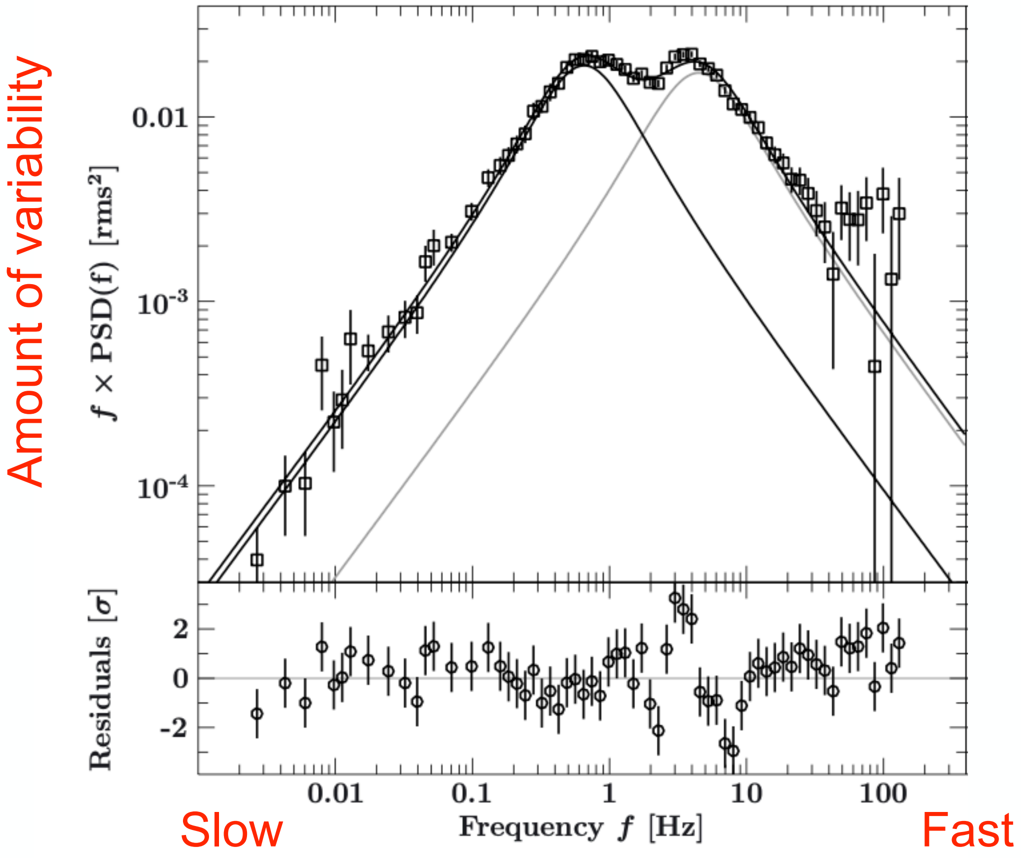
Cangemi et al. 2021



Droulans et al. 2010


MAXI J1820+070
LHS
MAXI J1348−630
LHS
Signal countrate (c/s)
Polarization angle (°)
Percentage of polarization
67%
99%
Cangemi et al. 2022

Black holes: Power spectra



Boeck et al. 2011

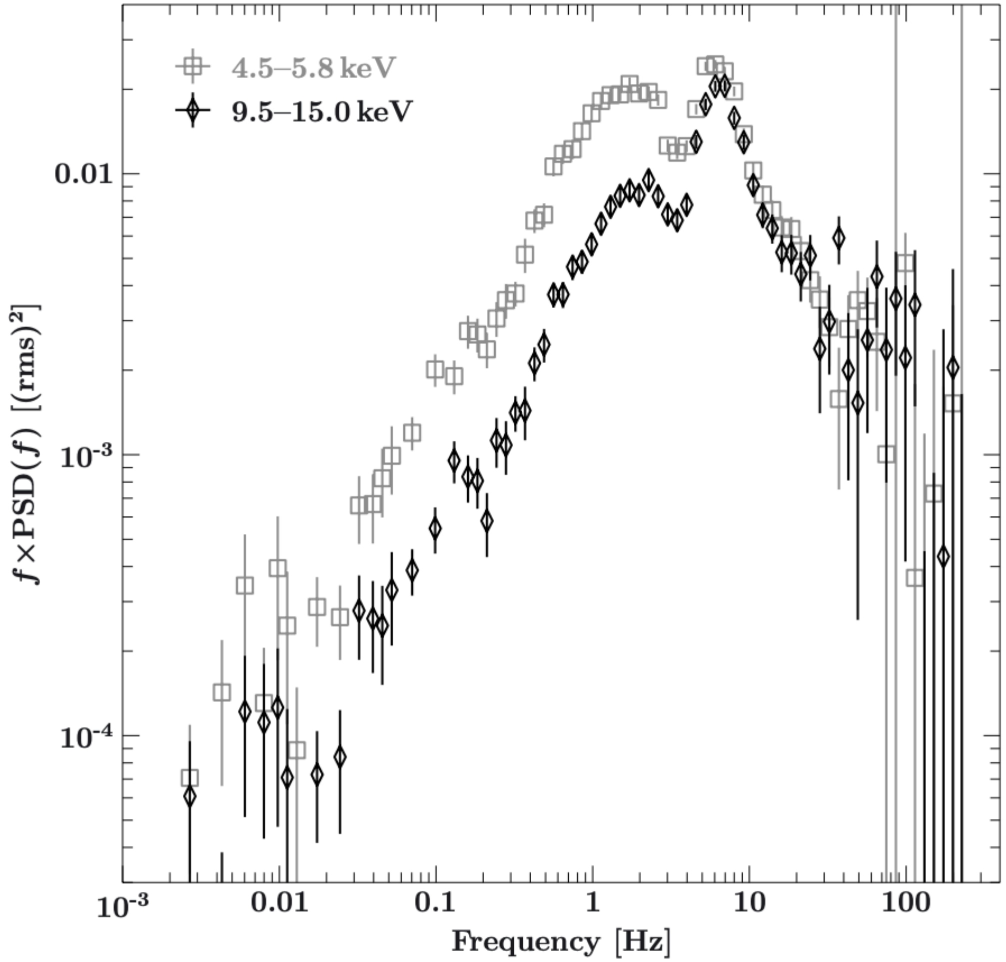
Power density spectrum

- ➤ a non-complex quantity obtained by multiplying the discrete Fourier transform and its complex conjugated quantity = the **PDS is the squared magnitude of the complex Fourier transform**
- ➤ measure of contribution of different frequencies to total variability
- ➤ XRBs: can typically be modelled with multiple broad & narrow Lorentzians

Papers VG finds especially good intros:

- Pottschmidt 2002 (PhD thesis)
- Nowak et al. 1999

Black holes: Power spectra

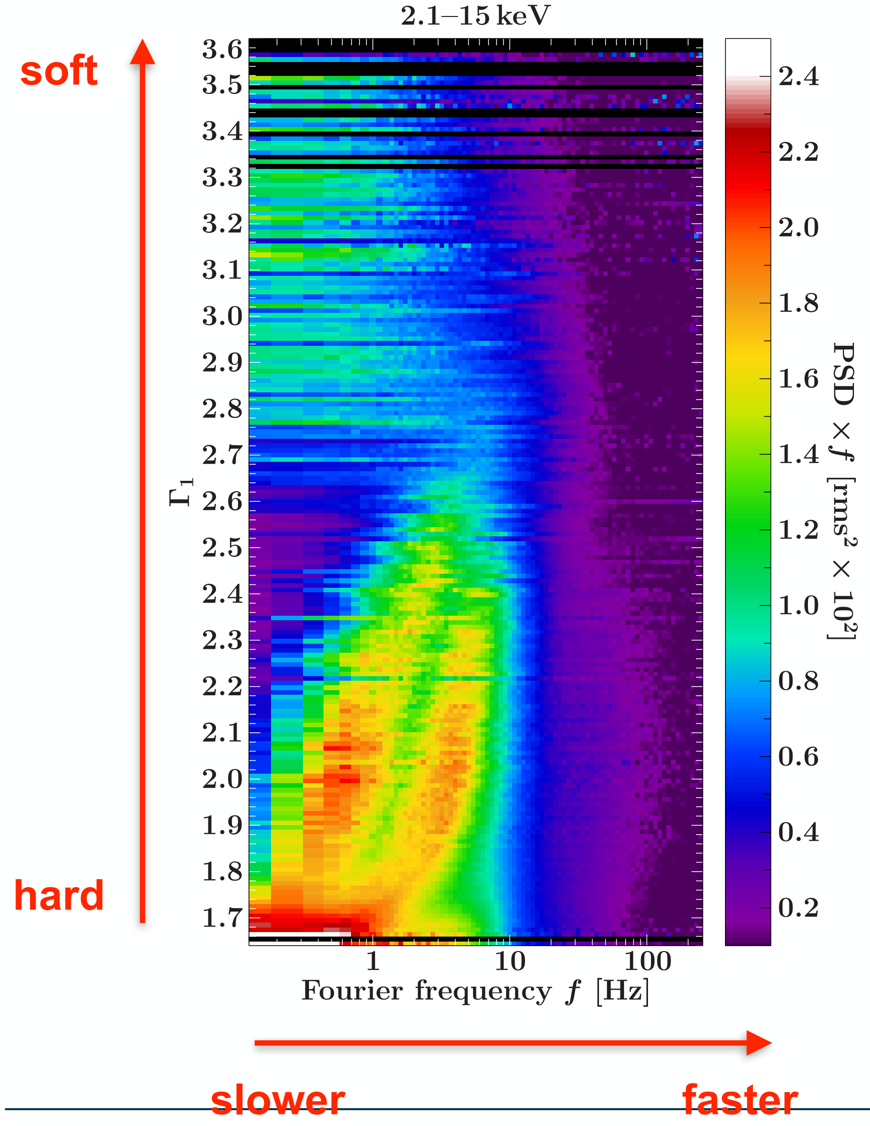


Boeck et al. 2011

Power density spectrum

- ➤ power spectra (& other timing properties) are energy dependent!

Power spectral evolution



Grinberg+ 2014

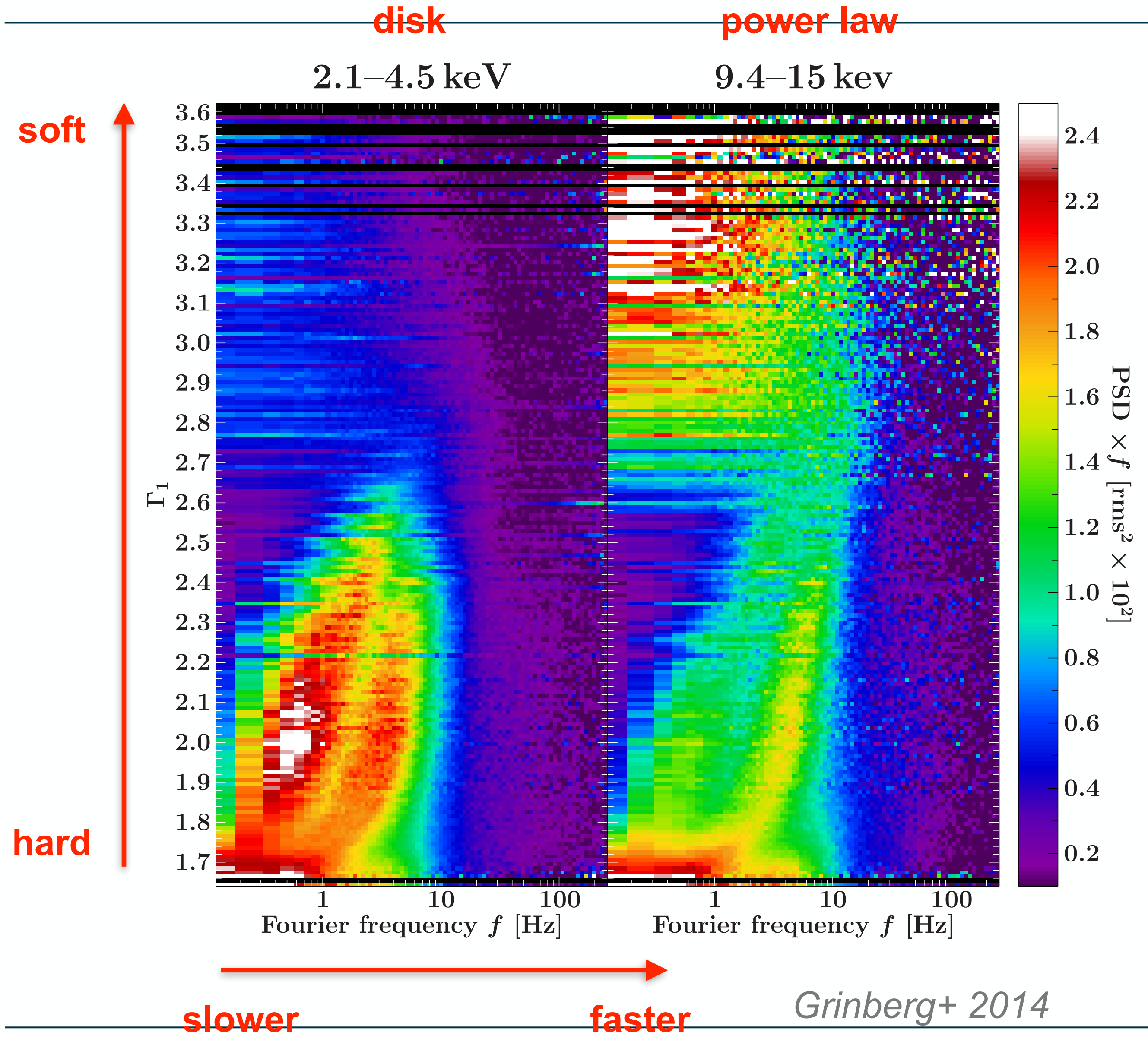
power spectra vs. spectral shape to trace the evolution of the power spectra

here: Cyg X-1 across multiple state transitions

- ➤ changes in variability properties when radio switches off
- ➤ hard state: higher frequency variability leads relatively stronger at higher energies
- ➤ soft state: if power law component present, it is highly variable

Some open questions: origin of the variability components? Models exist (propagating fluctuations; jets), but unclear which correct

Power spectral evolution



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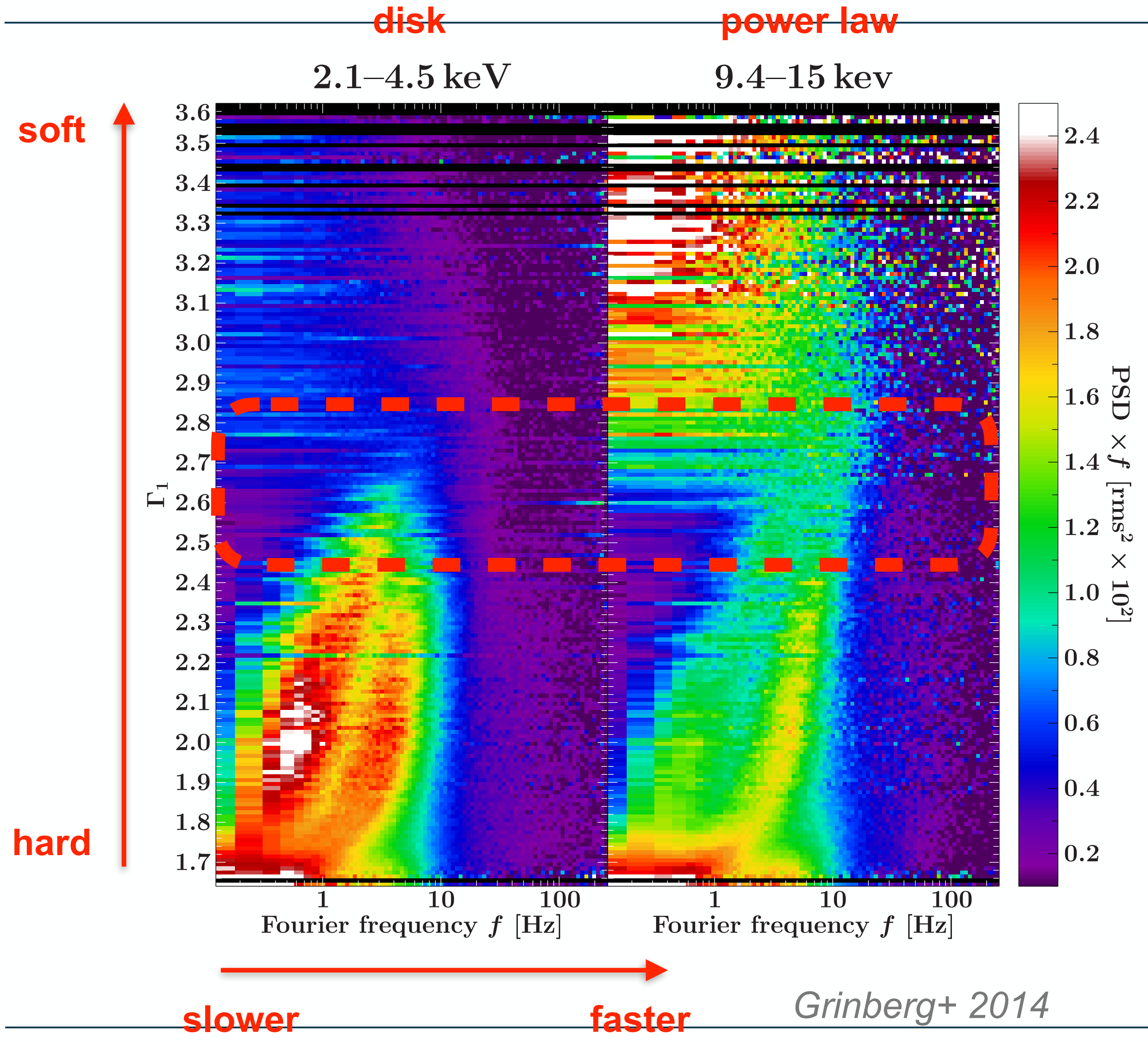

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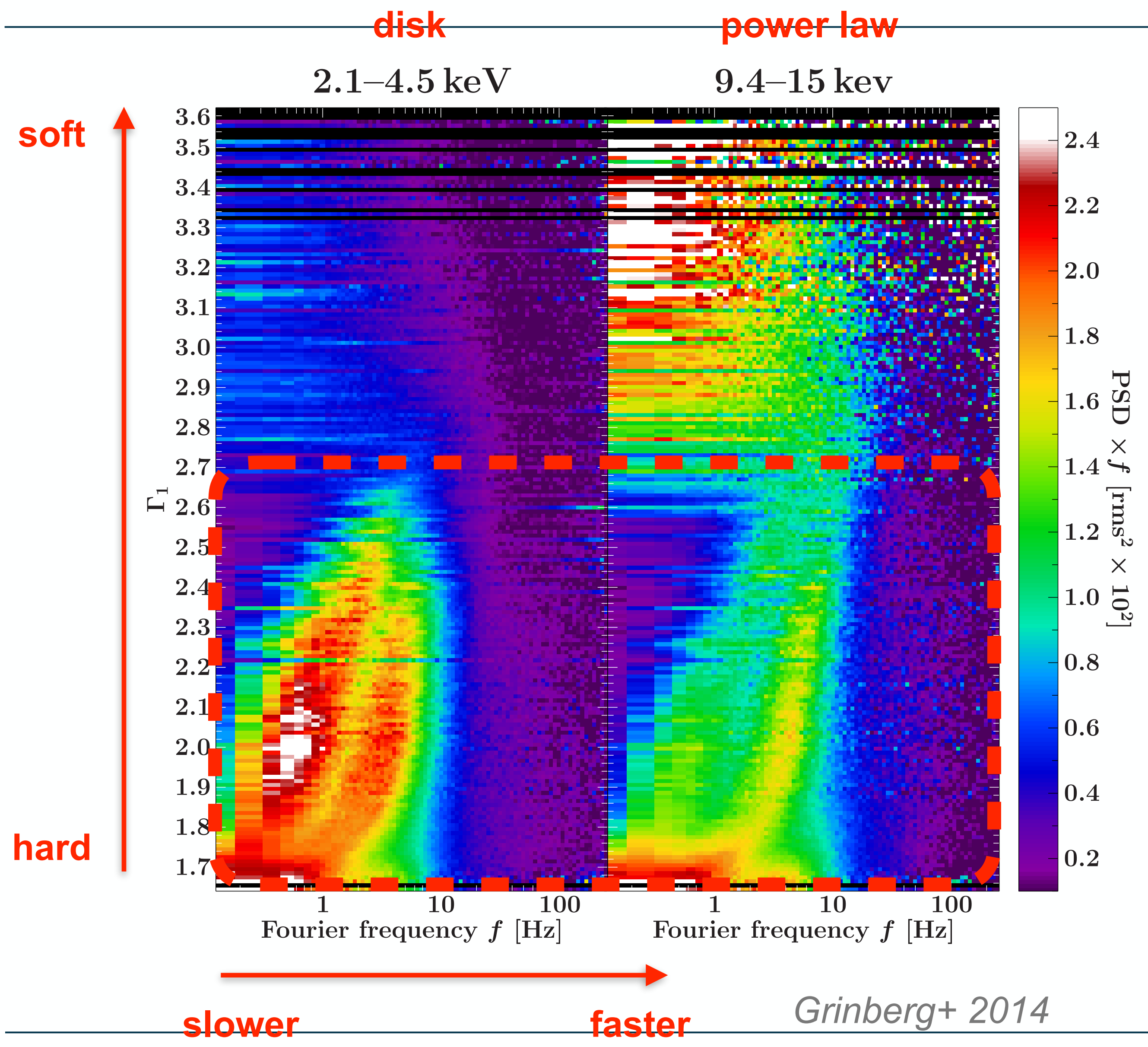

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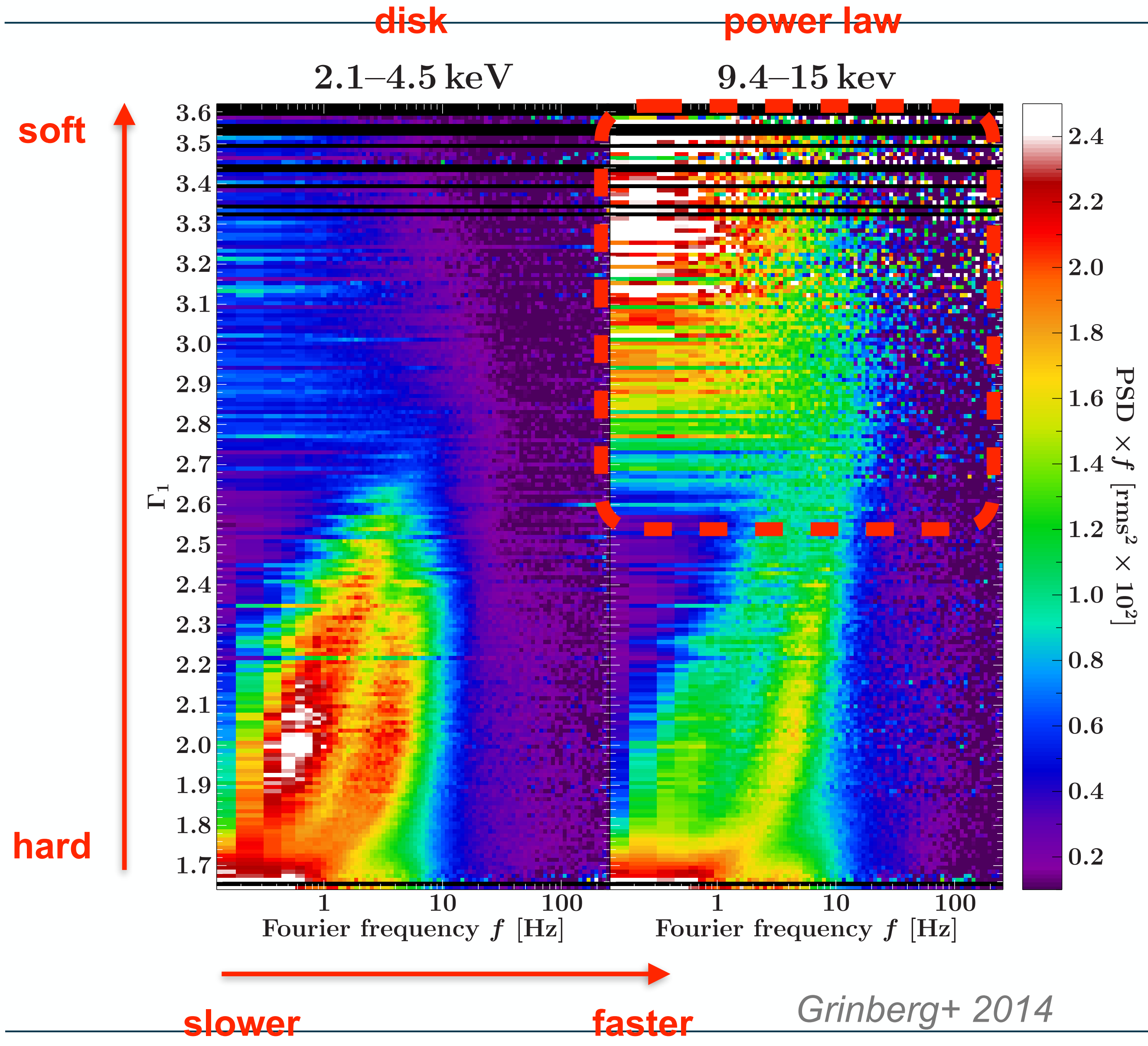

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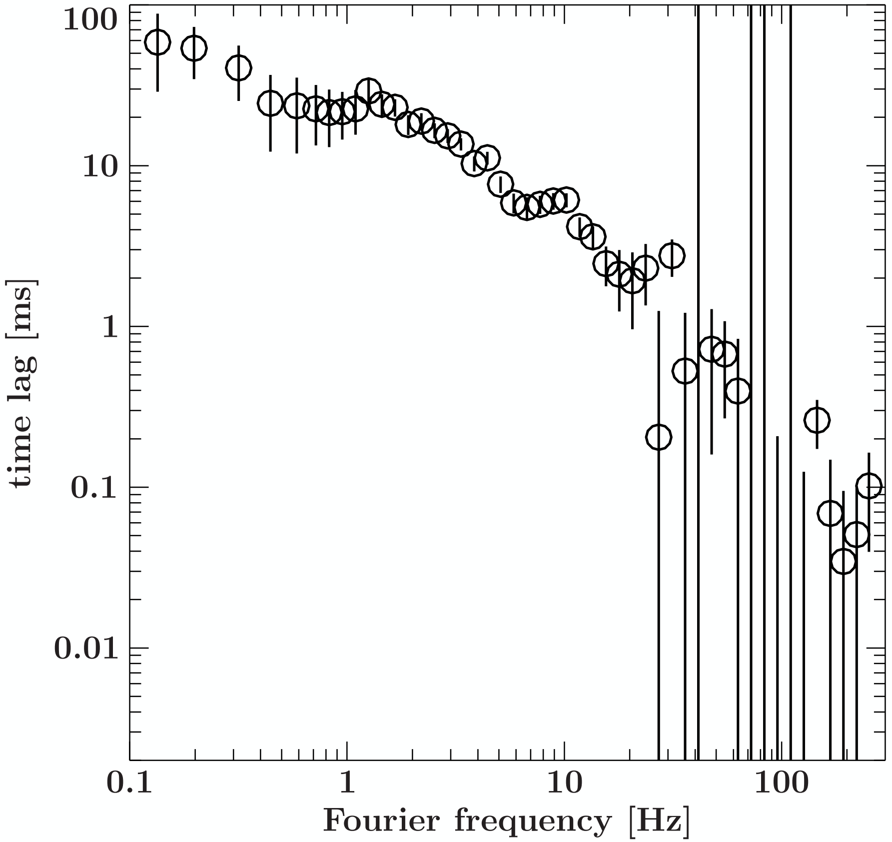
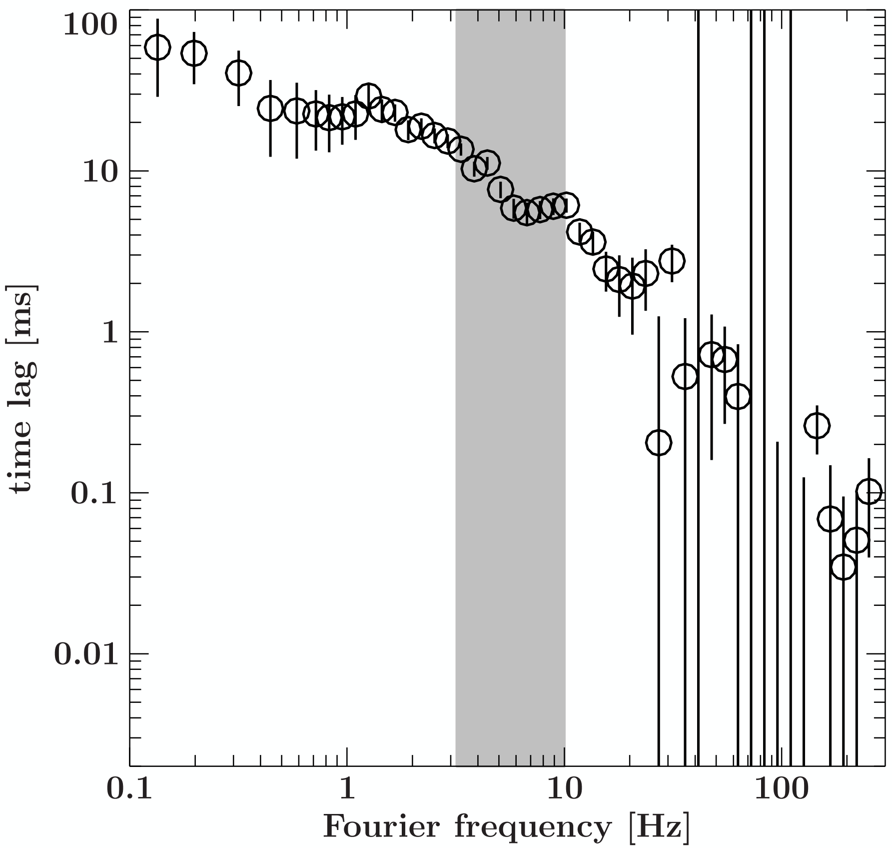
Timelags



Timelags

- ➤ Fourier-frequency dependent measure of the delay between the time series = difference in Fourier phase
- ➤ one “time lag” value usually refers to value averaged over Fourier frequencies
- ➤ time lag spectrum roughly proportional to $f^{-0.7}$ (e.g., Nowak et al. 1999), but shows features (e.g., Miyamoto & Kitamoto 1989, Nowak 2000, Pottschmidt et al. 2000)

Timelags



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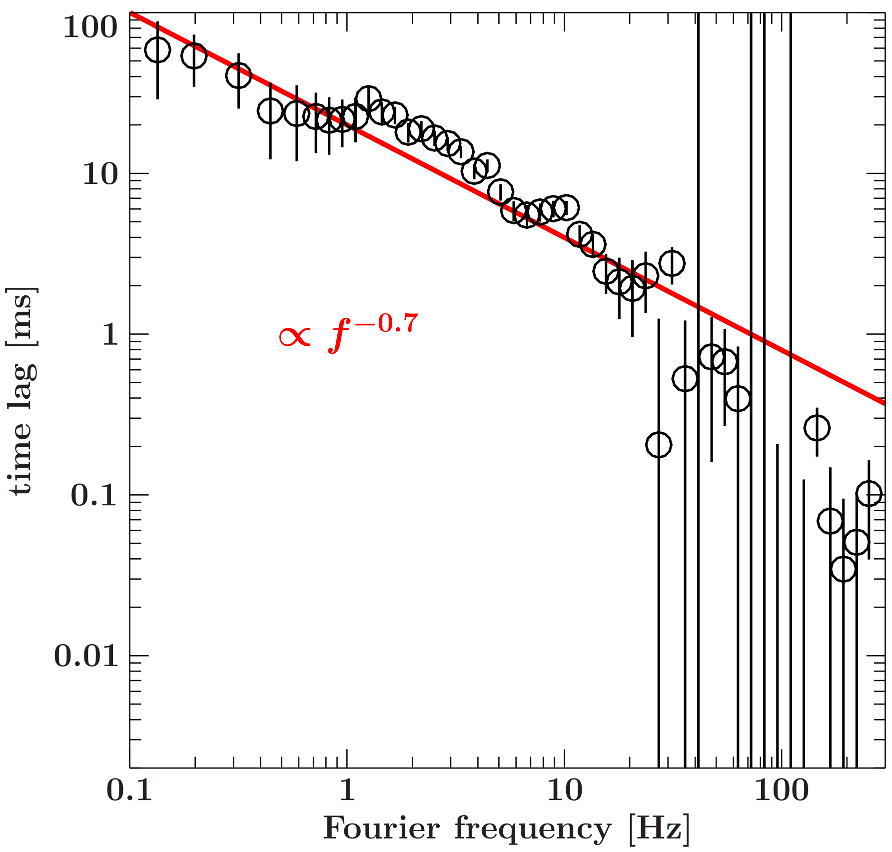

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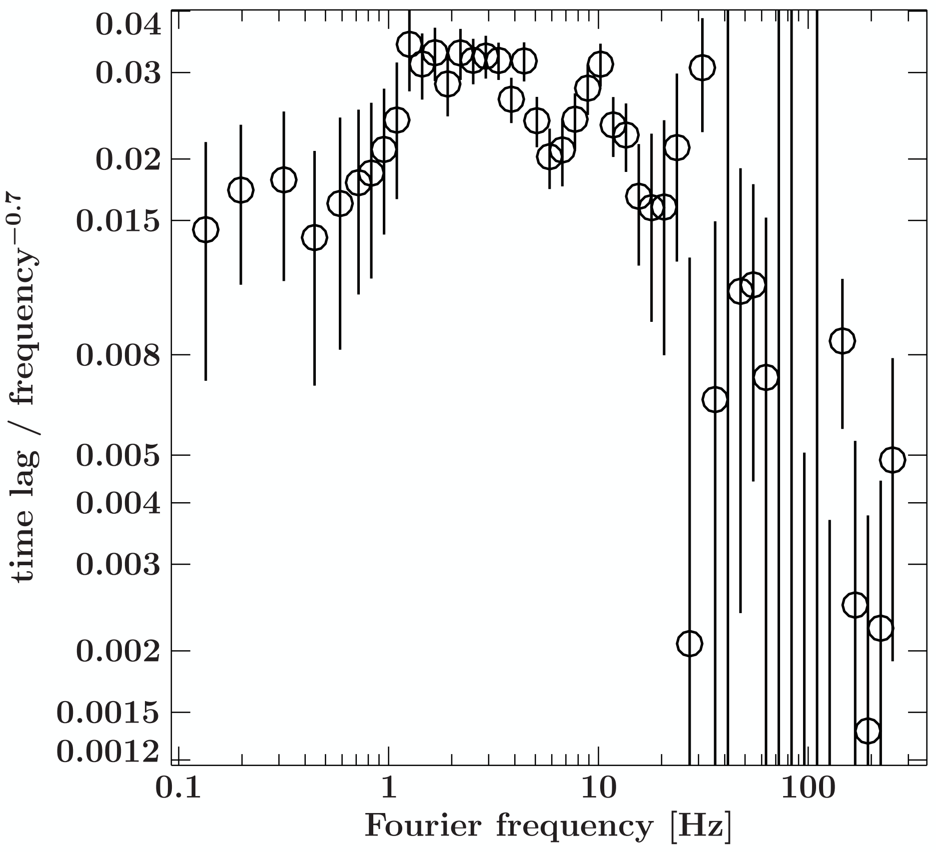

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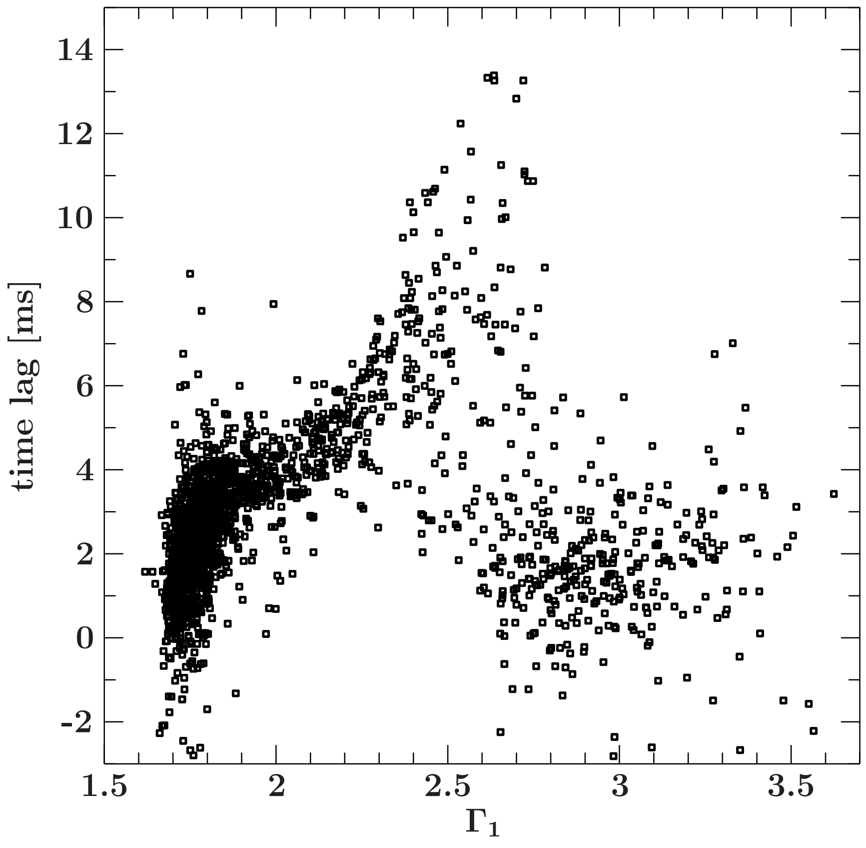
Hard lags

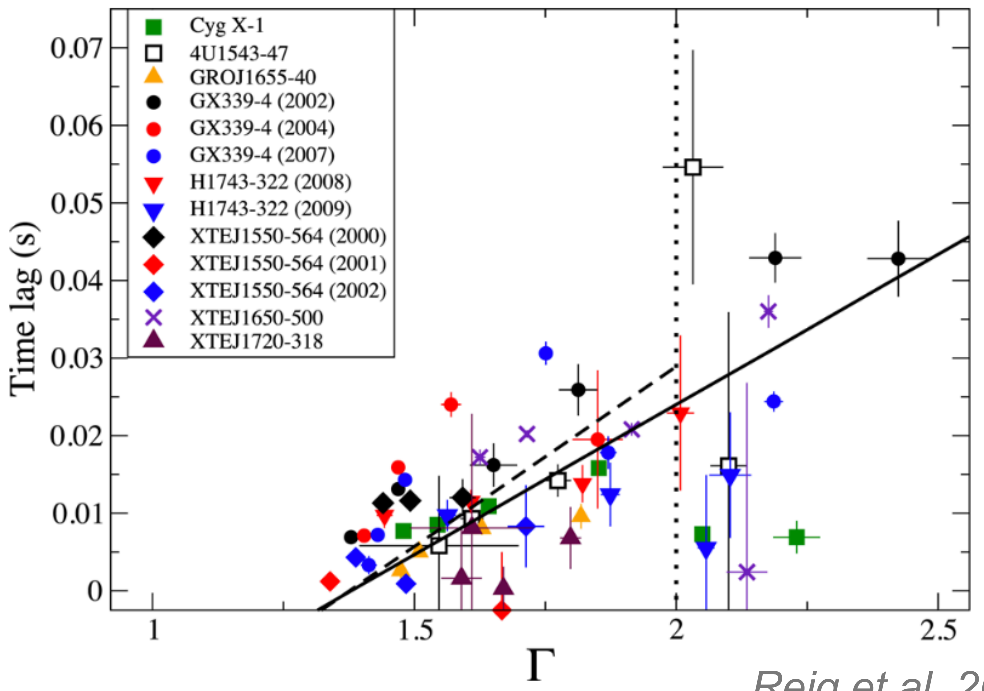
9.4-15 keV to 2.1-4.5 keV



Grinberg+ 2014; based on Pottschmidt et al. 2003

Hard X-ray lag soft X-rays

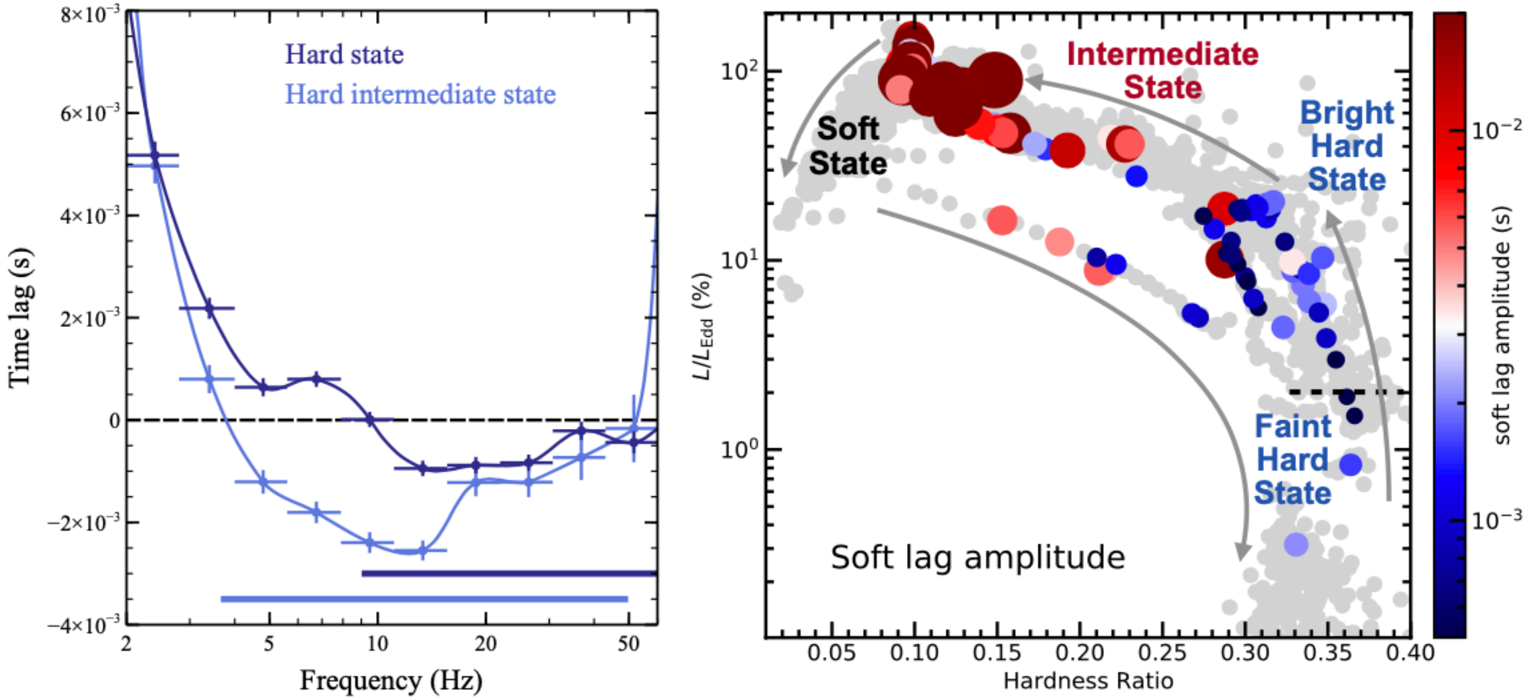
- ➤ increase in hard state
- ➤ return to small values in soft state
- ➤ models: propagating fluctuations, jets, …



Reig et al. 2018

Soft lags

0.3-1 keV to 1-4 keV



Kalemci et al. 2023 after Kara et al. 2021 & Wang et al. 2022

Soft X-rays lag hard X-rays

- first hints with RXTE, much better accessible with NICER
- increase in amplitude in decrease in frequency from hard to soft
- models: reverberation ("echo") from the disk, …

Accretion/ejection connection

Jets

- dominate spectrum in radio and partly up to near-IR
- "fundamental plane": X-ray/radio correlation in AGN and XRBs, connecting black hole accretion on all scales
- contribution to X-rays unclear! X-ray emission from jet vs. more extended corona vs. corona as base of the jet
- coincidence (type B QPOs) or partial coincidence (timelags) between changes in timing properties and radio flares from jet

Winds

- driving mechanism
  - thermal - implies large launching radii (10^4-10^5 R_G)
  - radiation pressure - unlikely in XRBs, not enough UV radiation
  - magnetic - viable, possible at smaller launching radii
- disappearance of wind absorption lines in hard state: over-ionization of the material, photoionization instabilities, geometri-cal obscuration of the outer disk or properties of wind driving?

Questions?

(HM)XBs as probes for their environment

X-ray binaries: The Zoo

A heterogeneous set of methods

- spectral (broad band vs. high res)
- timing / short-term variability
- spectral-timing
- polarization (low- vs. high energies)
- multiwavelength approaches
- theory

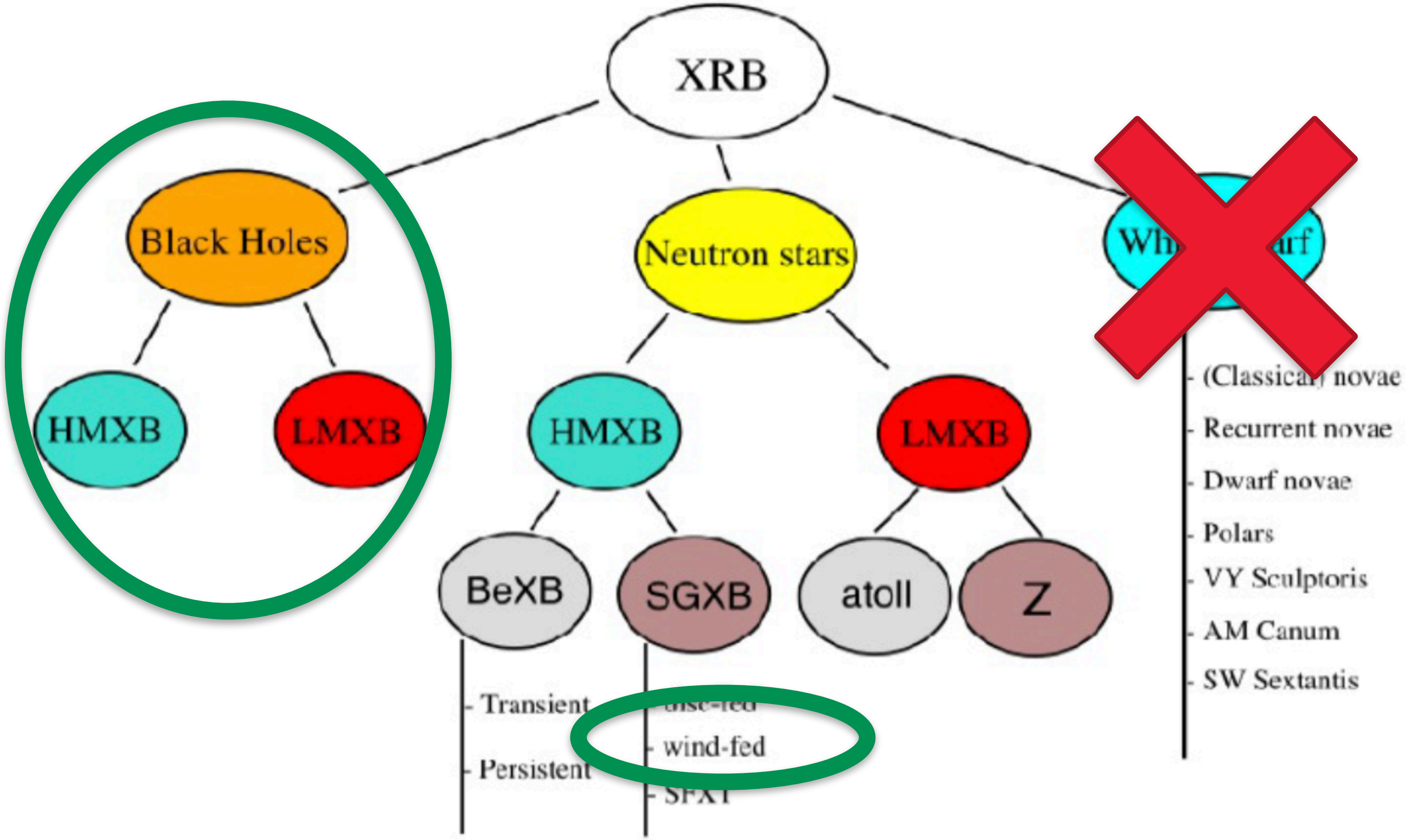
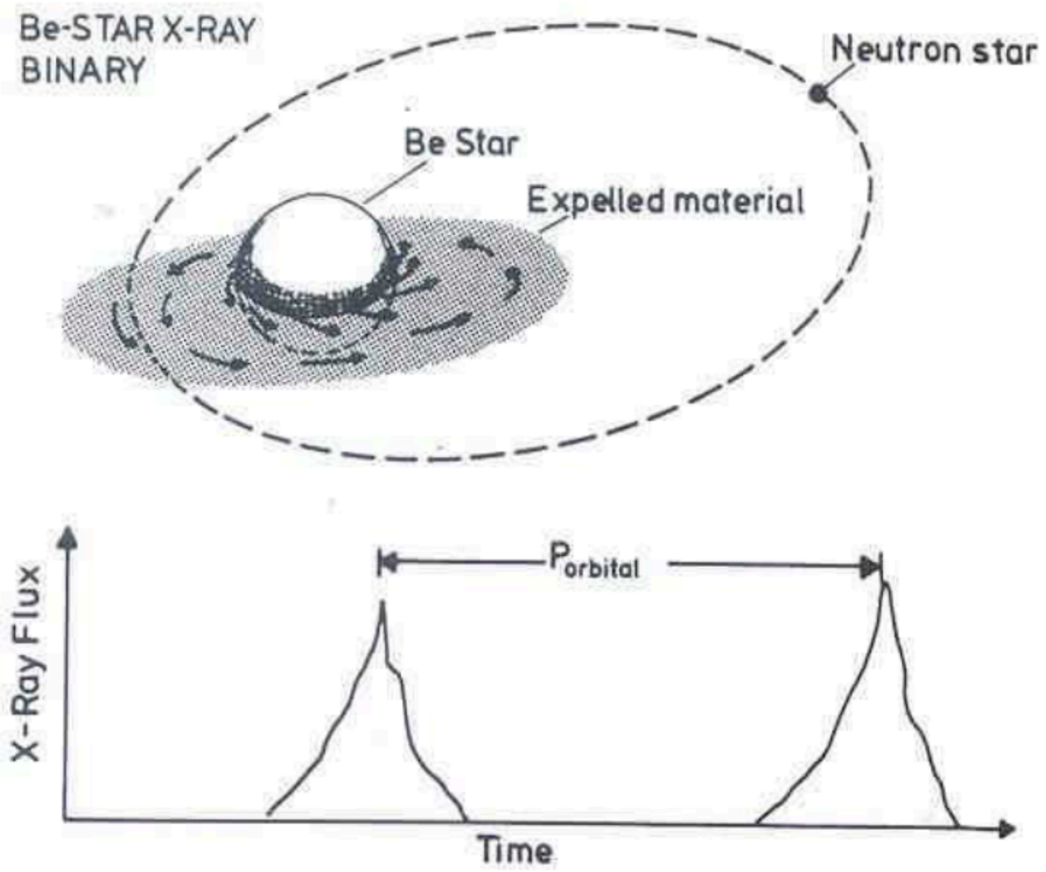


Figure 1.1: Classification of X-ray Binary Systems (Reig 2011)

HMXBs

- BeXRBs:
  - accretion from the Be-disk of the companion star
  - so far only neutron stars

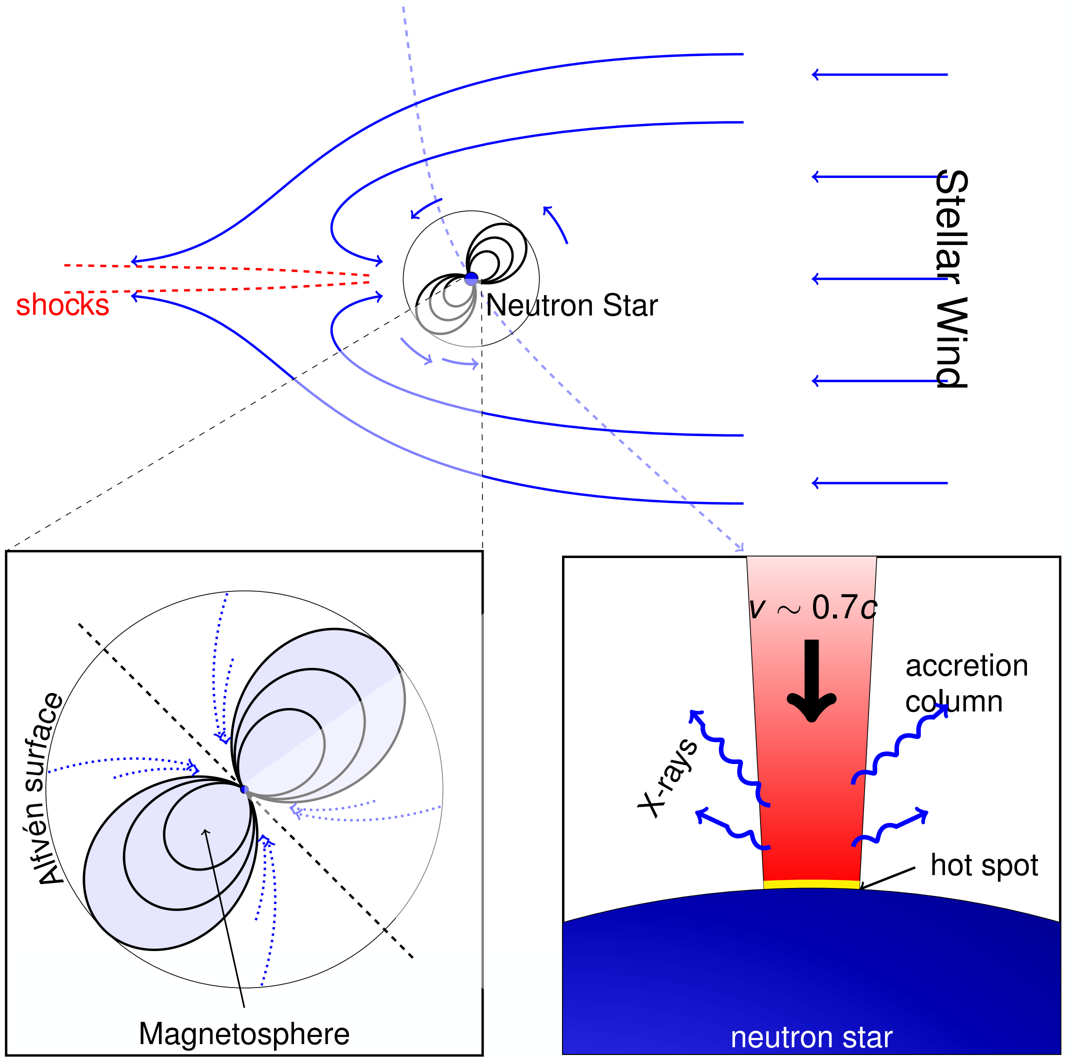
- SGXBs
  - accretion from the wind of a supergiant companion
  - usually wind fed, but some disk feeding possible (also mixed cases)
  - SFXTs important subclass with high dynamical range & shorts (~hours outbursts); outburst mechanism unclear



Van den Heuvel 2004

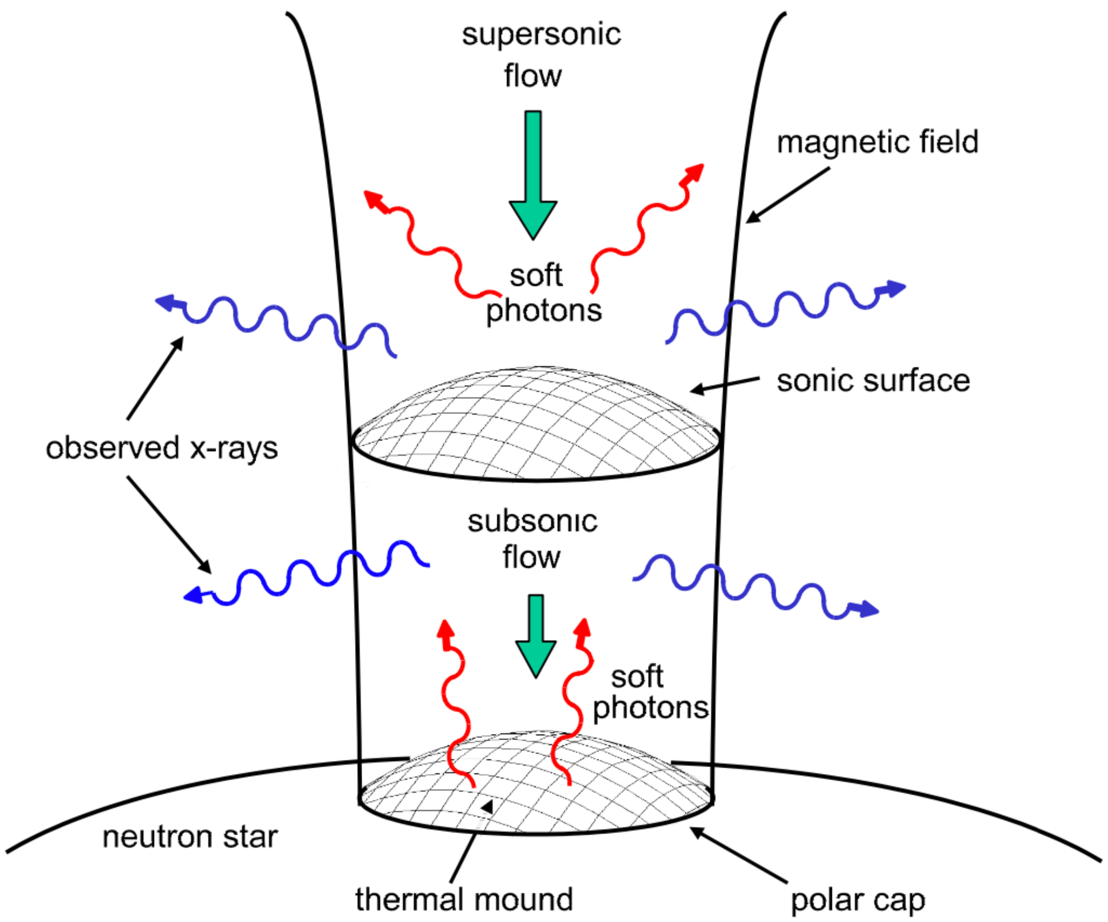
Accretion in highly magnetized neutron stars

- material captured by NS gravitational field
- material couples to magnetic field (no disk formation or a disk with a very large gap in the middle!)
- formation of accretion column close to NS surface
- cyclotron resonant scattering features ("cyclotron lines") in spectra of some neutron stars through quantization in high magnetic fields (direct measure of the B-field)
- strong pulse-phase dependence (LOS towards accretion columns)



Wilms 2014, after Davidson & Ostriker, 1973

Accretion in highly magnetized neutron stars



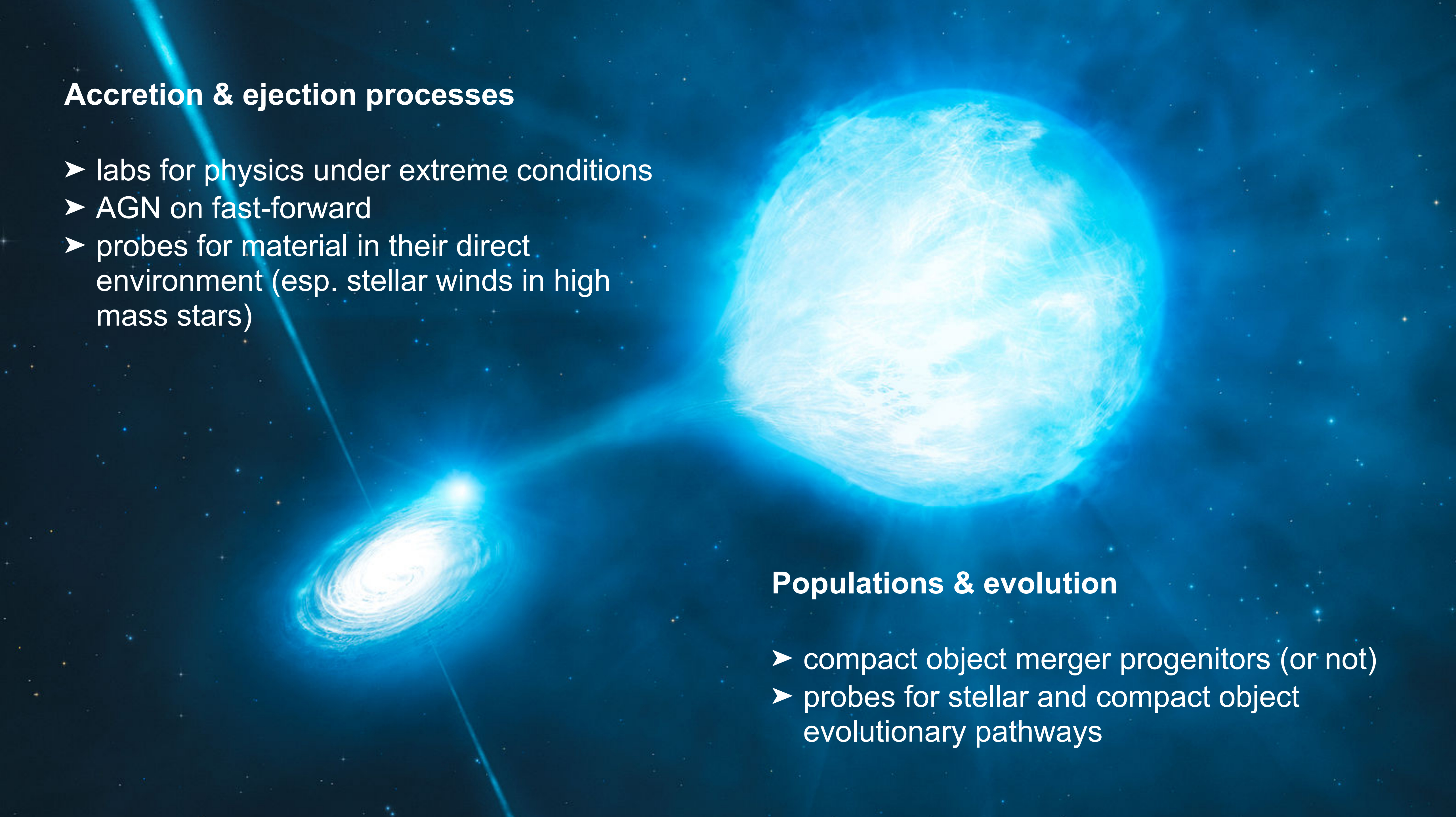
Becker & Wolff

Becker & Wolff (2005a,b, 2007): Accretion shock dominates formation of observed continuum

- accretion mound produces soft X-rays (bremsstrahlung)
- X-rays are upscattered in accretion shock (bulk motion Comptonization)
- hard X-rays diffuse through walls of accretion column

supercritical accretion: column locally super-Eddington, radiation balances accreted matter

subcritical accretion: Coulomb braking, some radiative pressure


Accretion & ejection processes
➤ labs for physics under extreme conditions
➤ AGN on fast-forward
➤ probes for material in their direct environment (esp. stellar winds in high mass stars)
Populations & evolution
➤ compact object merger progenitors (or not)
➤ probes for stellar and compact object evolutionary pathways

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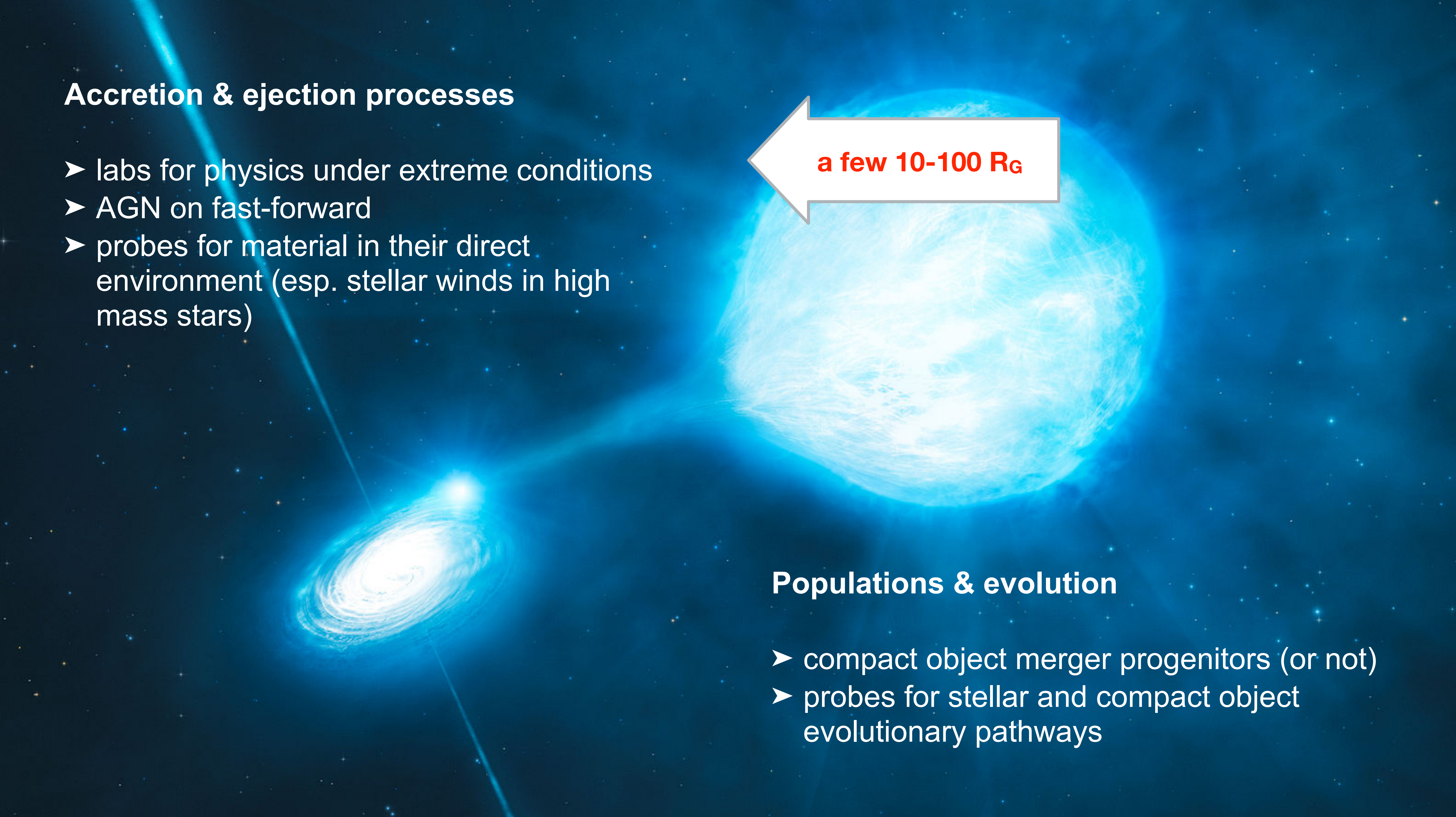

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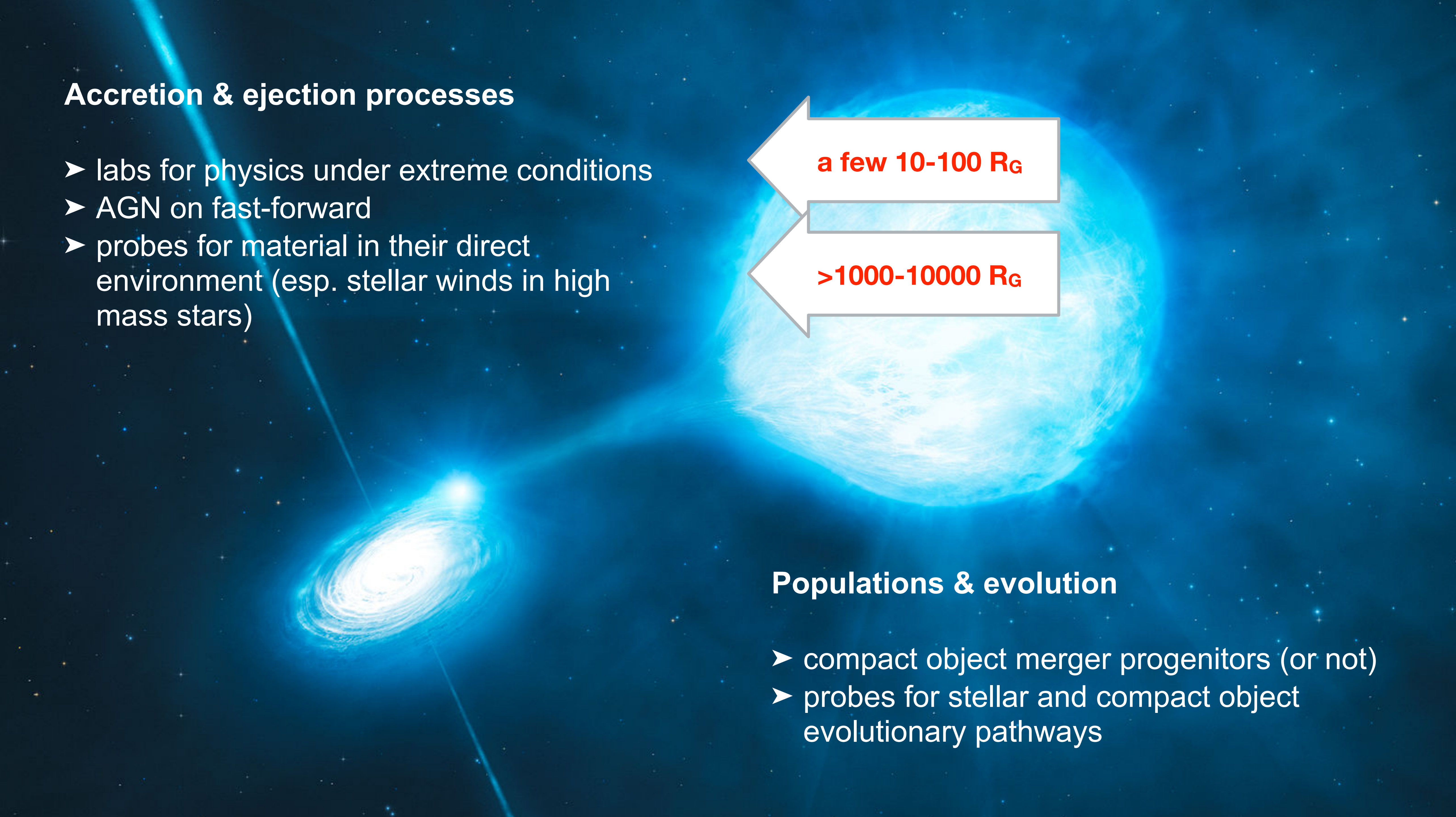

Populations & evolution

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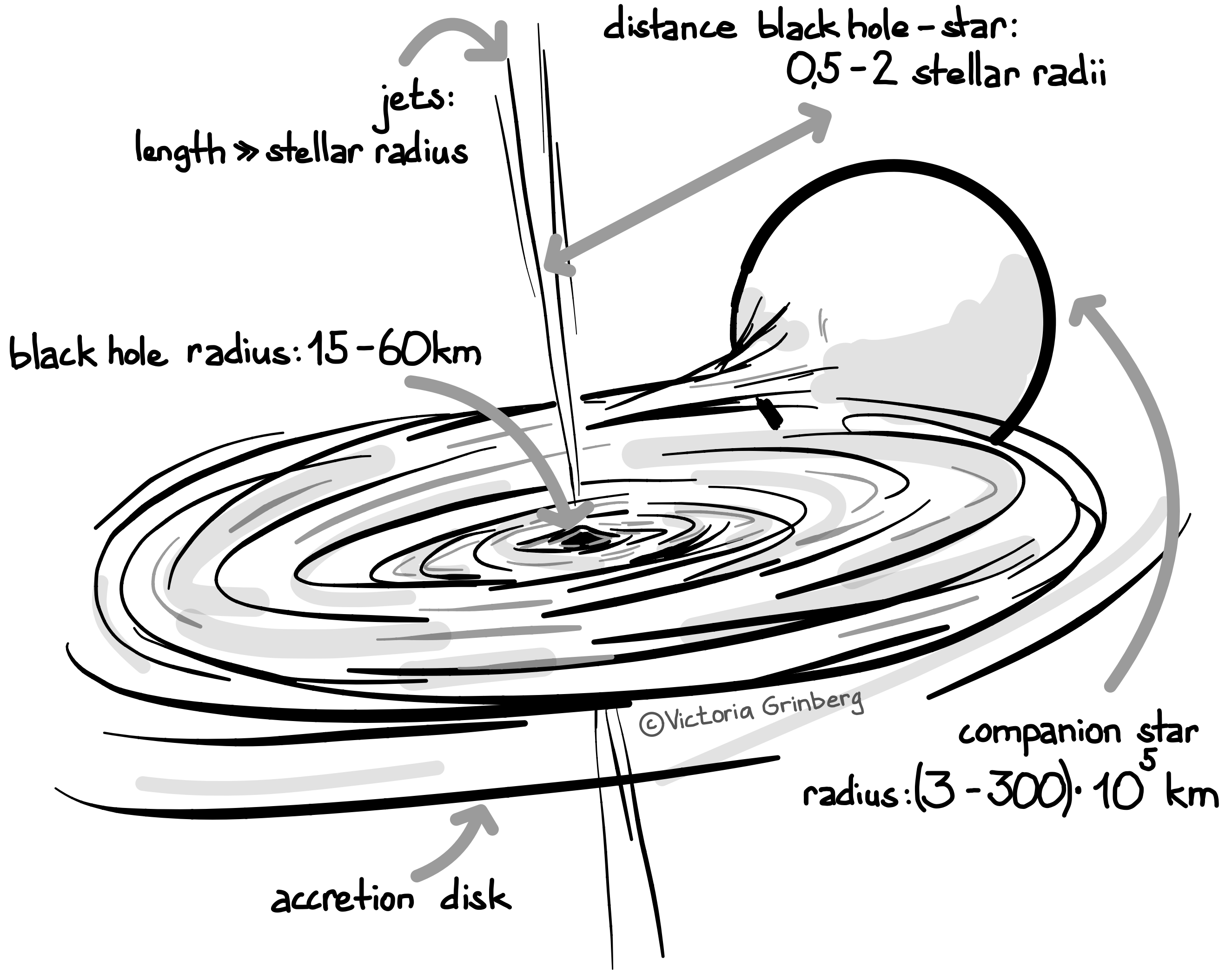
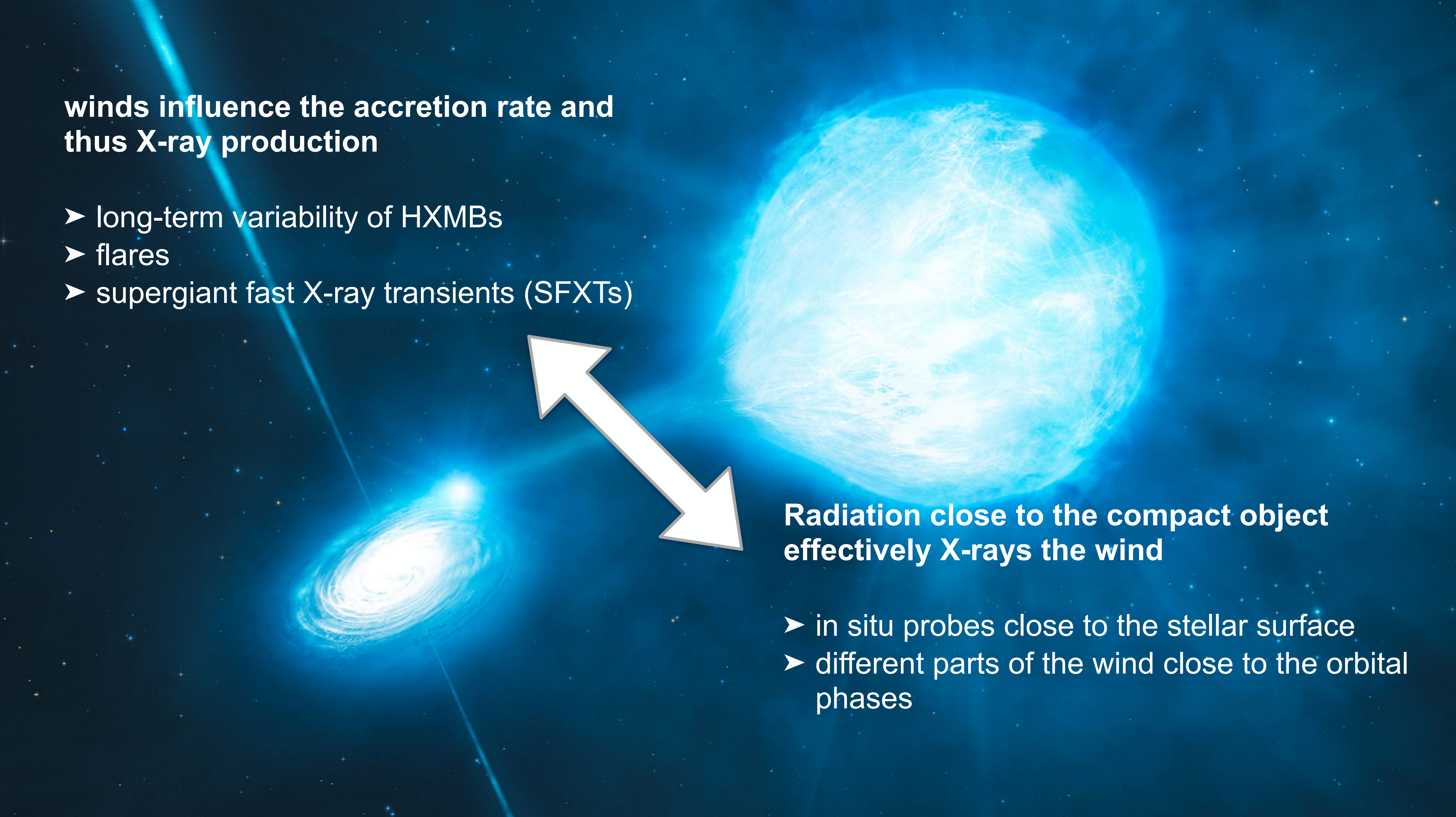
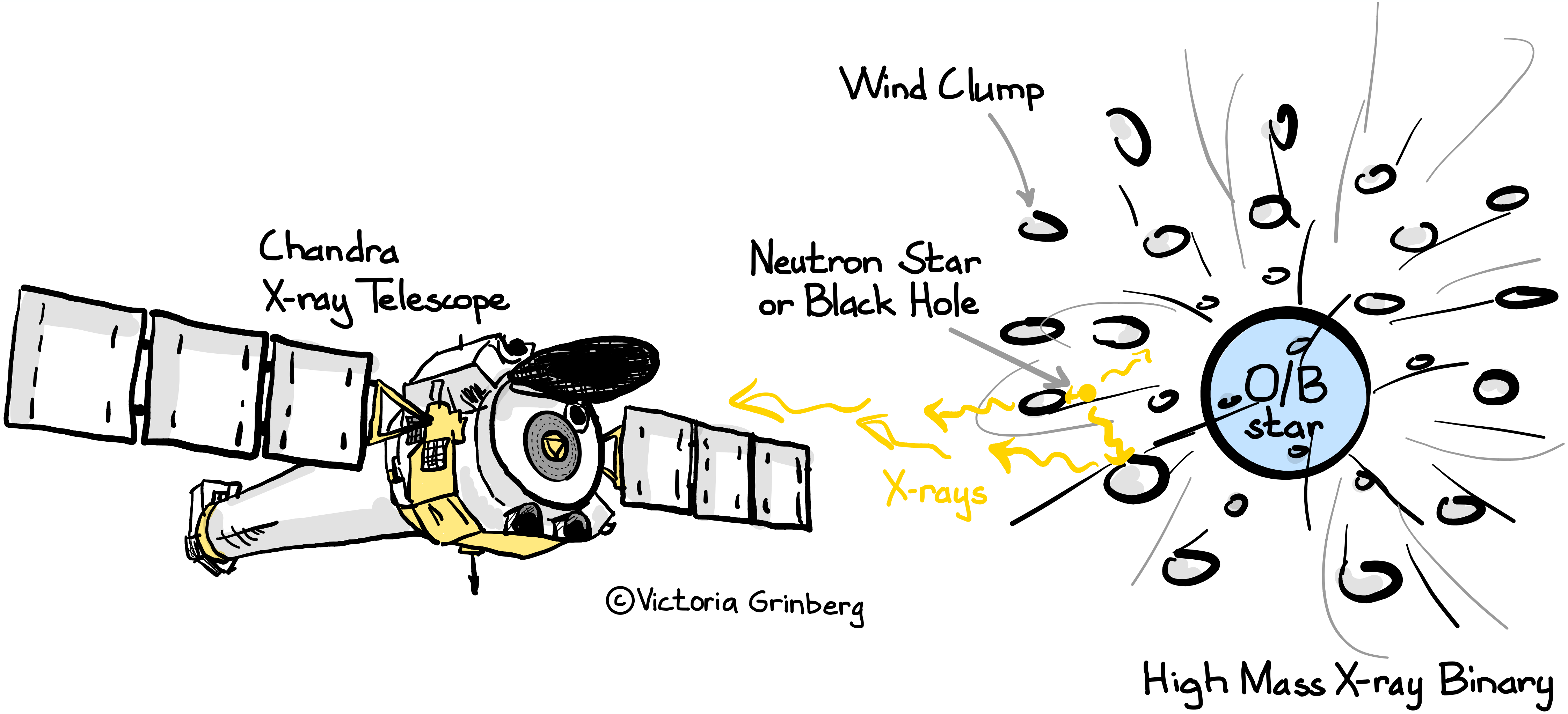
Scales in XRBs



- ➤ compared to the overall scales of the binary system, the complex physics close to the compact object is a point-like source!


winds influence the accretion rate and thus X-ray production
➤ long-term variability of HXMBs
➤ flares
➤ supergiant fast X-ray transients (SFXTs)
Radiation close to the compact object effectively X-rays the wind
➤ in situ probes close to the stellar surface
➤ different parts of the wind close to the orbital phases

One astronomers noise - is another's data!



Winds in massive stars

LH 72 in LMC; ESA/Hubble, NASA and D. A. Gouliermis

Line-driven winds:

- driven by radiation pressure (scattering of the star's UV radiation; CAK-winds after Castor, Abbott & Klein, 1975)
- mainly on UV lines
- mass loss $10^{-7} - 10^{-4}\ M_{\odot}/\mathrm{yr}$
- terminal velocity up to 3000 km/s

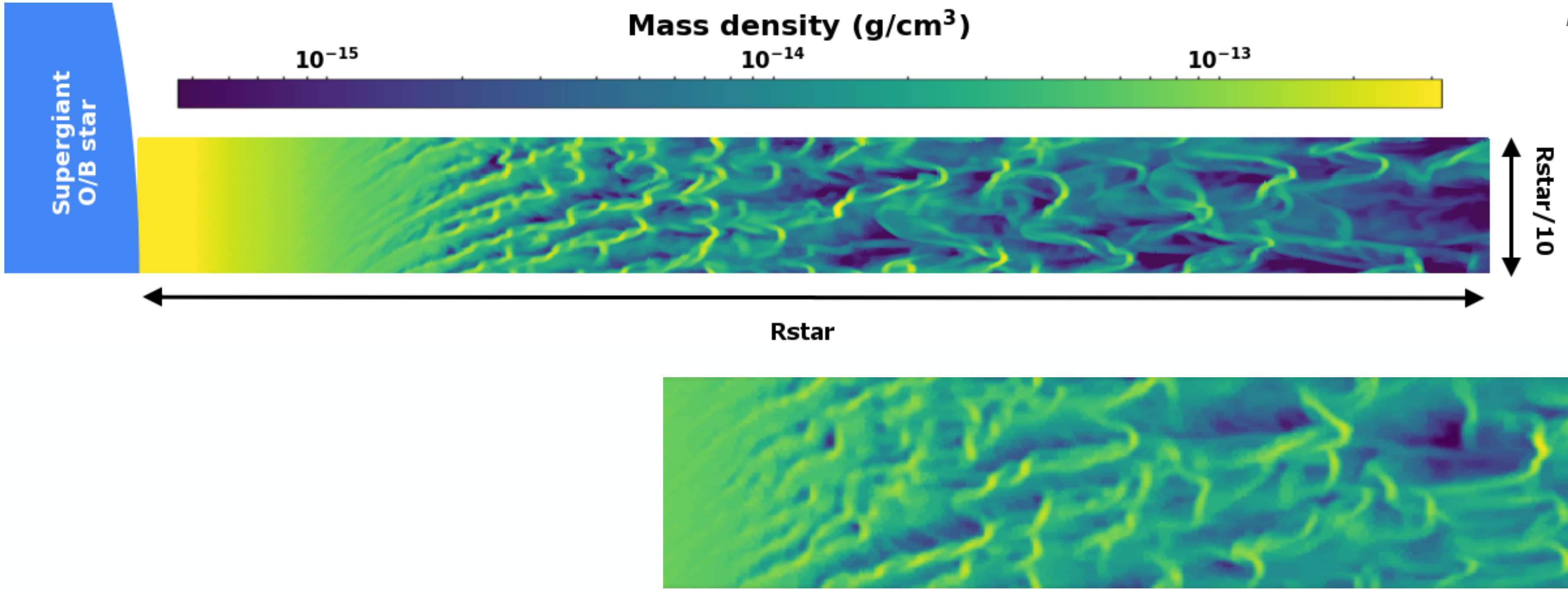
important for:

- evolution of the star itself
- supernova & gravitational wave progenitors
- star formation
- enrichment

But: strong differences in mass loss estimates

Winds structure

El Mellah+ 2018; Sundqvist+ 2018



Line-driving:

- ➤ unstable to velocity perturbations
- ➤ rapid growth of perturbations
- ➤ strong shocks lead to wind clumping

Multiple lines of evidence for wind clumping from single stars, but no way to probe individual clumps & thus to test theoretical wind models

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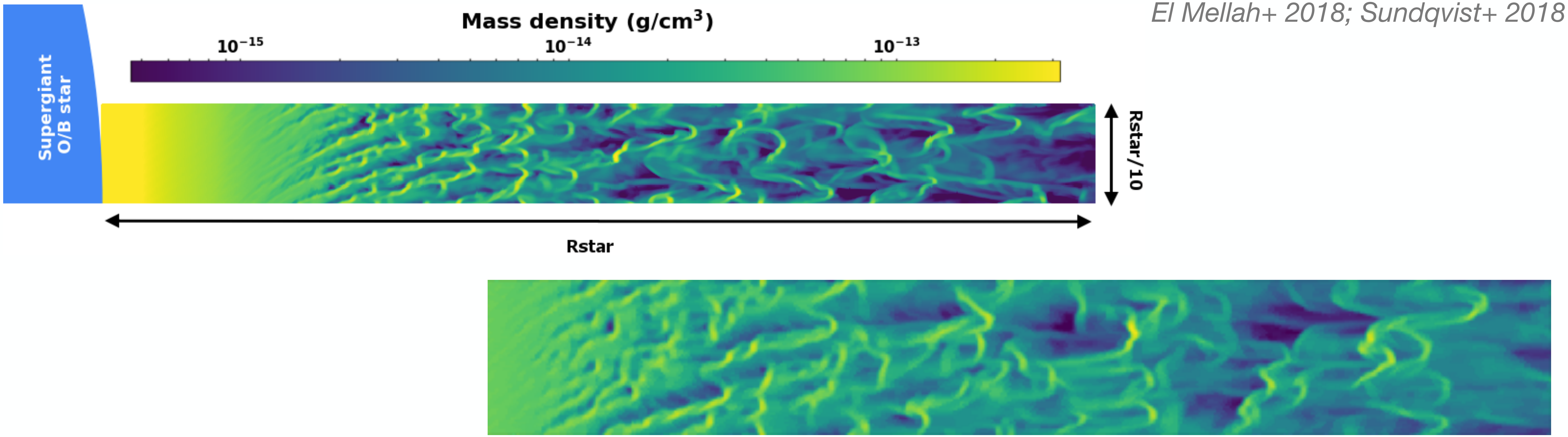

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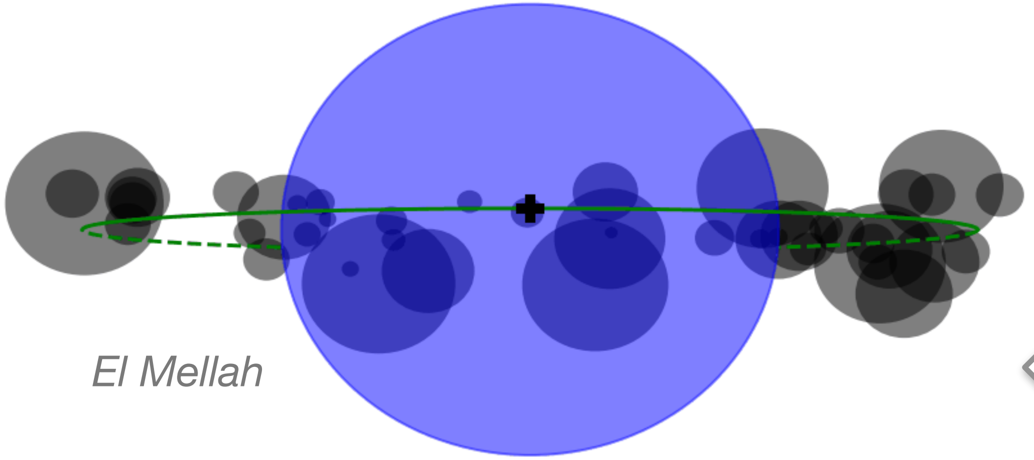
Absorption variability in HMXBs

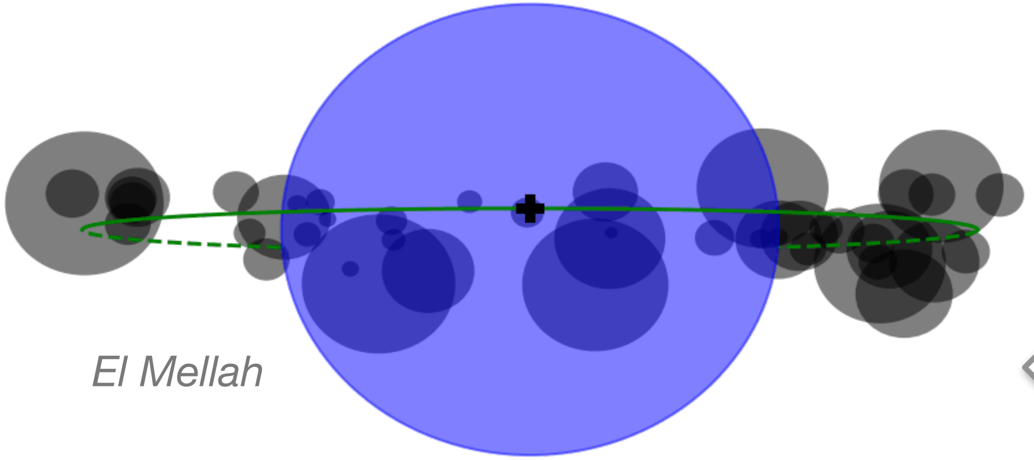


El Mellah

varying absorption as clumps pass through the line of sight: “dips”

- typical clump crossing times ~a few 10s-1000s
- not accessible with today’s high resolution X-ray instruments (& only in brightest sources with non high res instruments!)
- chance to probe the structure of clump plasma

Absorption variability in HMXBs



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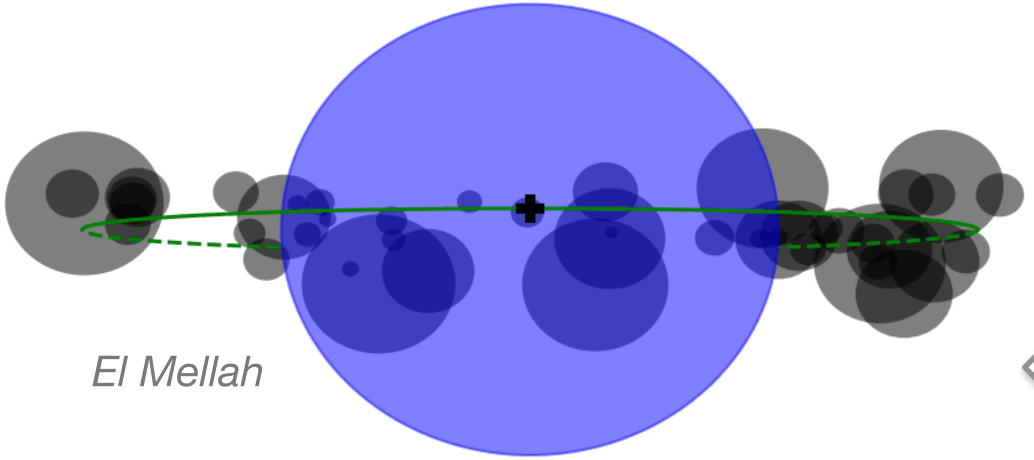

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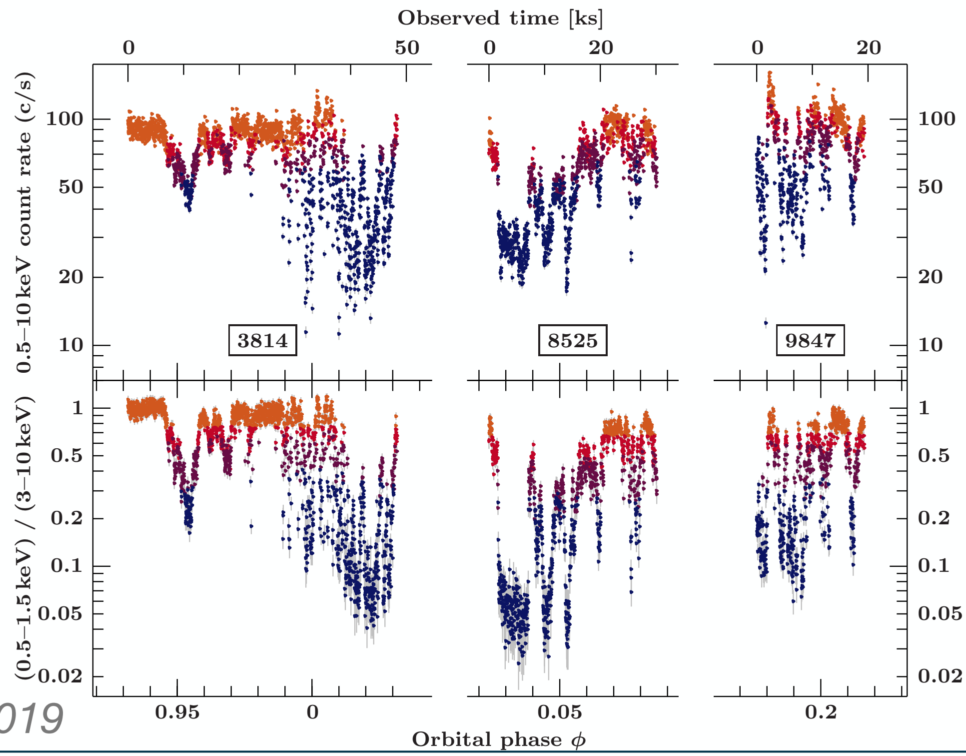

Hirsch+ 2019

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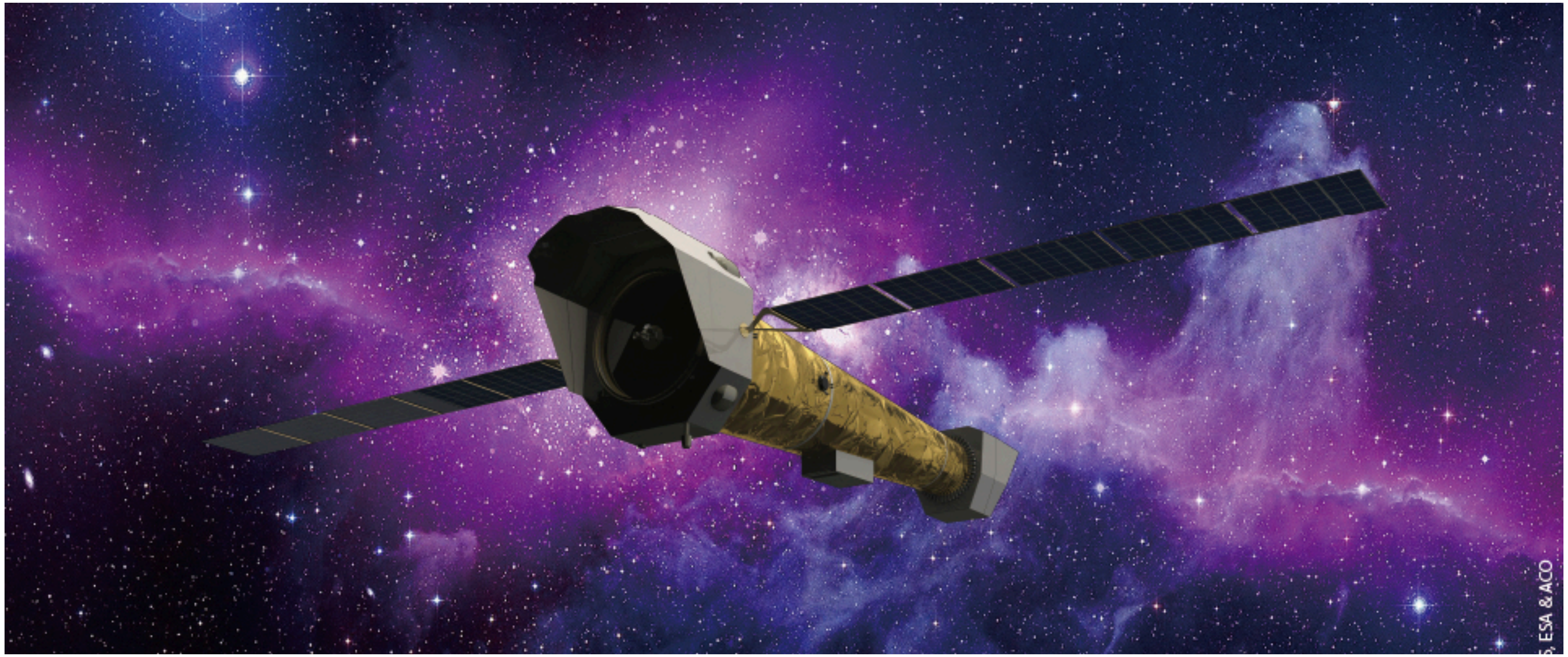
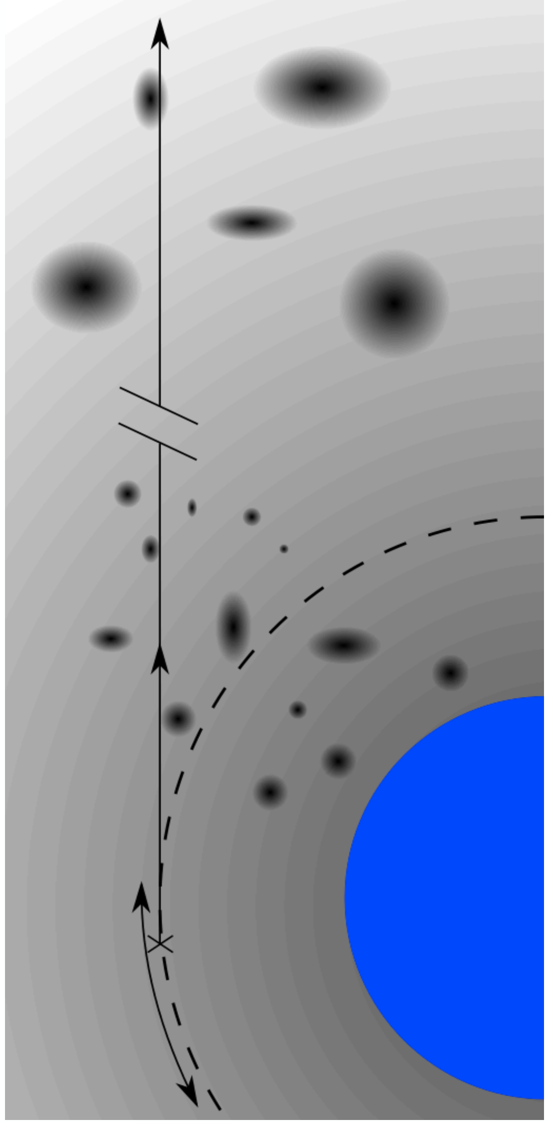
(Old) Athena science requirements



R-SCIOBJ-322: Athena shall determine the geometry, porosity and mass-loss rate of stellar winds of isolated massive stars, especially in the presence of magnetic fields, for a sample of Galactic massive stars. **Time resolved spectral analysis of X-ray emission from a sample of high mass X-ray binaries hosting supergiant companions will provide an independent and representative probe of massive star wind properties.**

Big questions



Grinberg+ 2017

Wind properties:

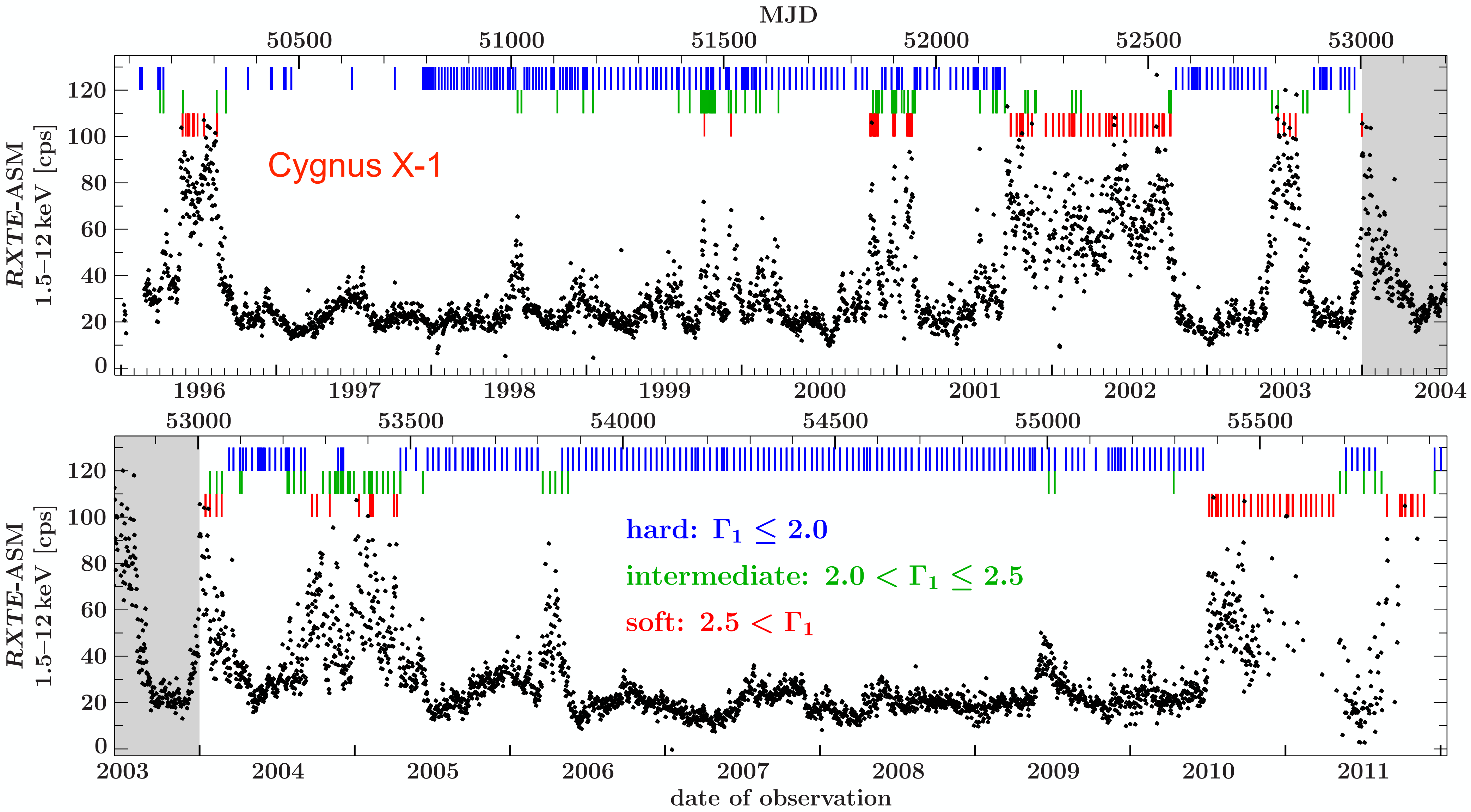
- clumps: structure, size, shape & occurrence
- clumping onset
- wind acceleration zone
- wind's response to changes in irradiation
- co-rotating interaction regions (CIRs)
- mass loss rate

Accretion structure:

- clumps: structure, size, shape & occurrence
- accretion & photoinization wake structure
- clumpy accretion
- disk formation

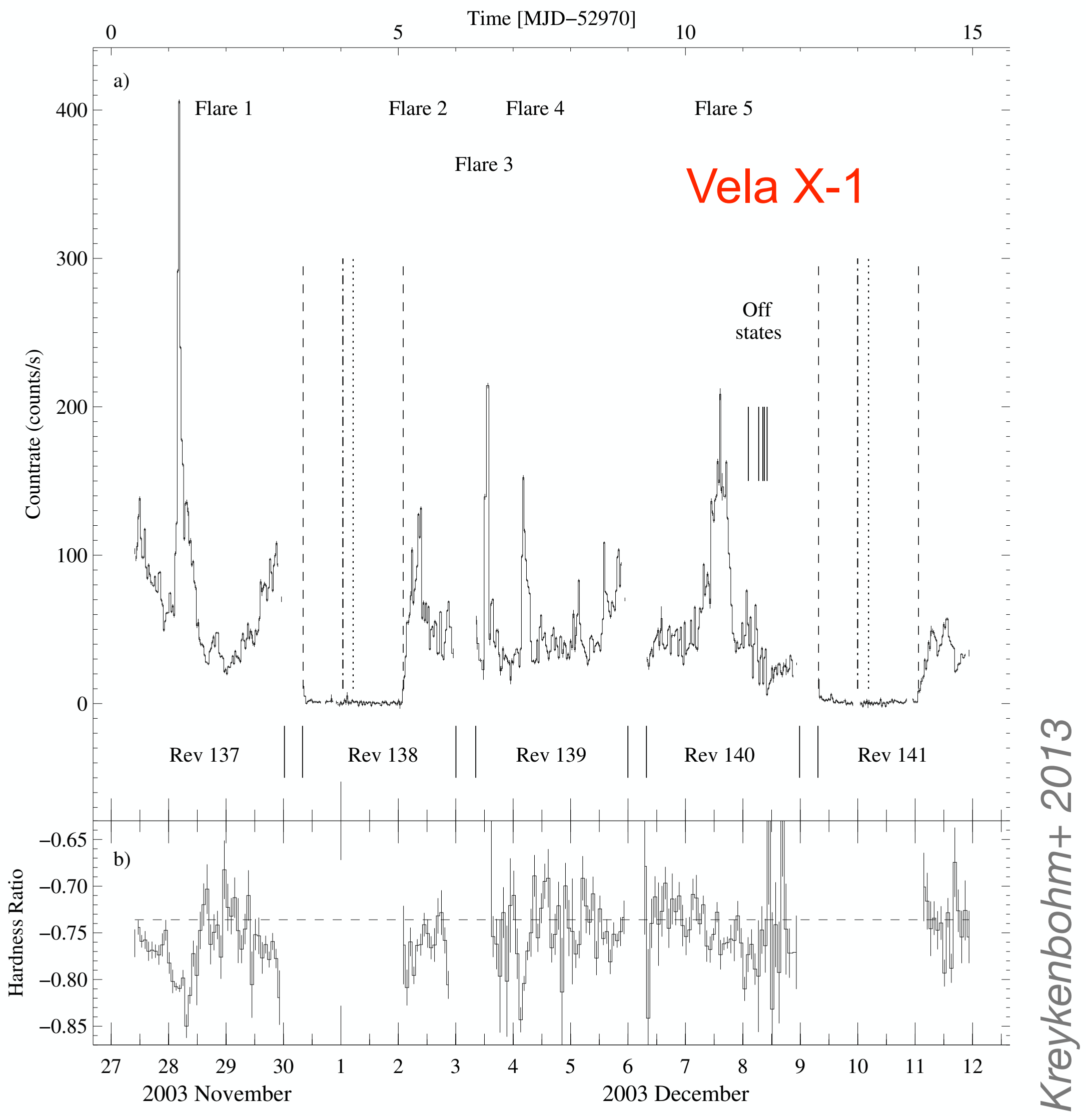
mass loss rates in O/B stars
accretion history of HMXBs

Challenge I: variability



Grinberg+ 2013

Challenge I: variability



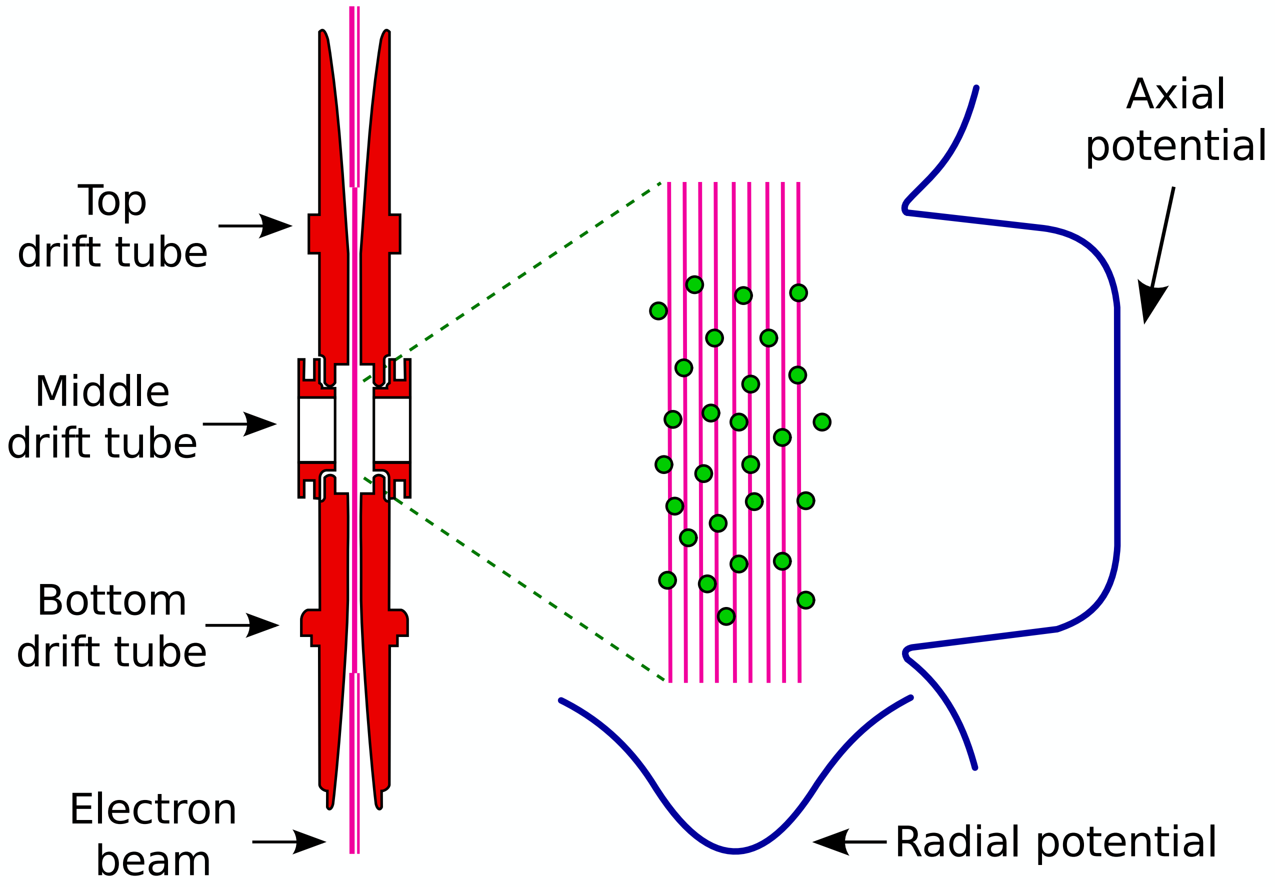
- ➤ continuum and wind variability need to be disentangled!
- ➤ variable continuum emission can influence wind material (e.g. through ionization)

Challenge II: Atomic data

clumps are denser & colder $\Longrightarrow$ lower ionization lines (theory easier for H- & He-like lines, really hard otherwise!)

Observations: $E_{\rm obs} \neq E_{\rm lit} \Longrightarrow$ Gas properties or lack of knowledge of atomic physics?

solution: lab measurements!



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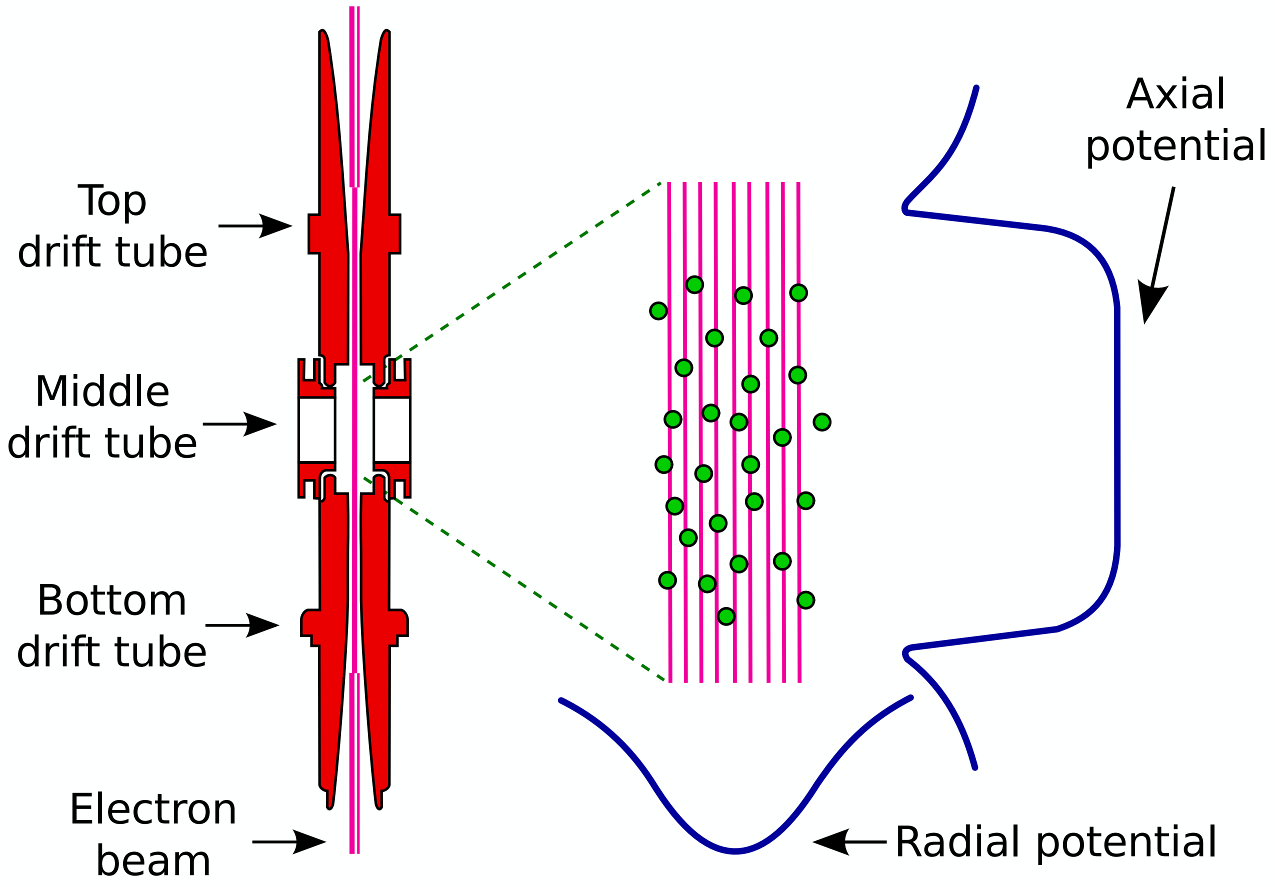
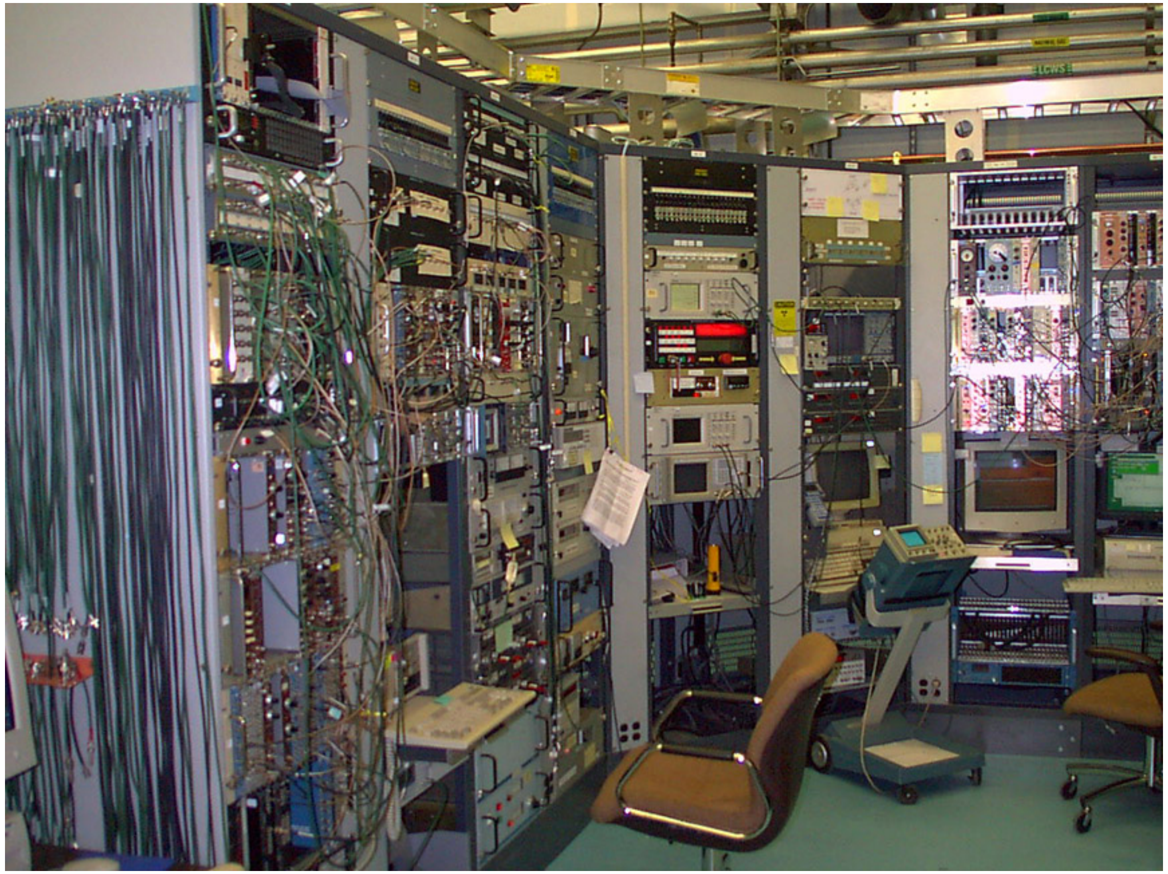
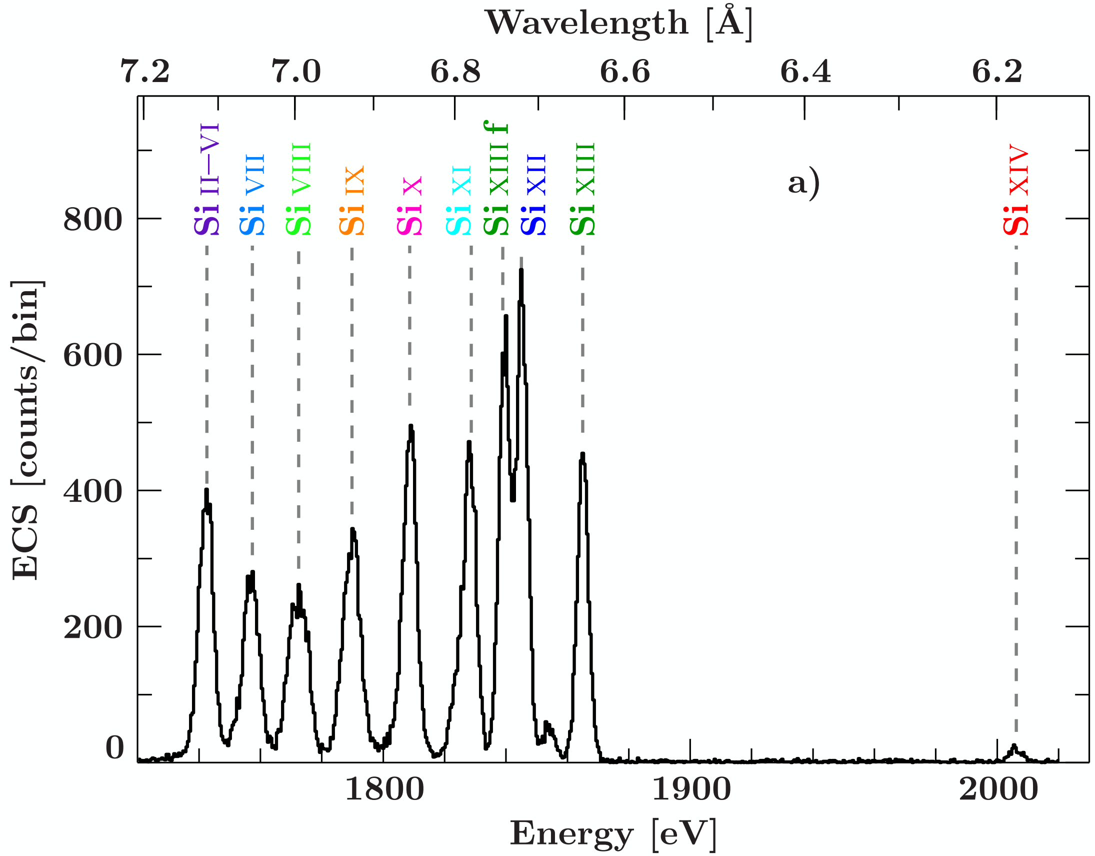


https://ebit.llnl.gov/overviewEBIT.html

Challenge II: Atomic data





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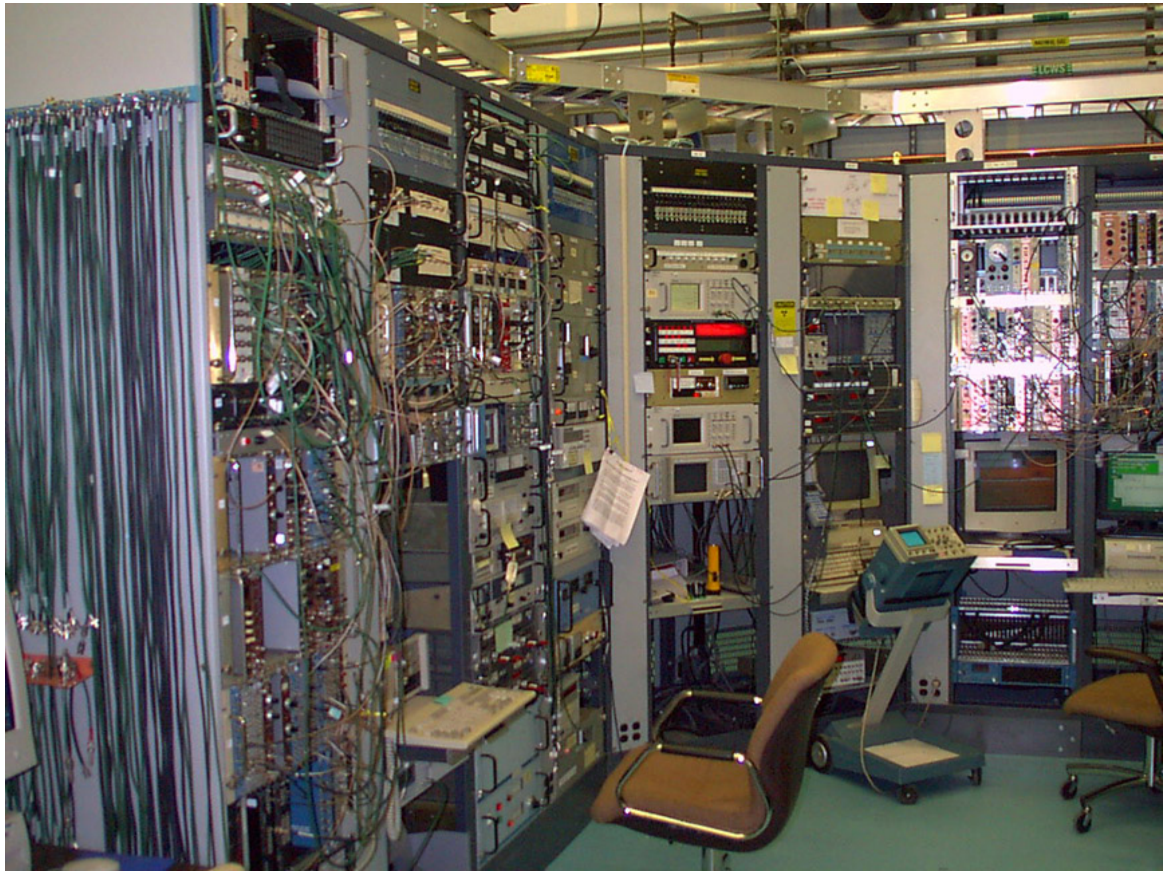
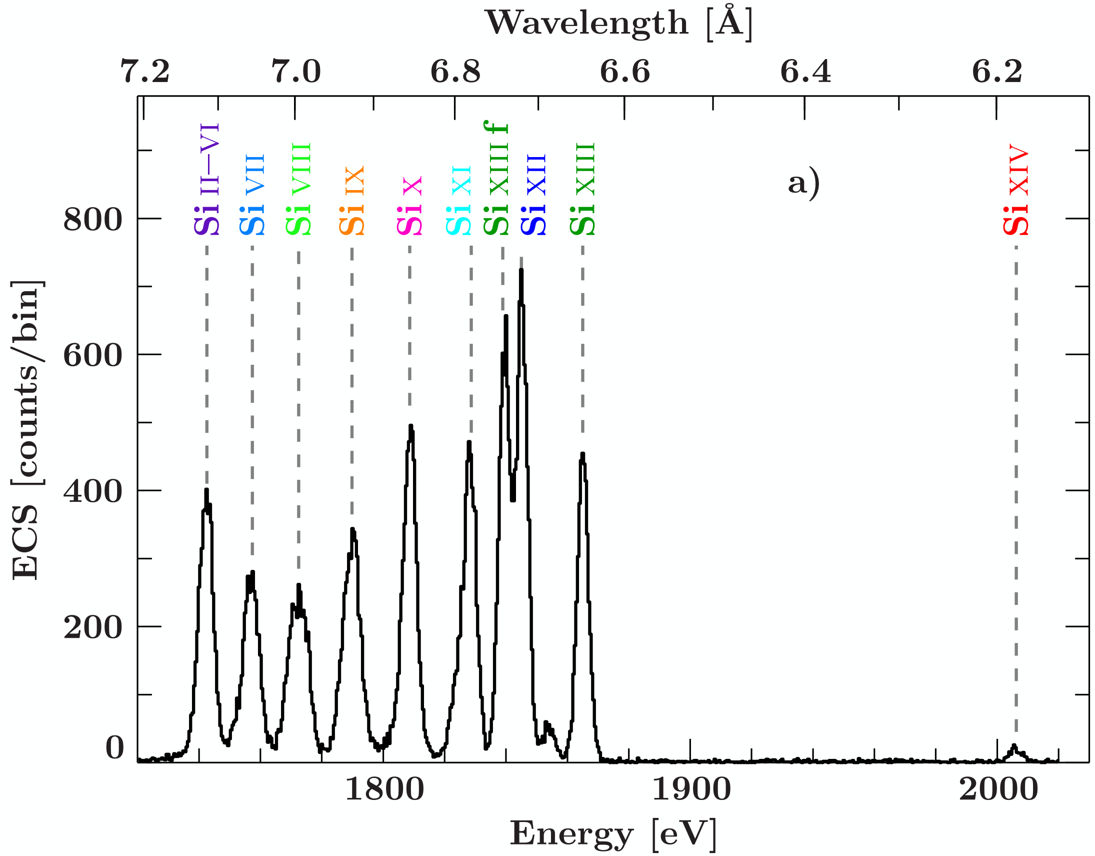
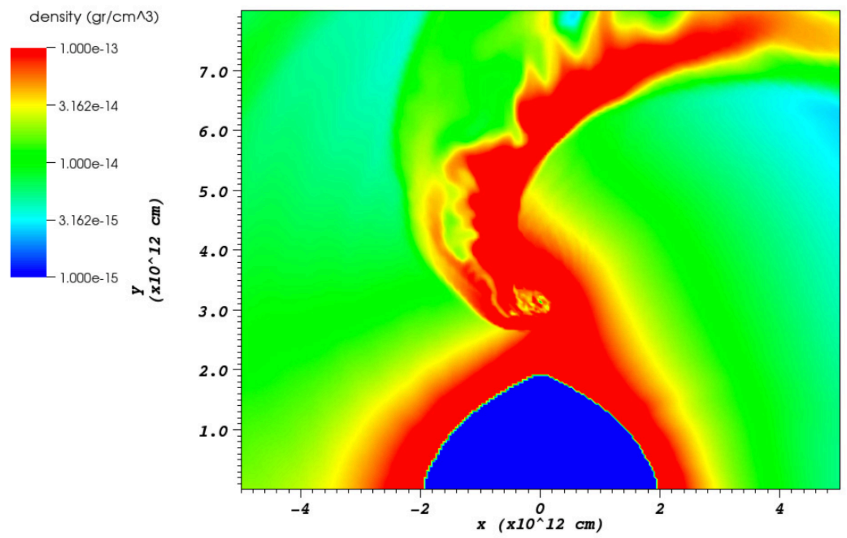


N. Hell (LLNL)

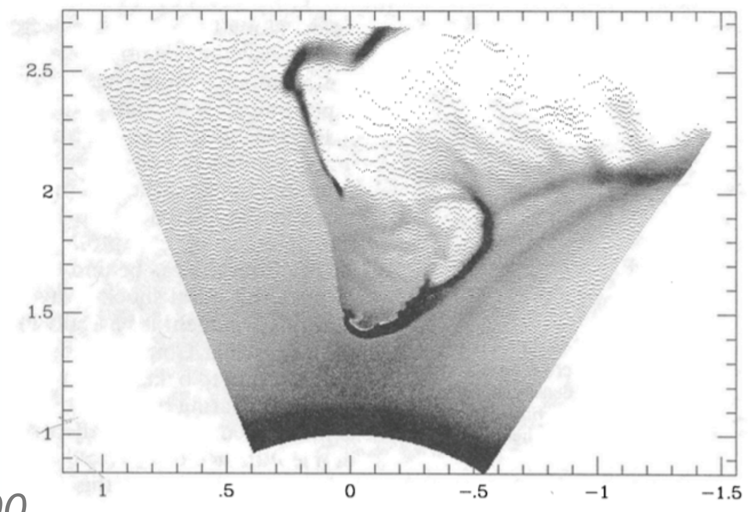


Hell et al. 2016

Challenge III: compact object-wind interaction



Manousakis et al. 2013



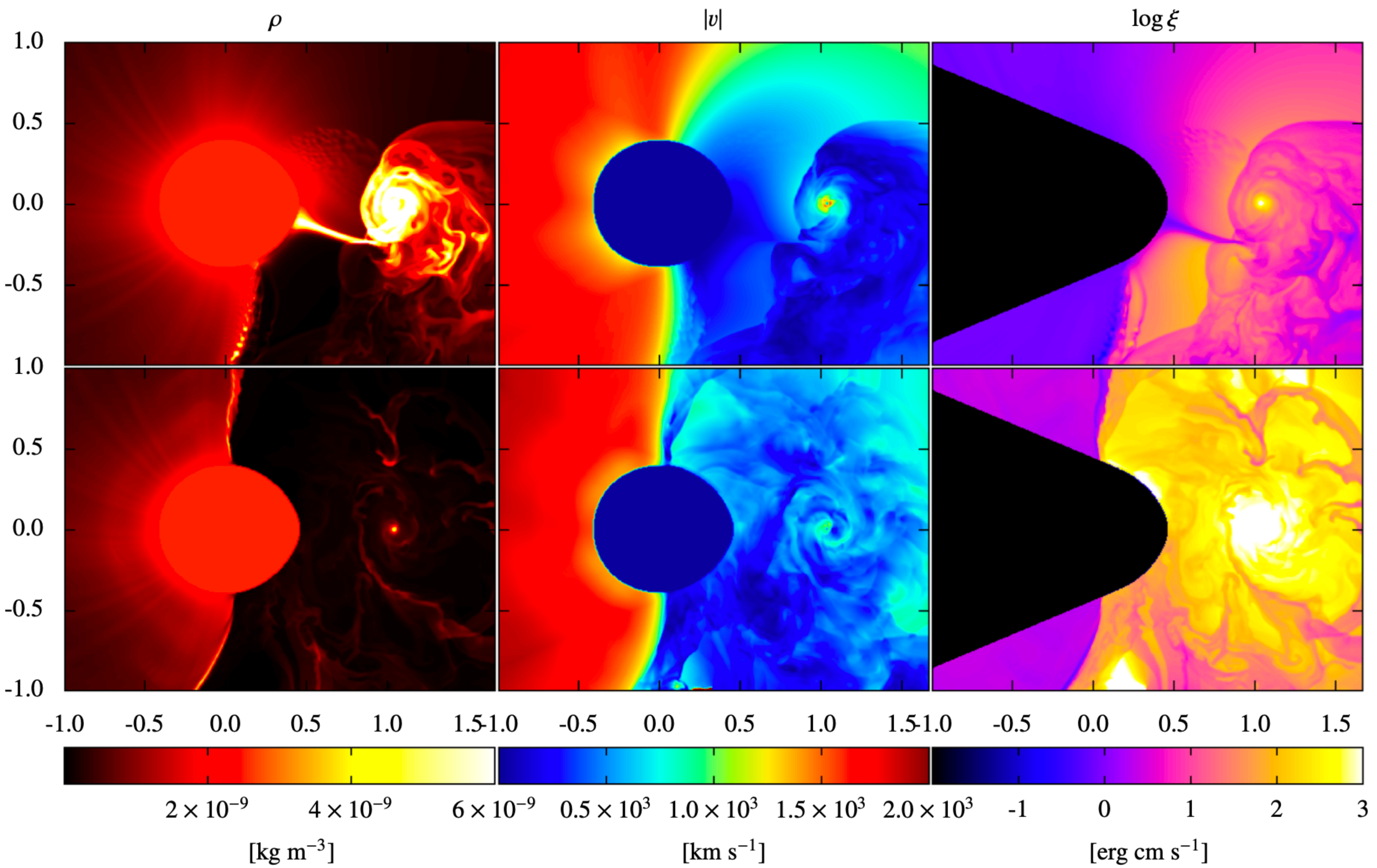
Blondin+ 1990

compact object disturbs the wind, resulting in large-scale wind structure (wakes, focussed wind)

- ➤ accretion wake: focussing of the wind through gravity
- ➤ photoionization wake: shocks on inter-face between wind and ionized plasma around neutron star

Most analytical & numerical models work with smooth winds only (but work by El Mellah & collaborators)

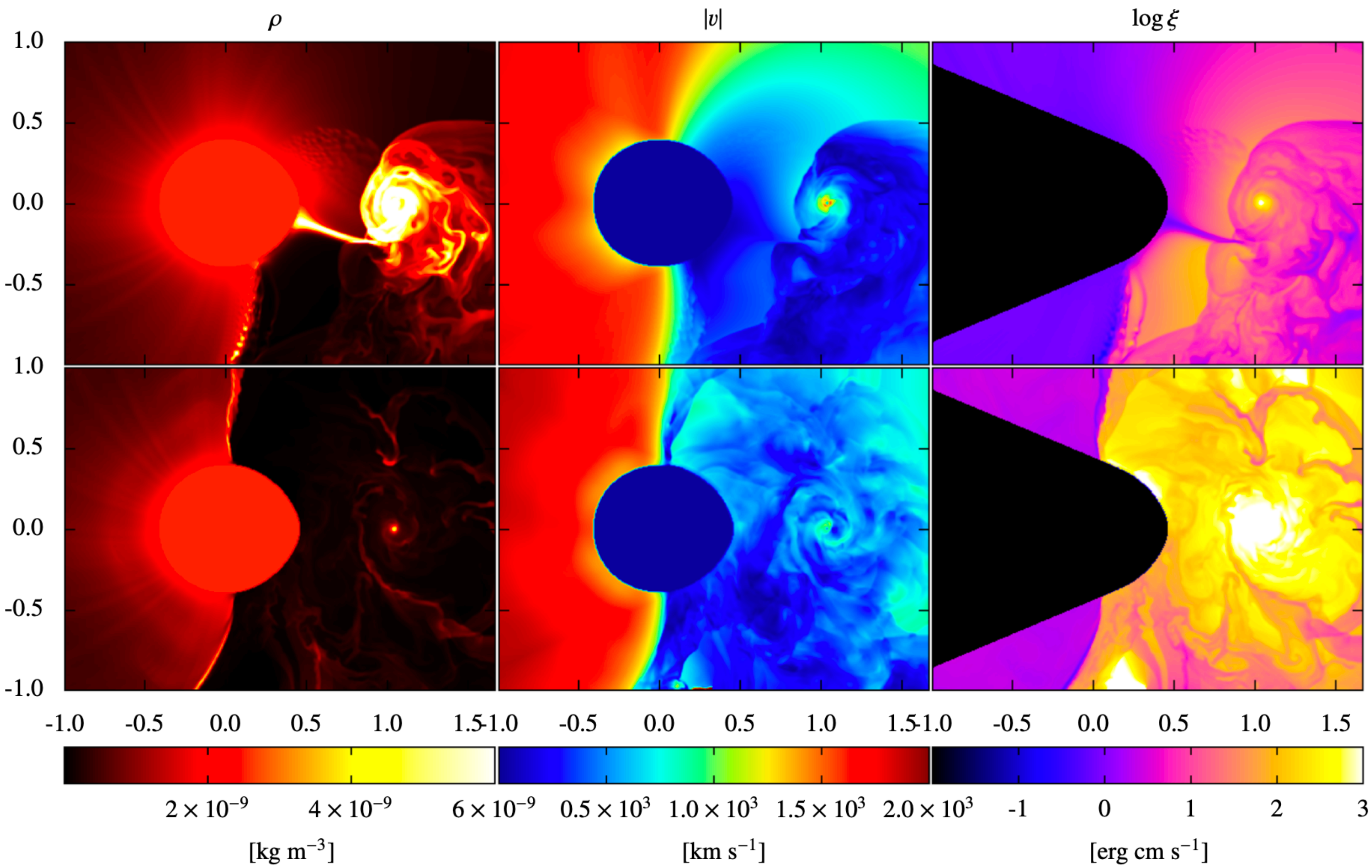
Challenge III: compact object-wind interaction



changes in illumination lead to changes in wind structure!

Cechura + Hadrava, 2015

Chance: compact object-wind interaction



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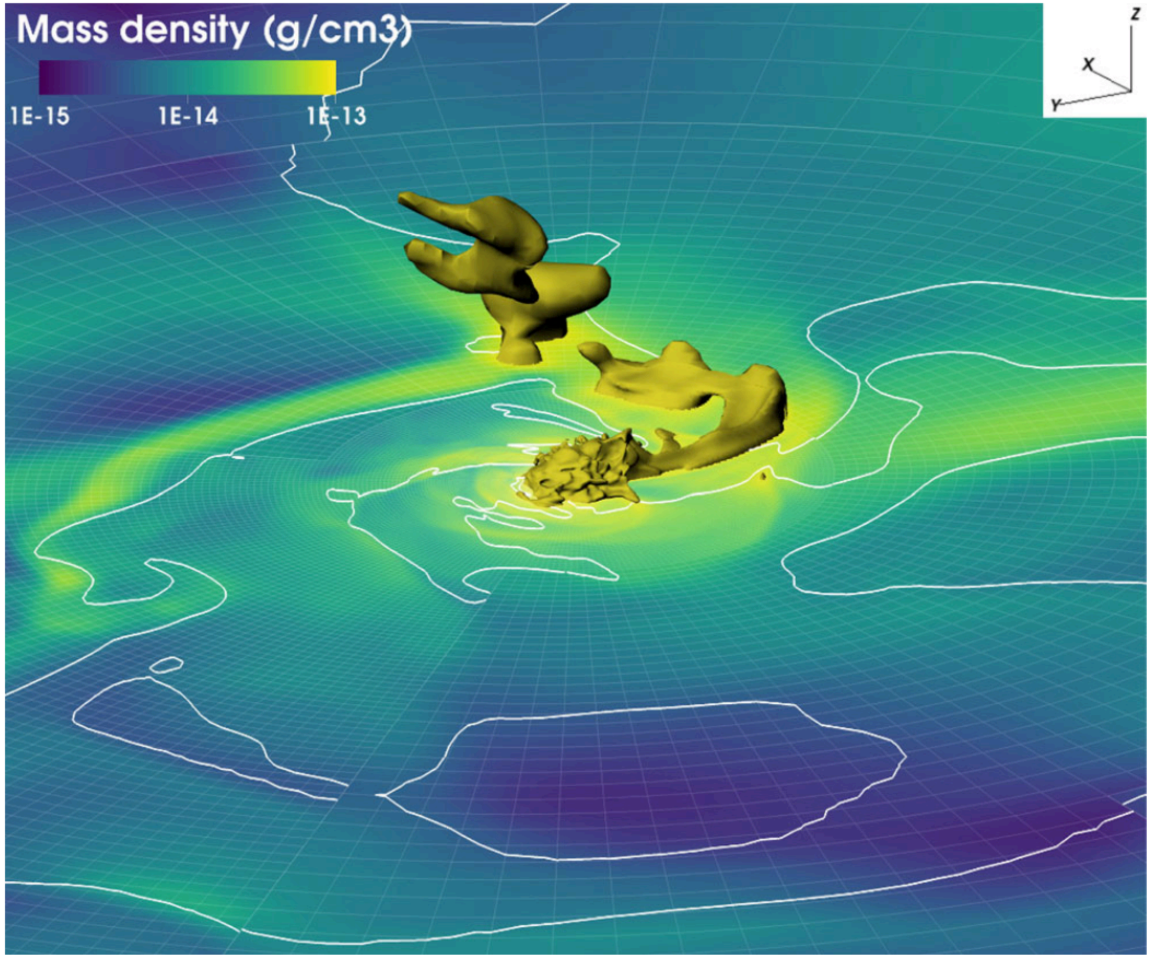
Clumpy accretion simulations



El Mellah+ 2018

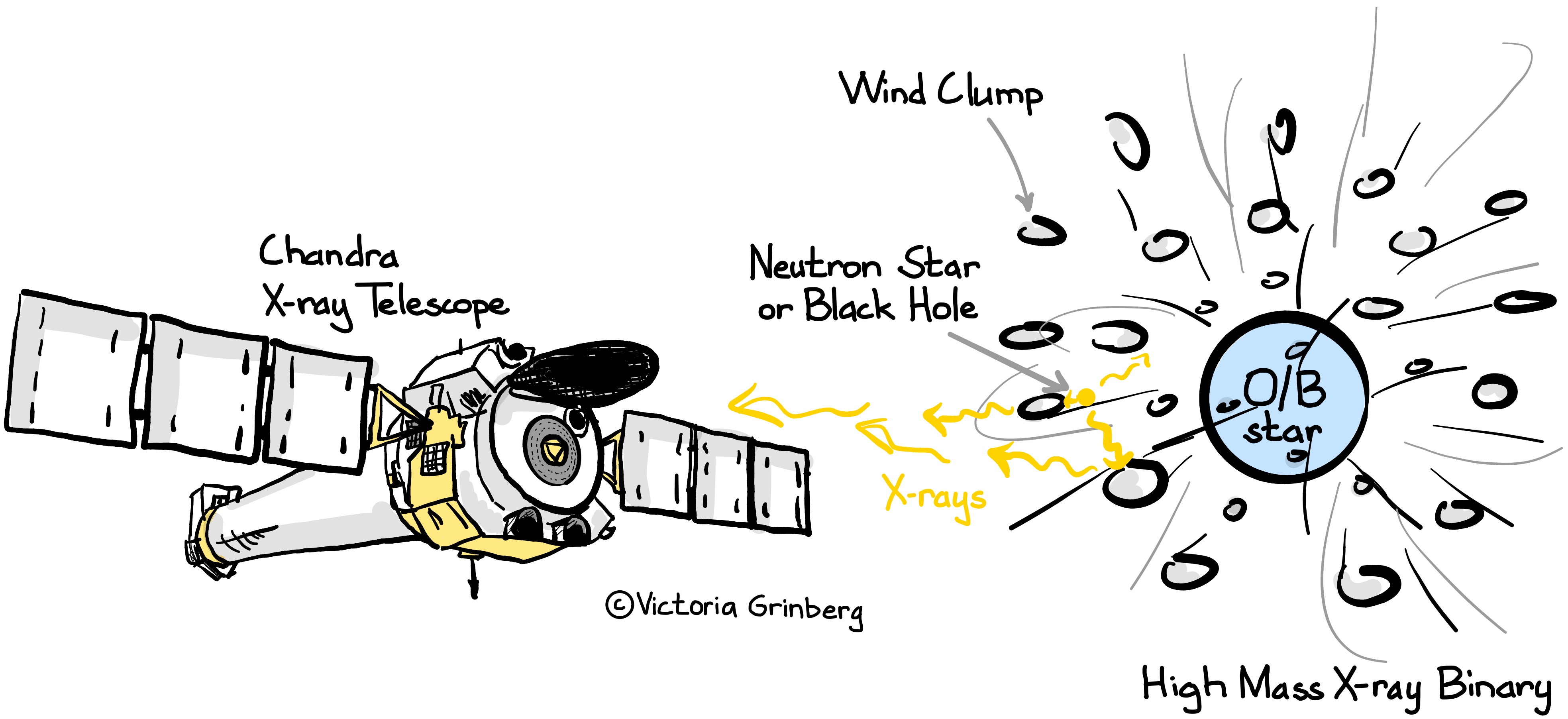
- ➤ 3D hydro simulations
- ➤ inhomogeneous flow and formation of bow shock
- ➤ complex effects close to the compact object (angular momentum conservation!)

Questions?

Questions?

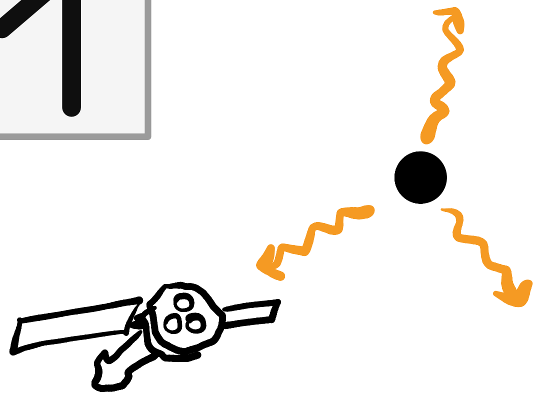
Next: how do we do stuff?

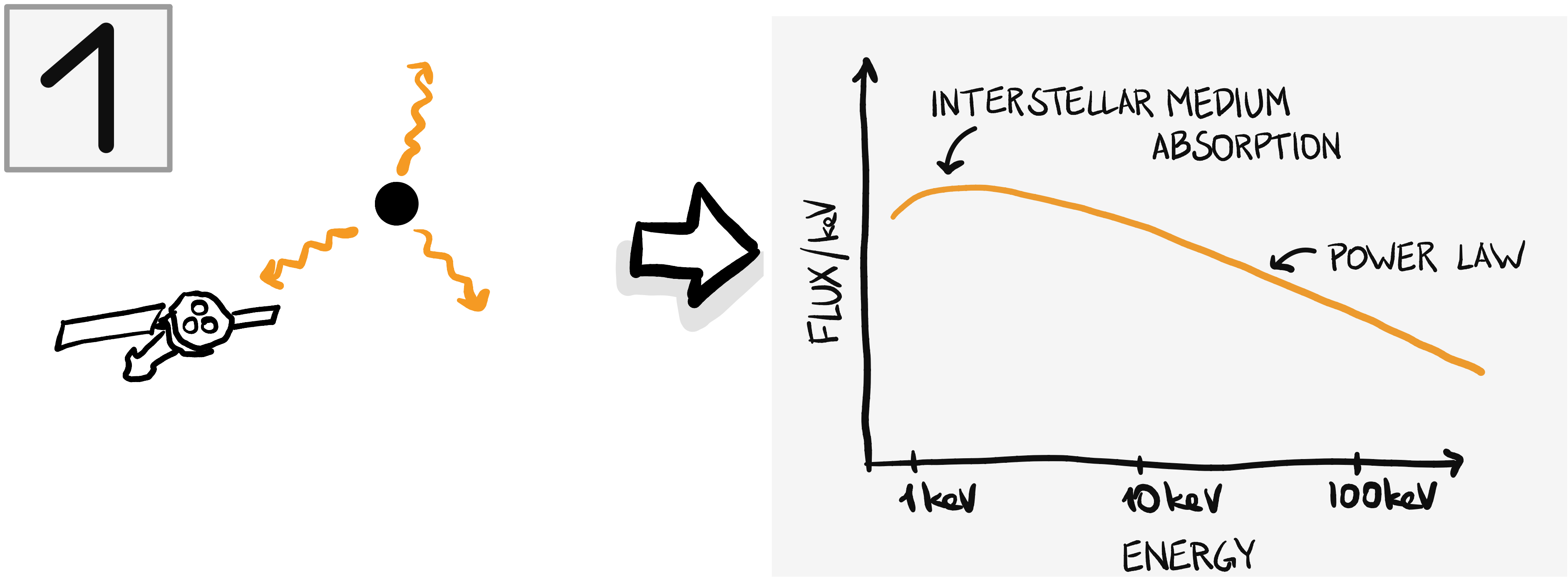
Observational approaches



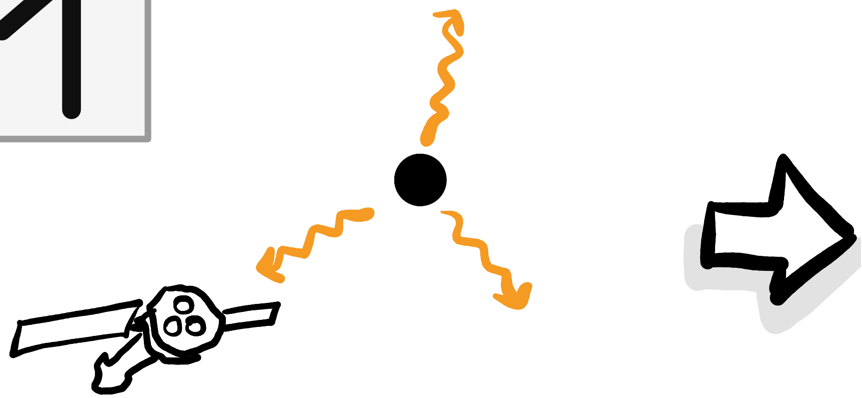
- ➤ broadband absorption traces wind structure
- ➤ narrow features traces plasma properties

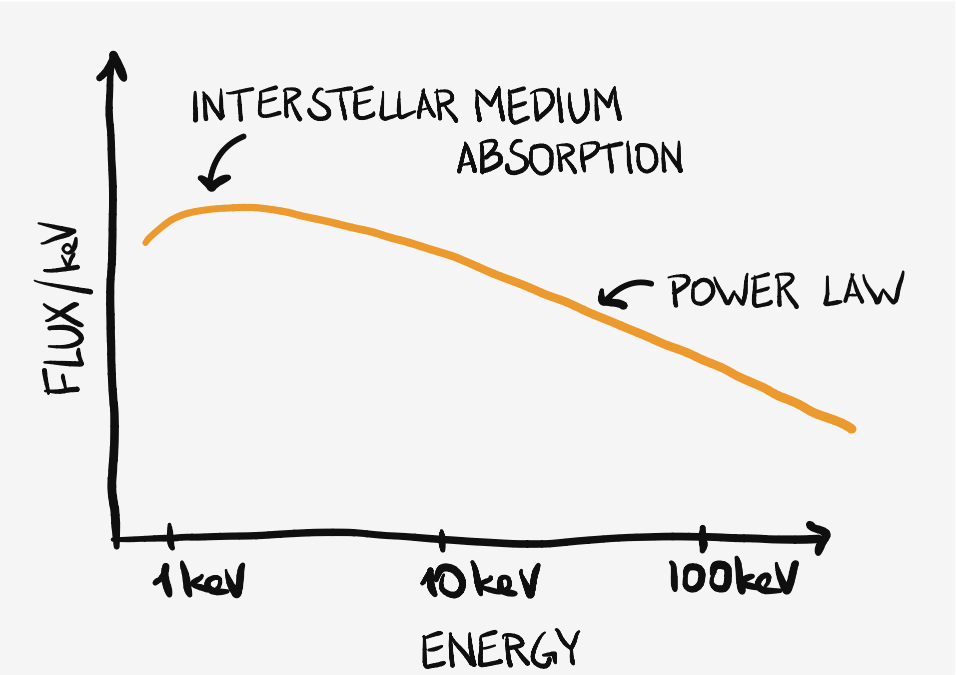
1




1
INTERSTELLAR MEDIUM ABSORPTION
POWER LAW
FLUX / keV
1 keV
10 keV
100 keV
ENERGY

1




INTERSTELLAR MEDIUM
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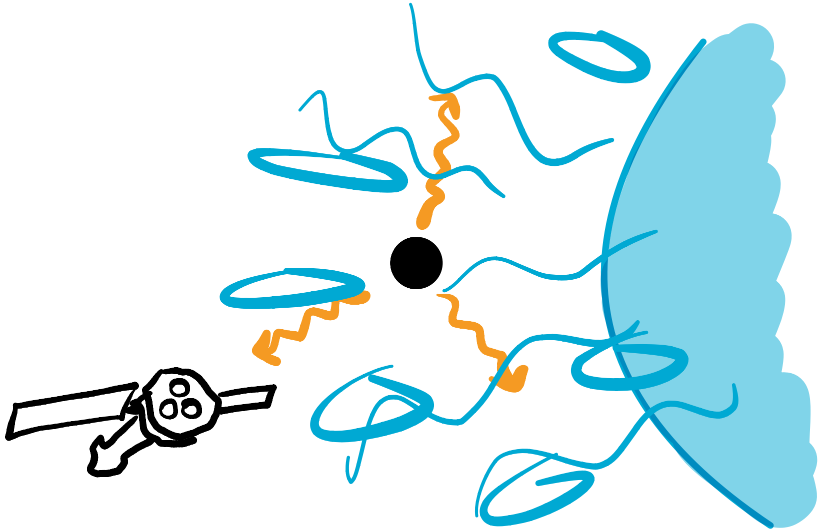
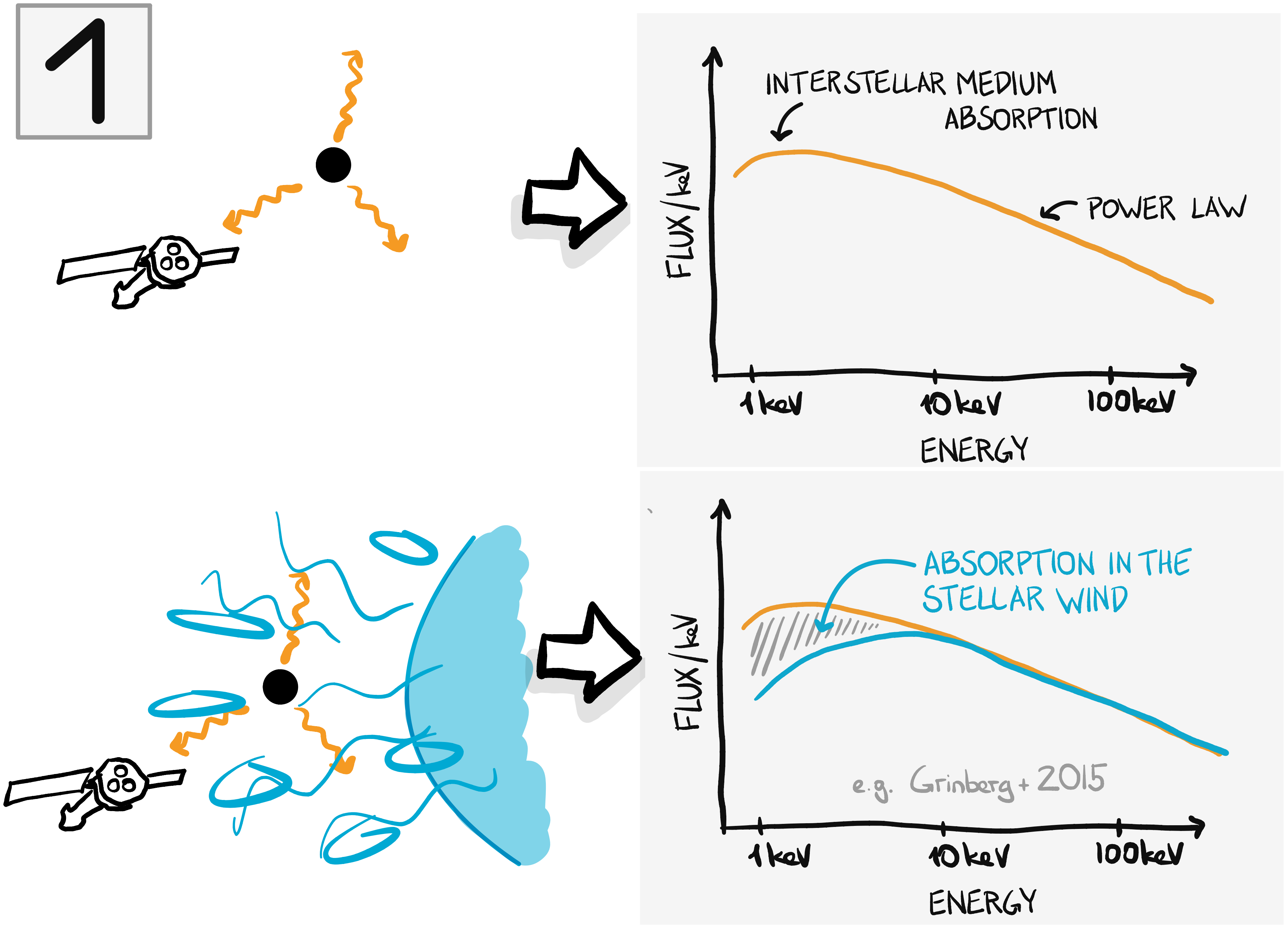
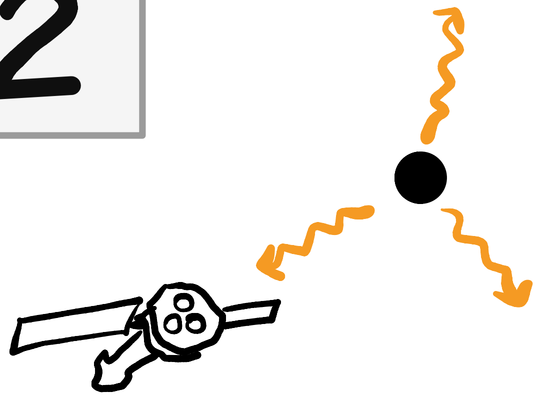
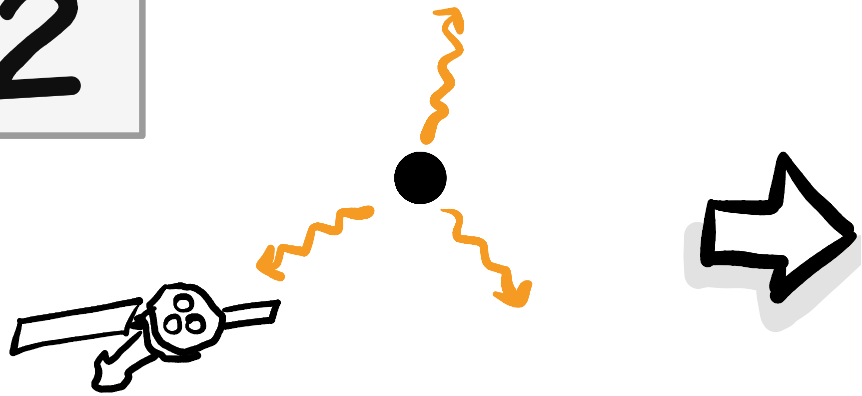


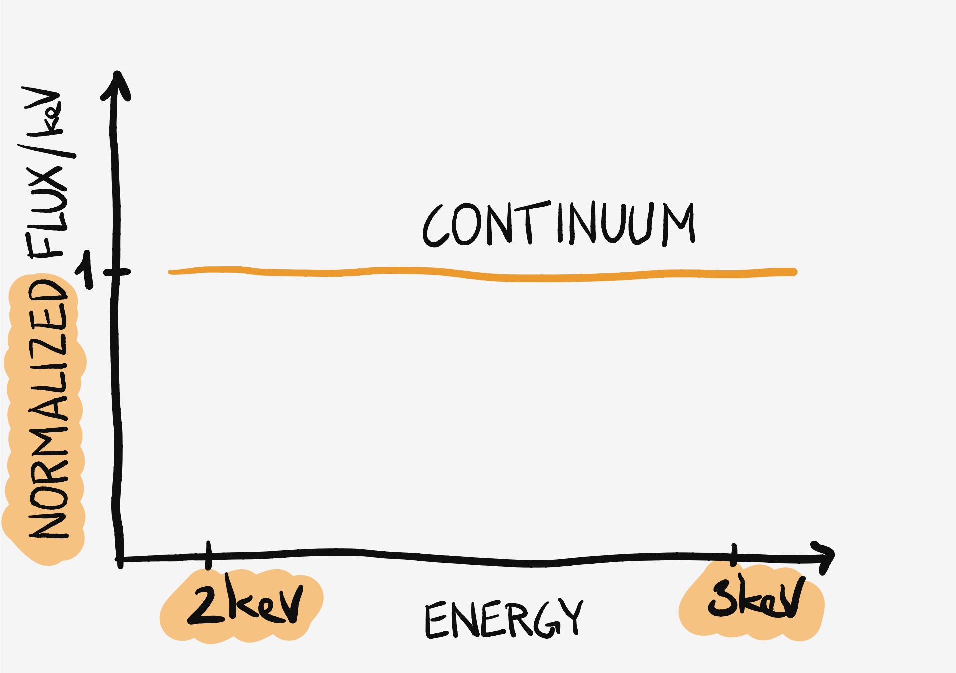

1
INTERSTELLAR MEDIUM ABSORPTION
POWER LAW
FLUX / keV
1 keV
10 keV
100 keV
ENERGY
ABSORPTION IN THE STELLAR WIND
FLUX / keV
e.g. Grinberg + 2015
1 keV
10 keV
100 keV
ENERGY

2



2





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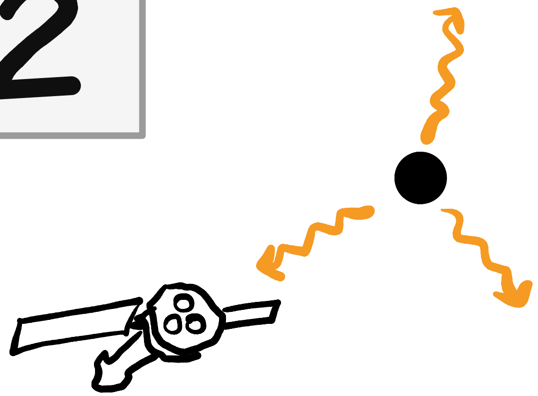
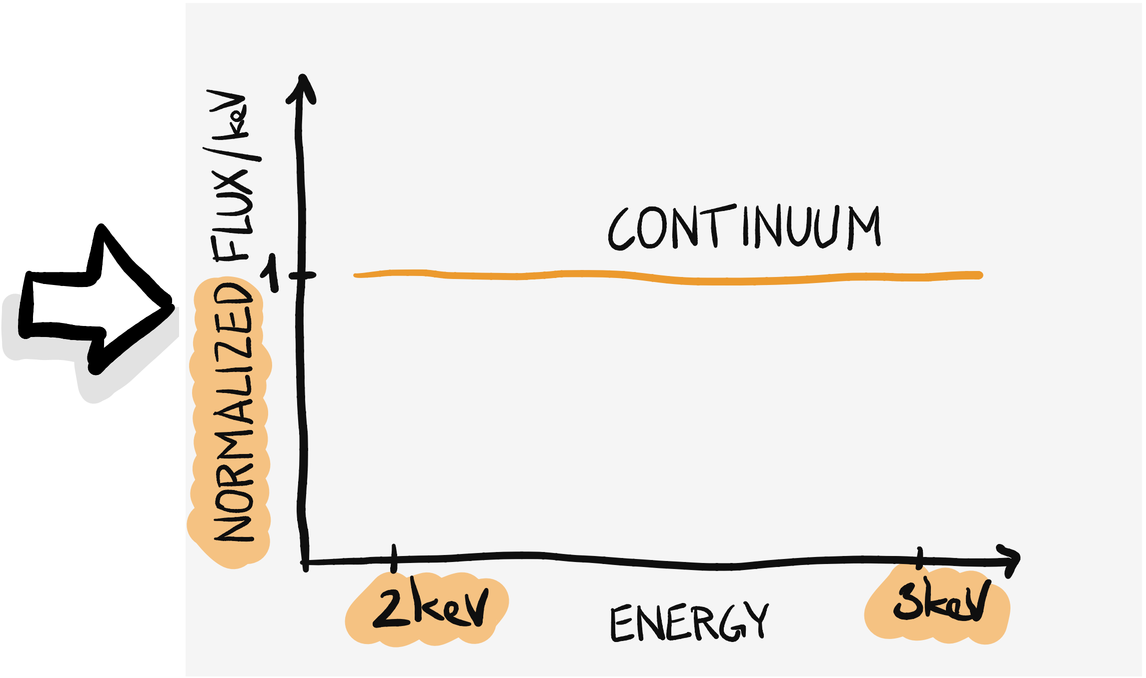
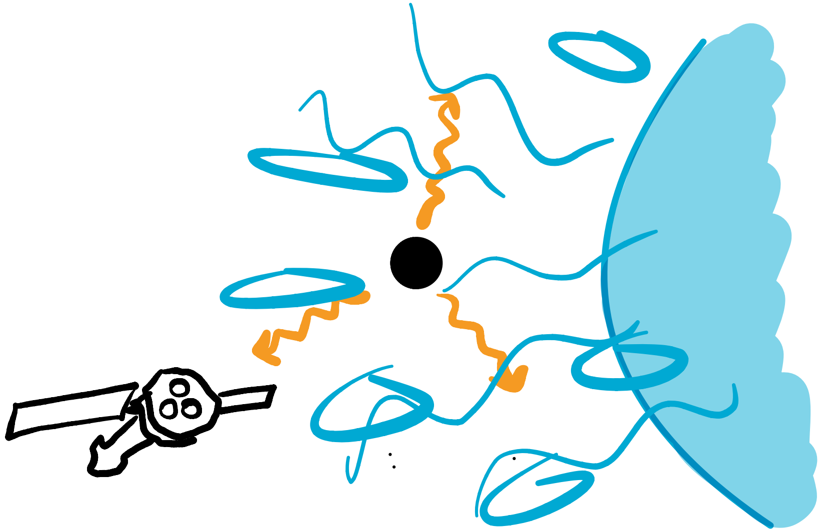
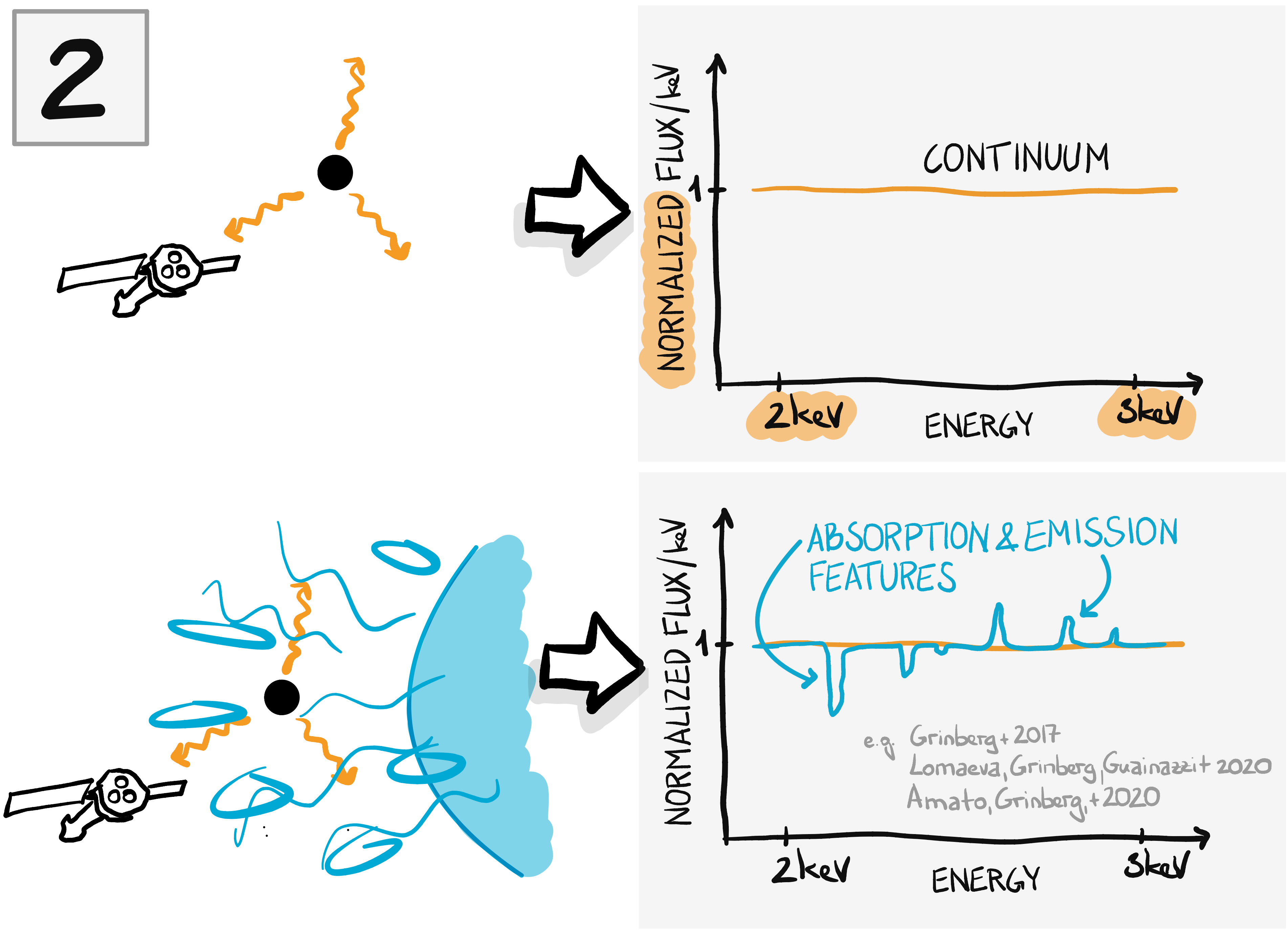


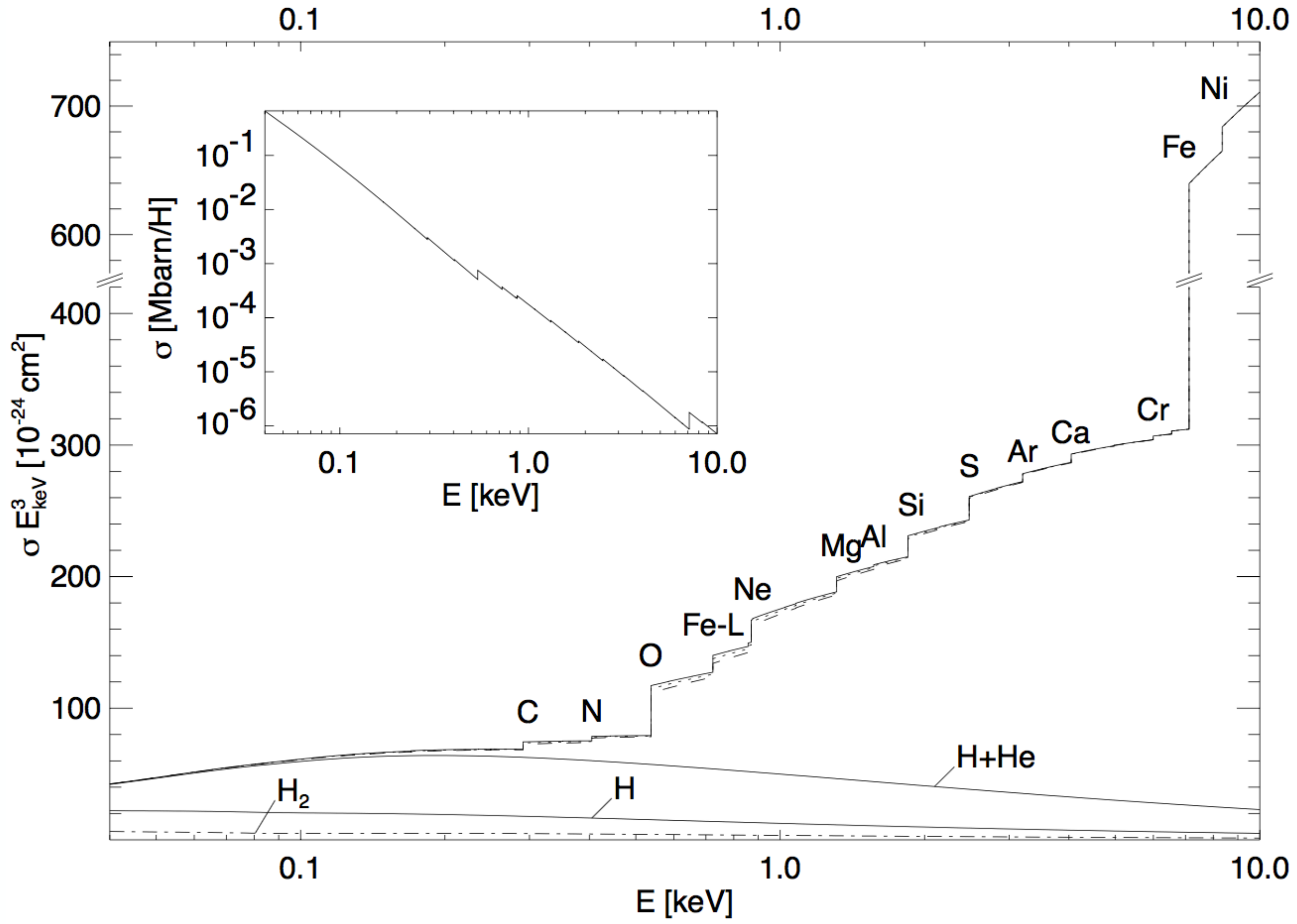






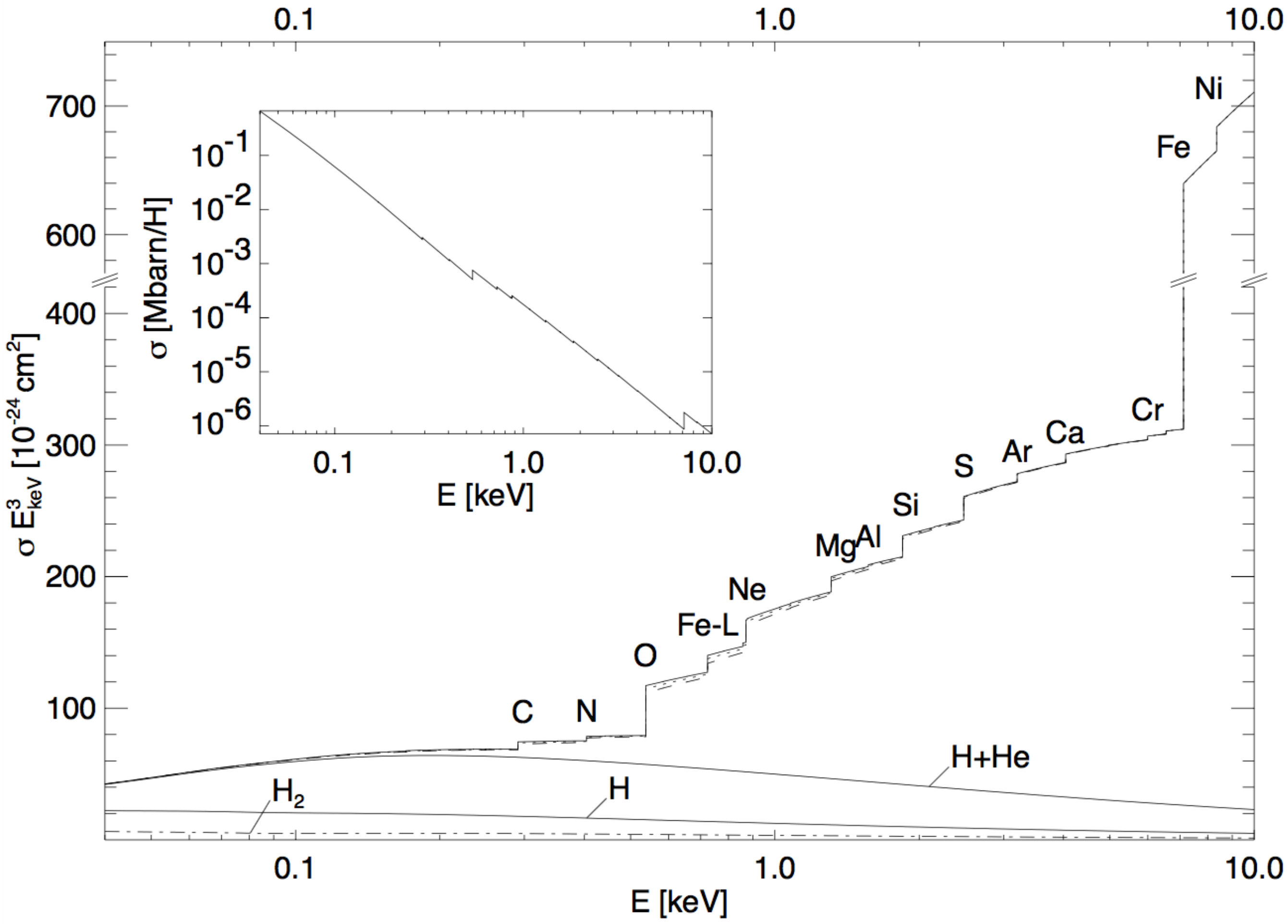
2
NORMALIZED FLUX/keV
1
CONTINUUM
2keV
ENERGY
3keV
NORMALIZED FLUX/keV
1
ABSORPTION & EMISSION FEATURES
e.g. Grinberg+2017
Lomaeva, Grinberg, Guainazzi+ 2020
Amato, Grinberg,+2020
2keV
ENERGY
3keV

Measuring absorption in X-rays



Wilms+ 2000

Measuring absorption in X-rays



Wilms+ 2000

- energy dependent absorption
- measured in equivalent hydrogen column density
- assumes known cross-sections and abundances

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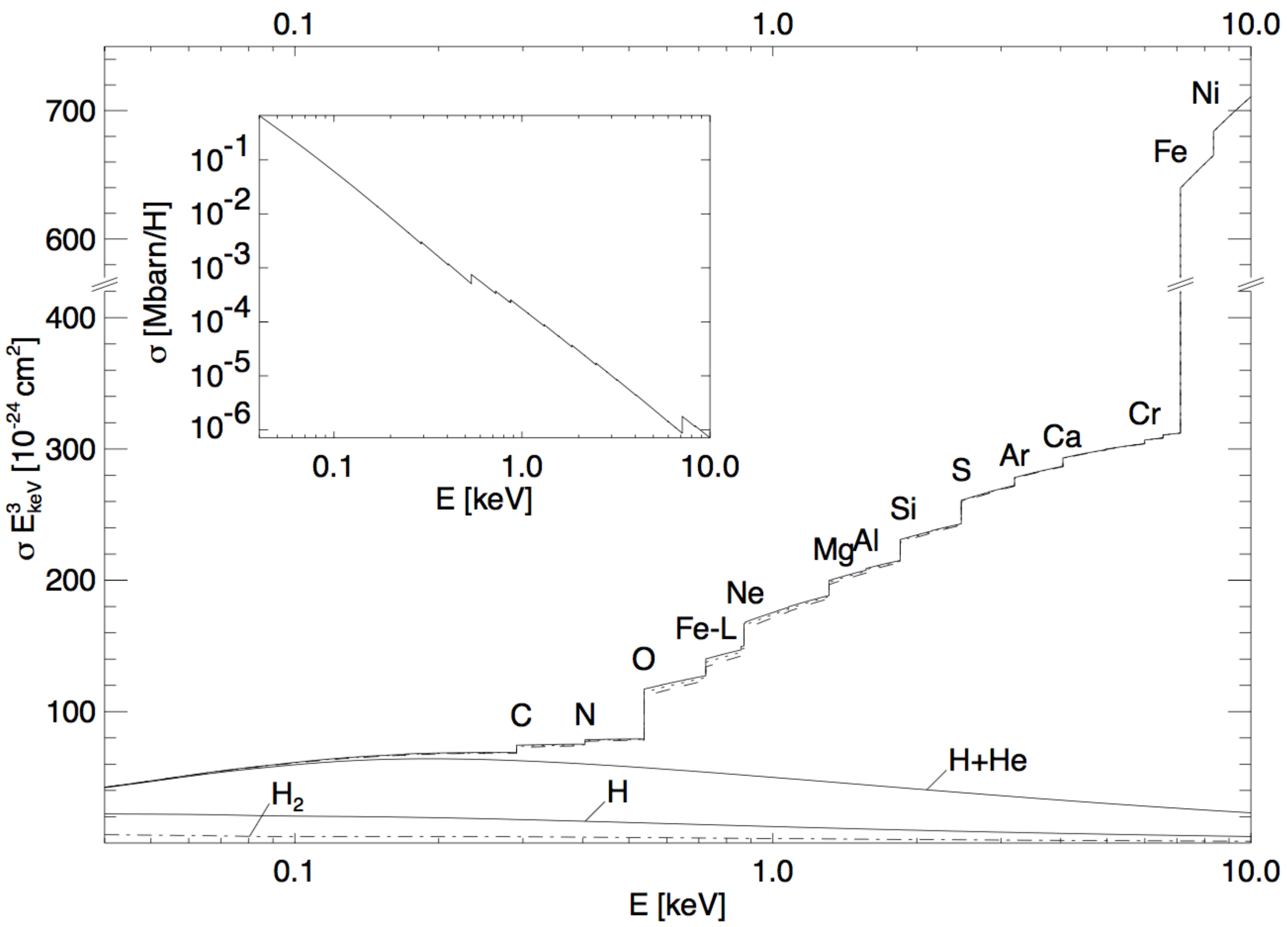


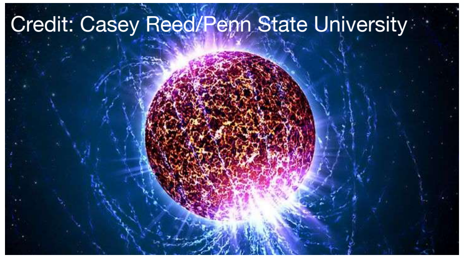
Wilms+ 2000

- energy dependent absorption
- measured in equivalent hydrogen column density
- assumes known cross-sections and abundances

A plea:

- use modern models (e.g. tbabs)!
- state your abundances!

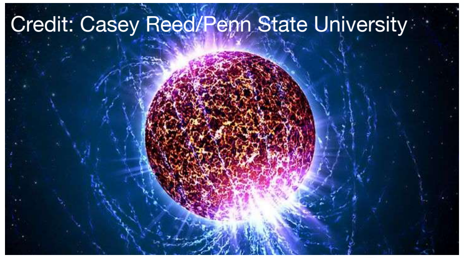
Partial coverers

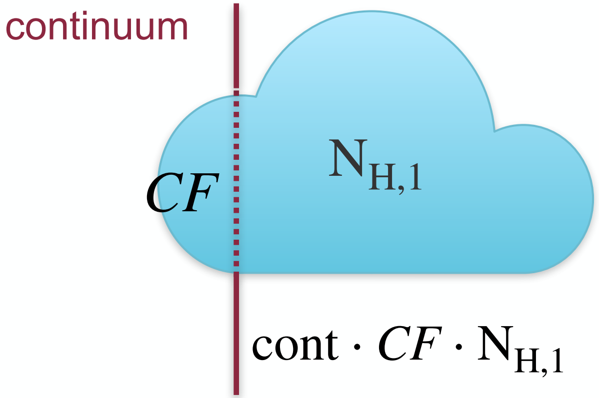


continuum

Diez+ 2022

Partial coverers

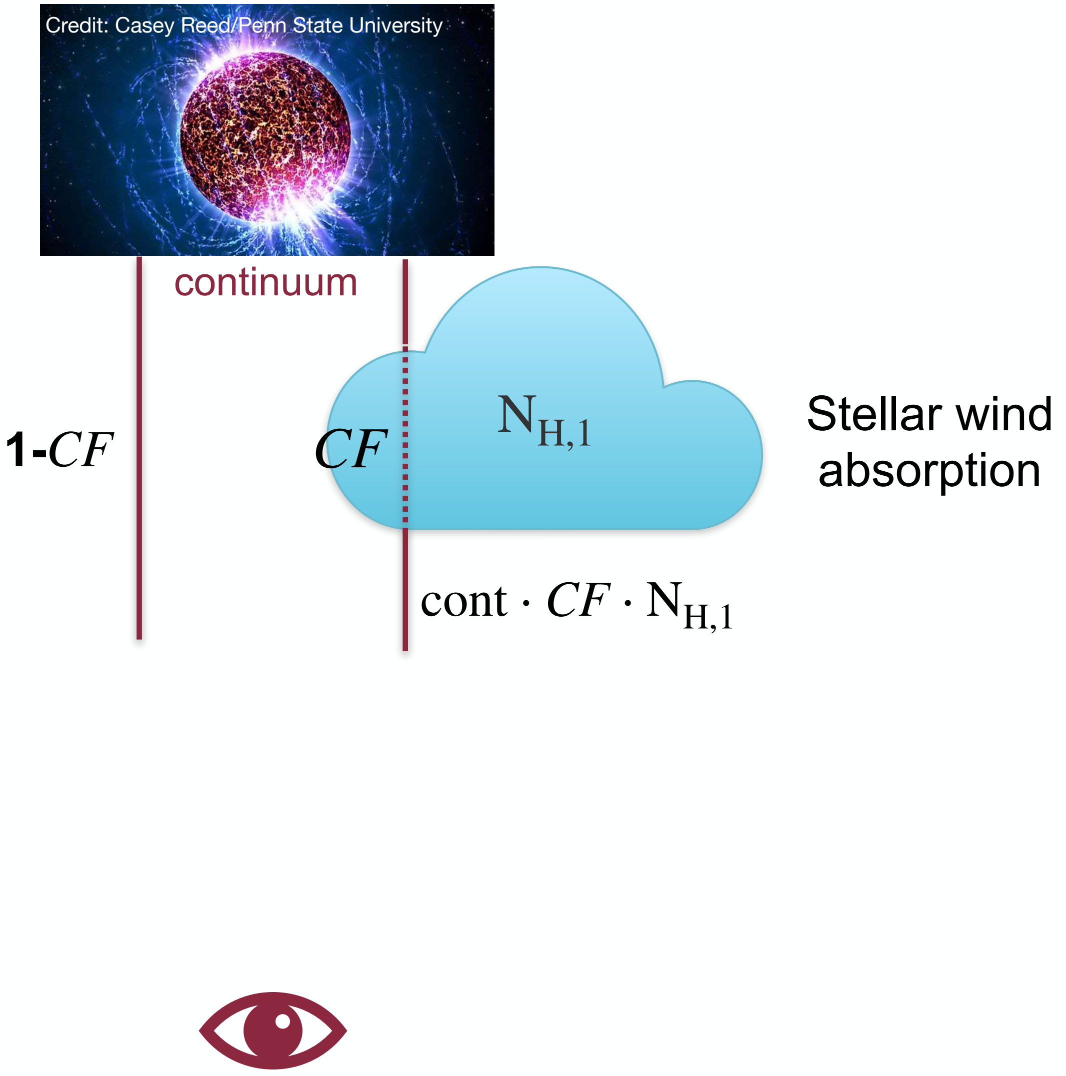




Stellar wind absorption

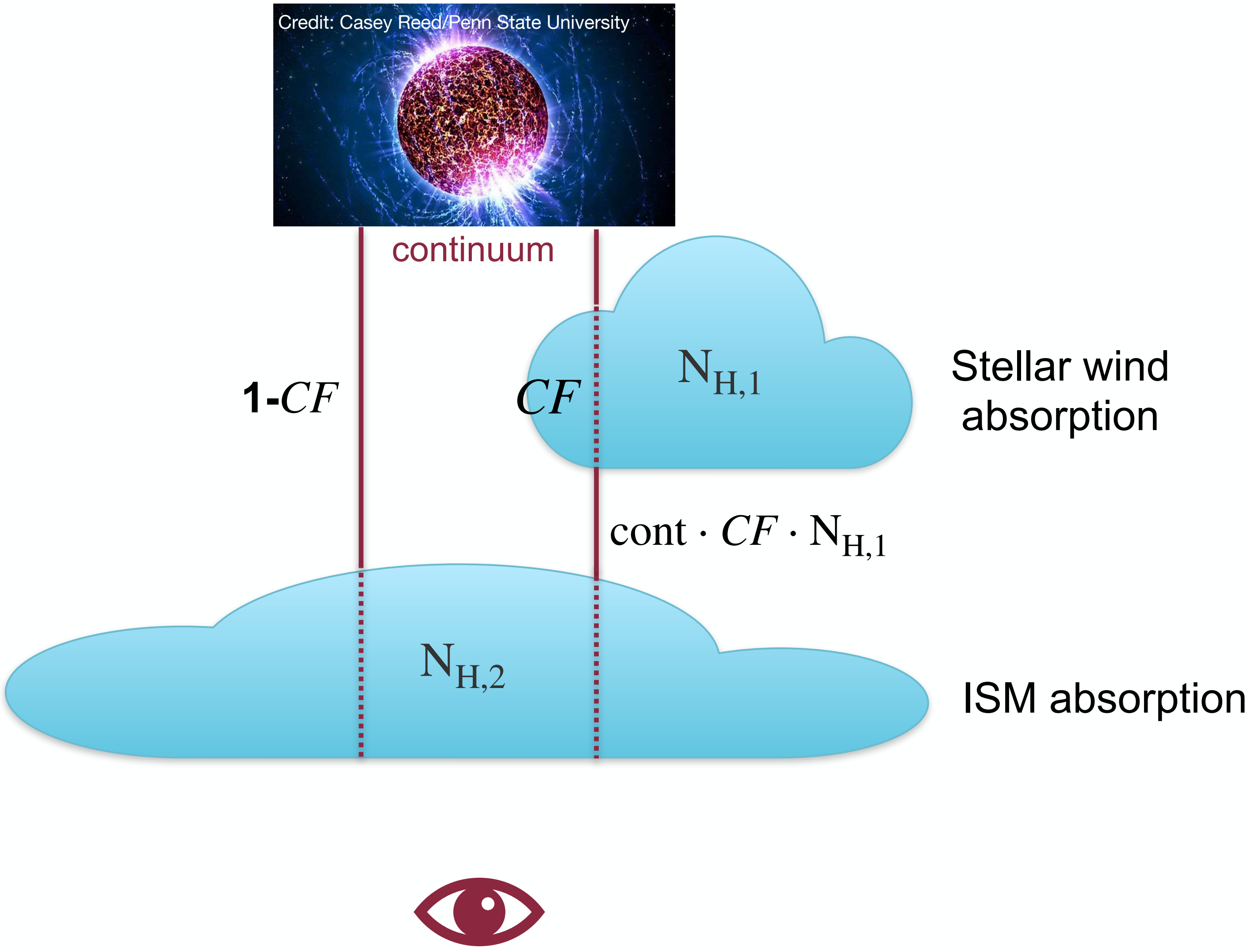
Diez+ 2022

Partial coverers



Diez+ 2022

Partial coverers



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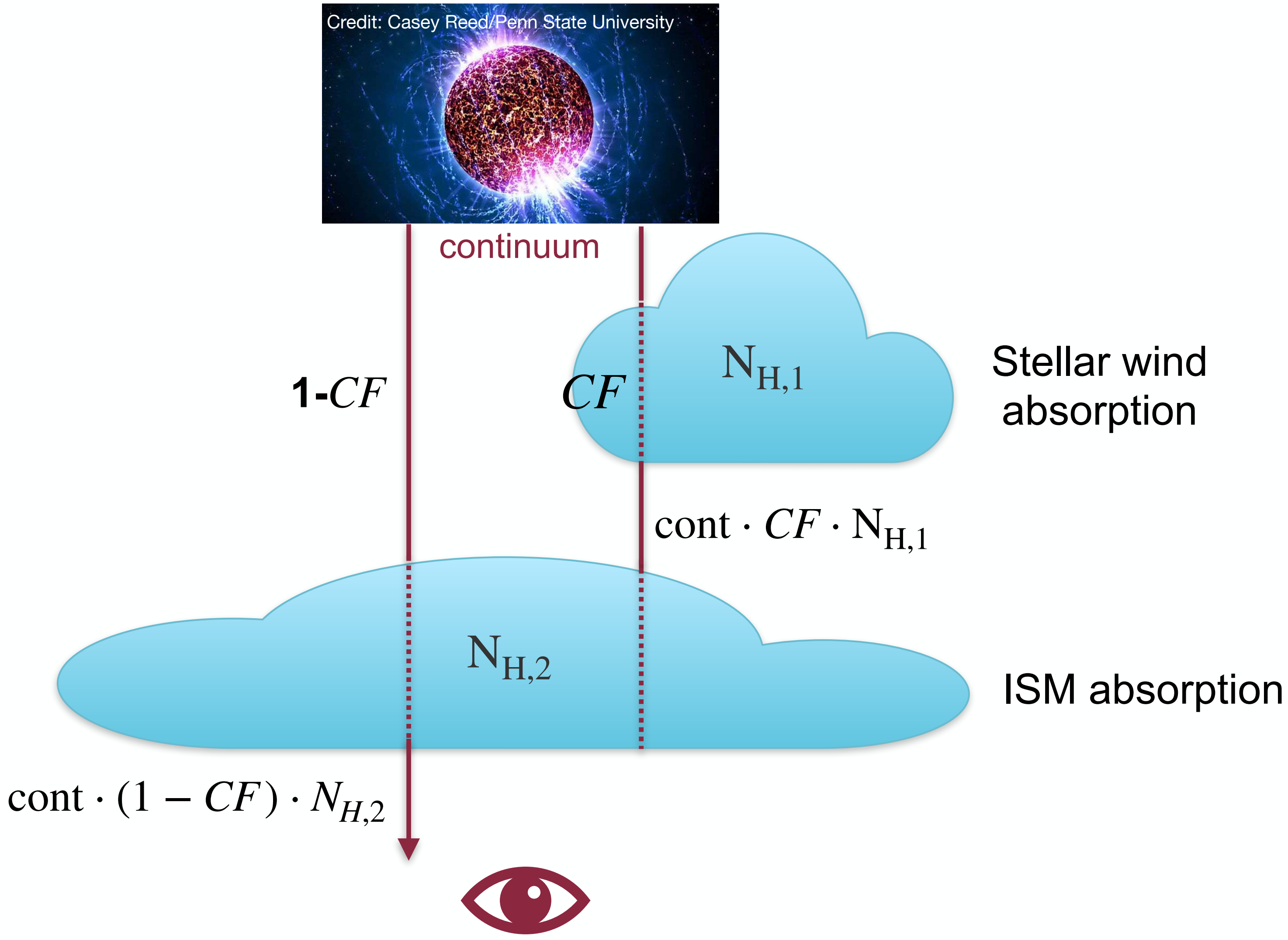

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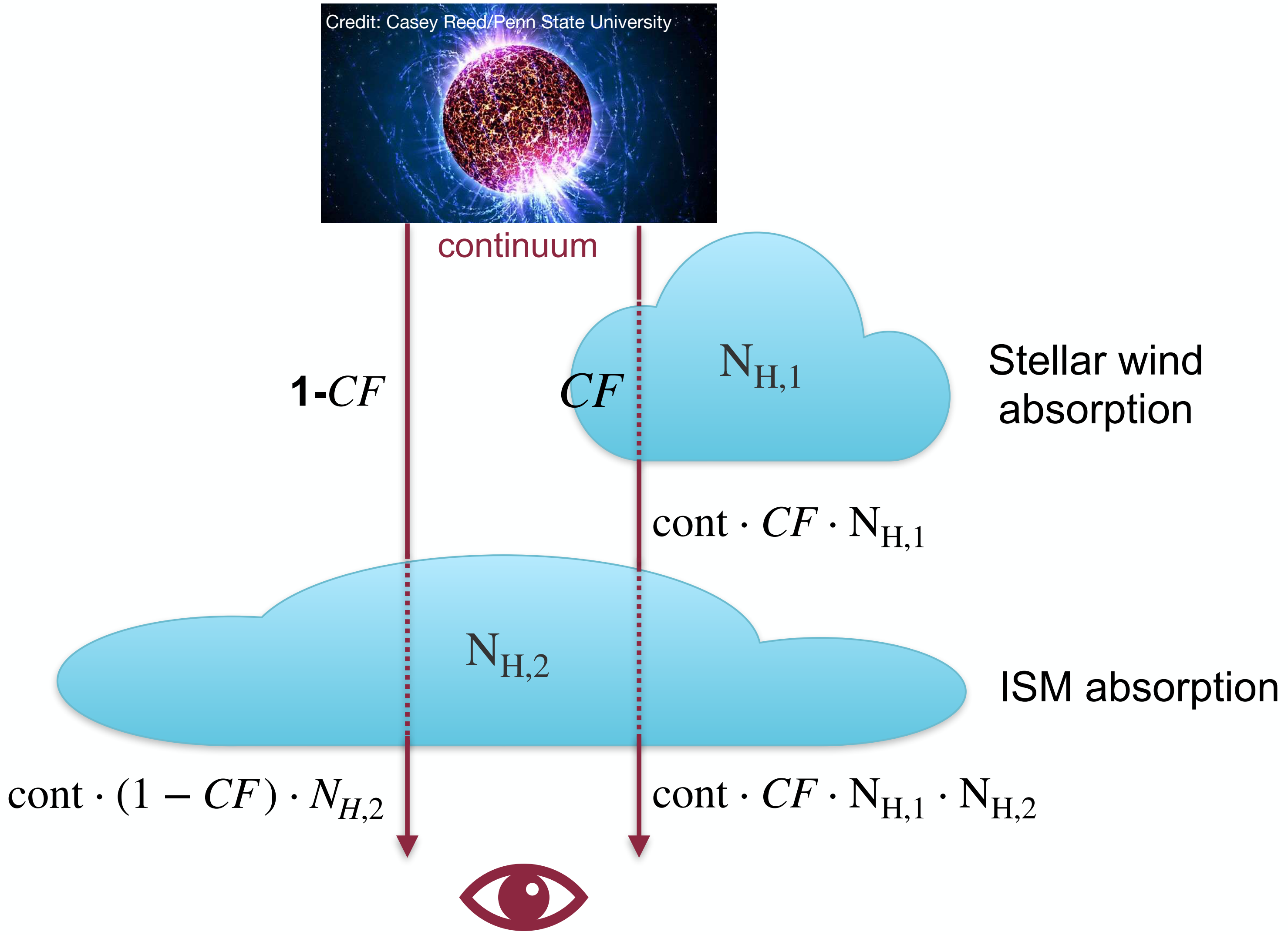

Diez+ 2022

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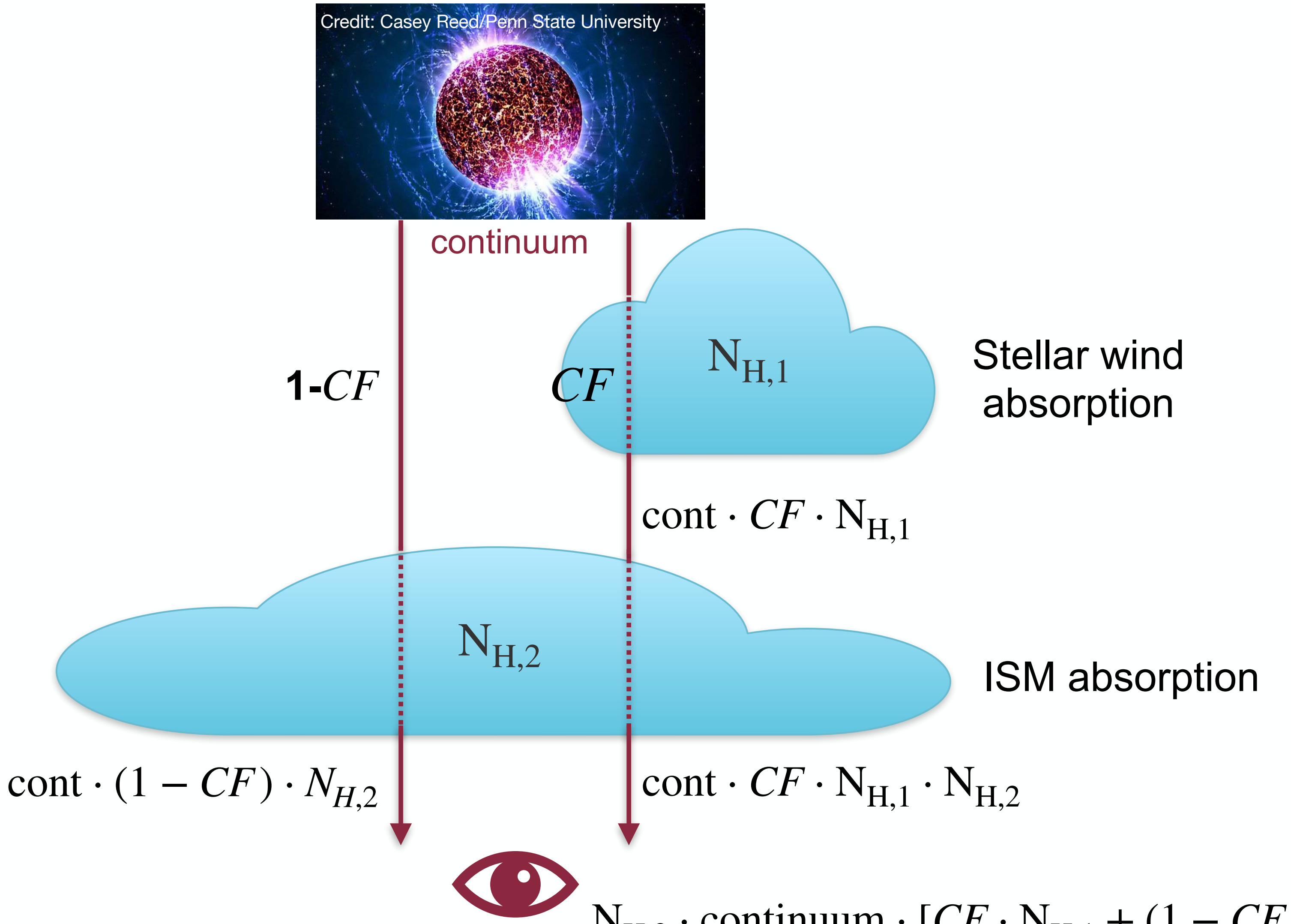
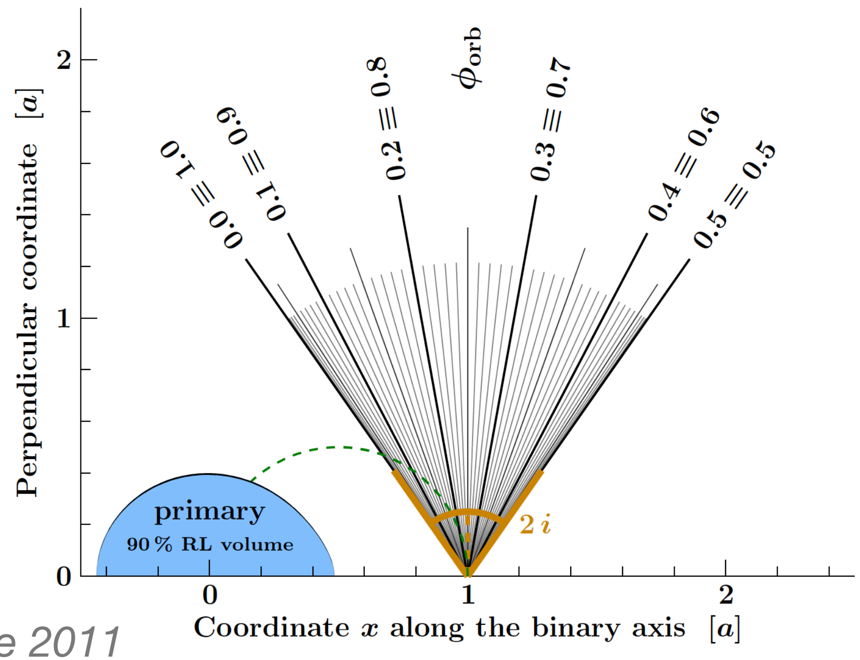


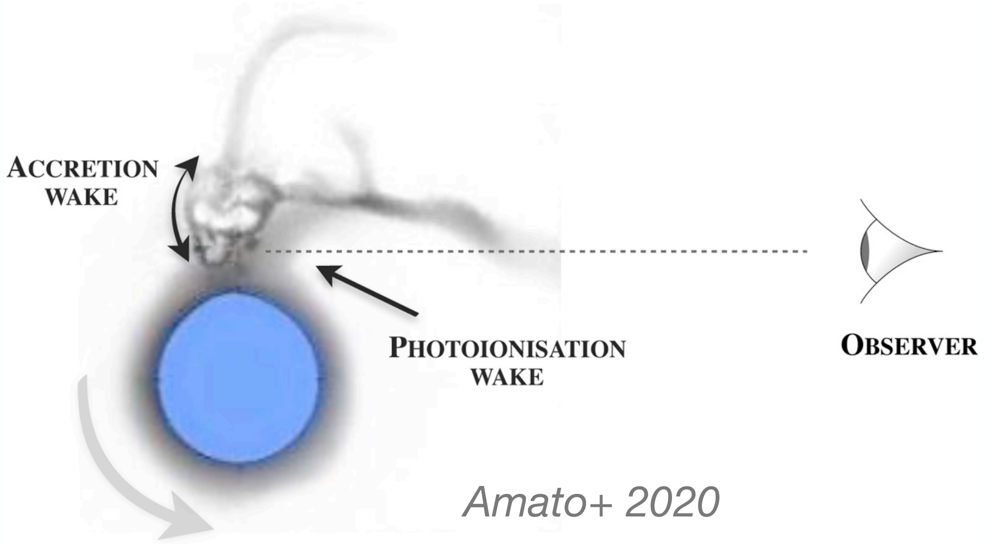
$$\mathrm{N}_{\mathrm{H},2} \cdot \mathrm{continuum} \cdot [CF \cdot \mathrm{N}_{\mathrm{H},1} + (1 - CF)]$$

Diez+ 2022

Two test cases



Hanke 2011



Amato+ 2020

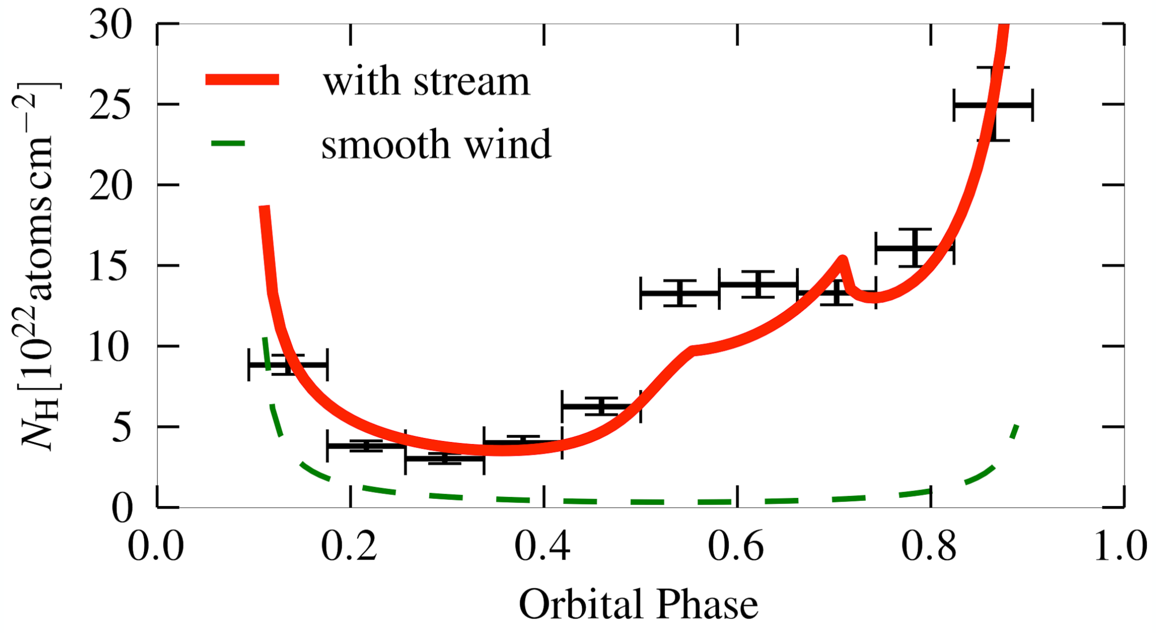
Cygnus X-1

- black hole
- inclination of ~30°
- focussed wind & (small) disk

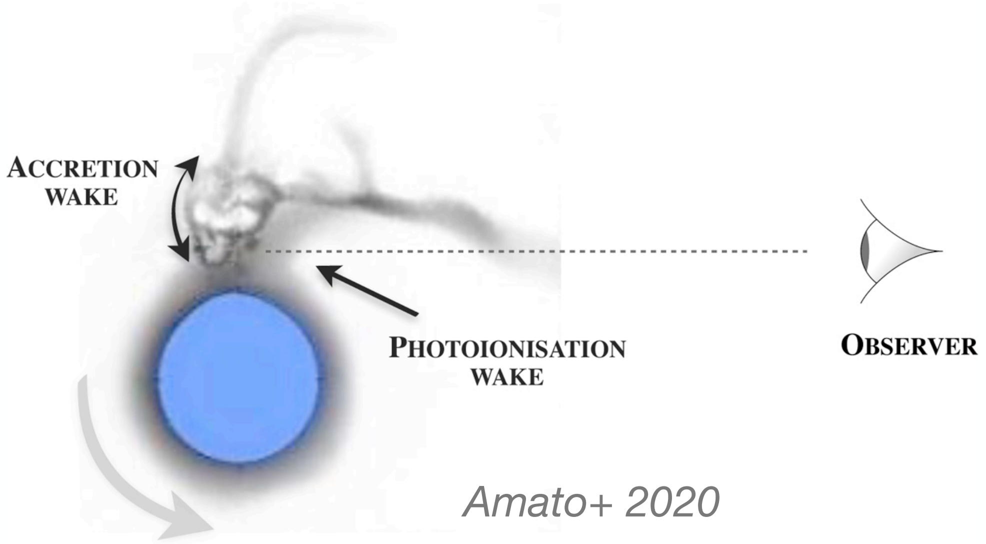
Vela X-1

- highly magnetized neutron star
- eclipsing
- wind accretion; wakes

Vela X-1



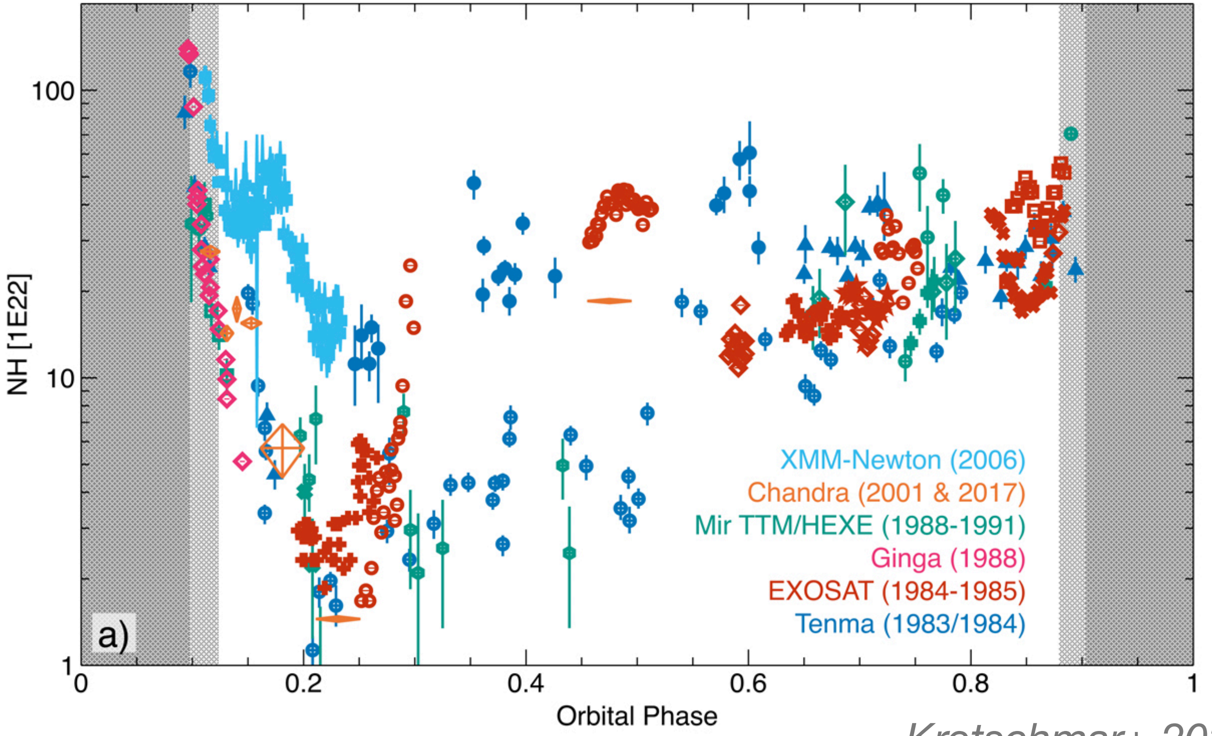
Doroshenko+ 2013



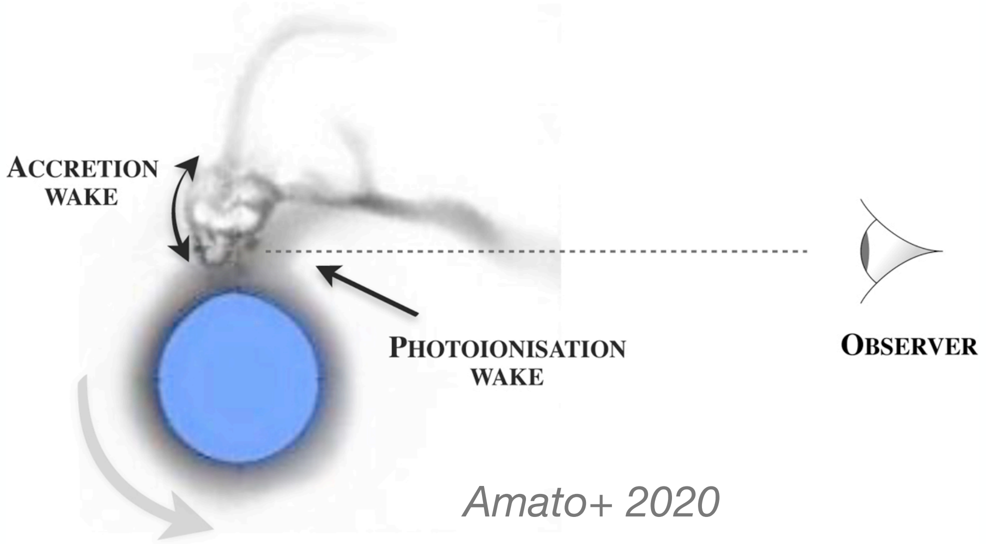
Amato+ 2020

MAXI data, averaged over ~120 orbits: the average shape of absorption along the orbit

Vela X-1



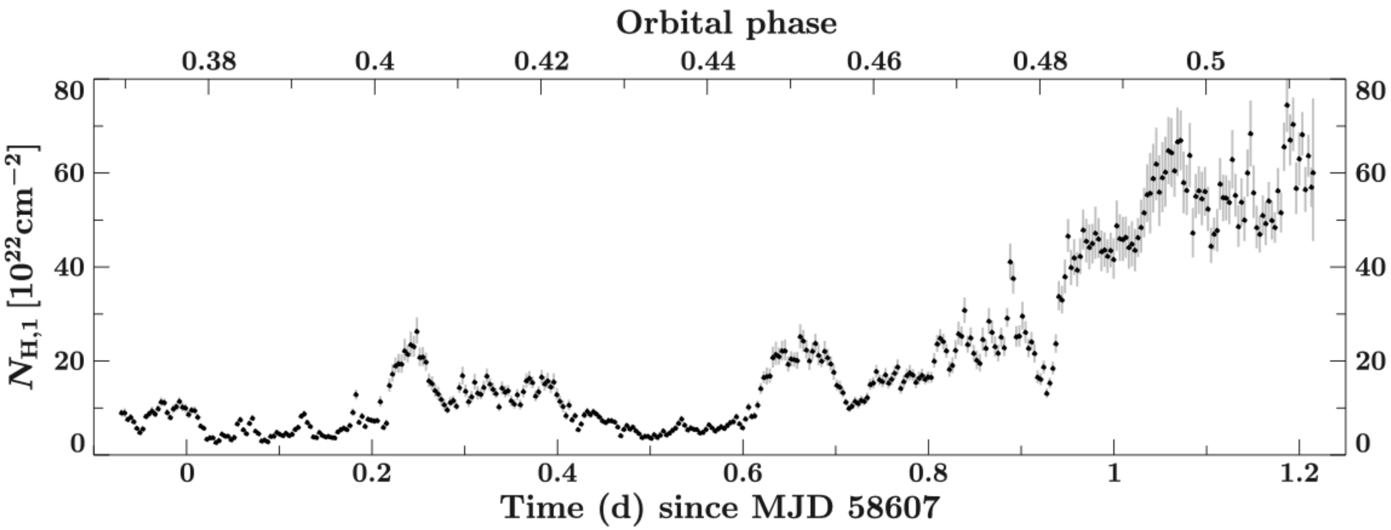
Kretschmar+ 2021

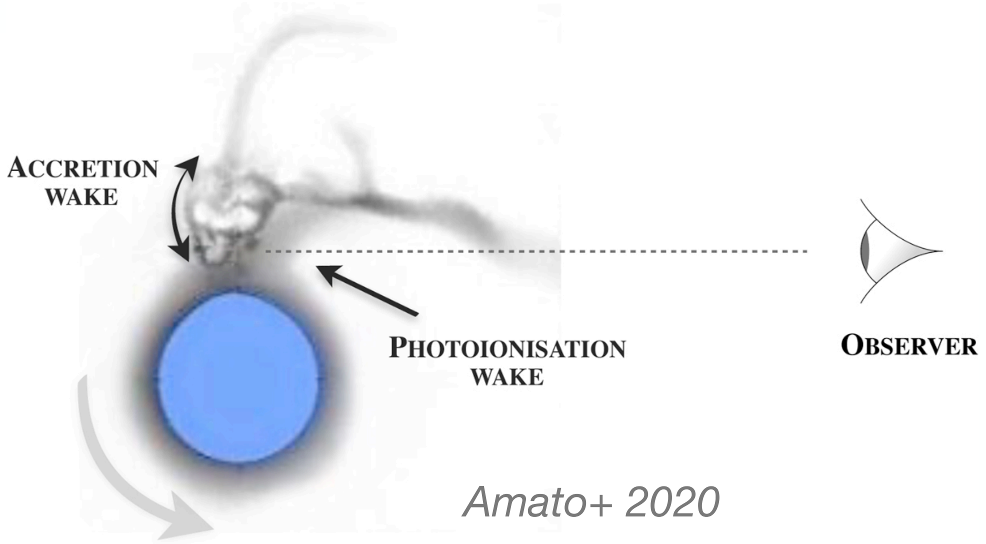


Amato+ 2020

individual orbits: highly variable wind structure

Vela X-1



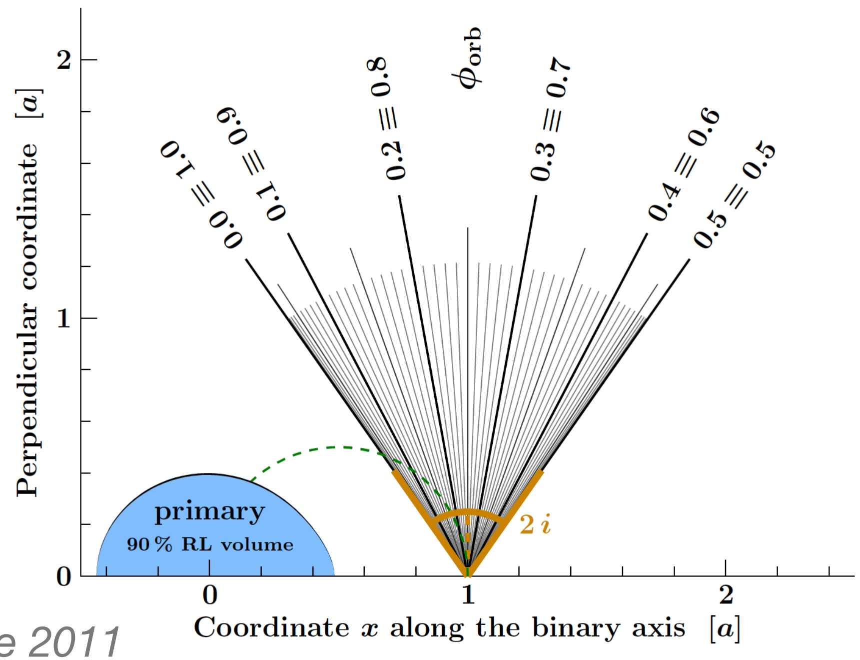


Amato+ 2020

Diez+ 2023

Tracing the onset of the wake: large-scale structure & smaller scale variability

Cygnus X-1



Hanke 2011

Grinberg 2015

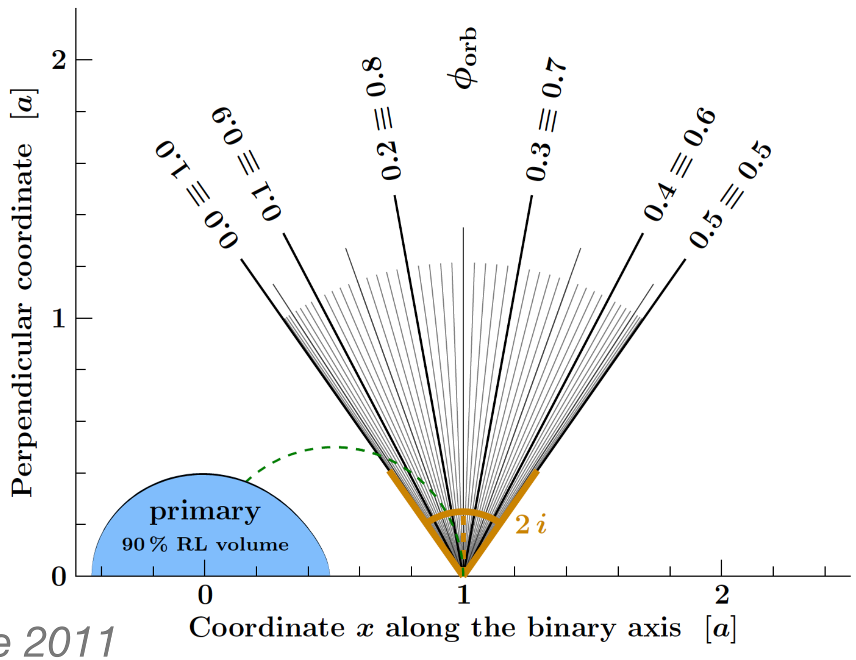
Cygnus X-1

➤ black hole

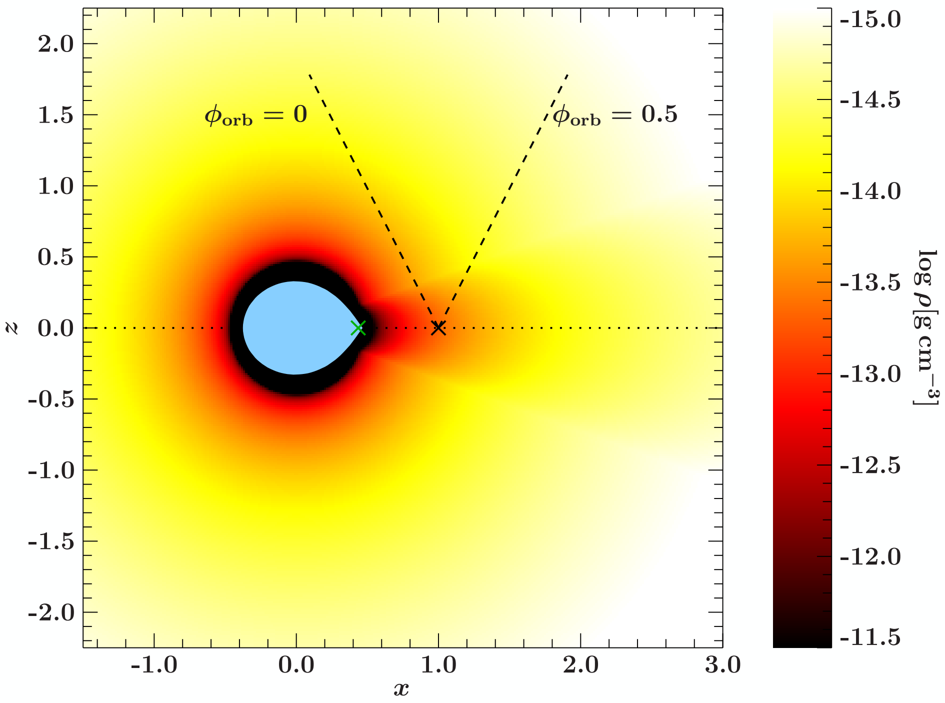
➤ inclination of ~30°

➤ focussed wind & (small) disk

Cygnus X-1



Hanke 2011



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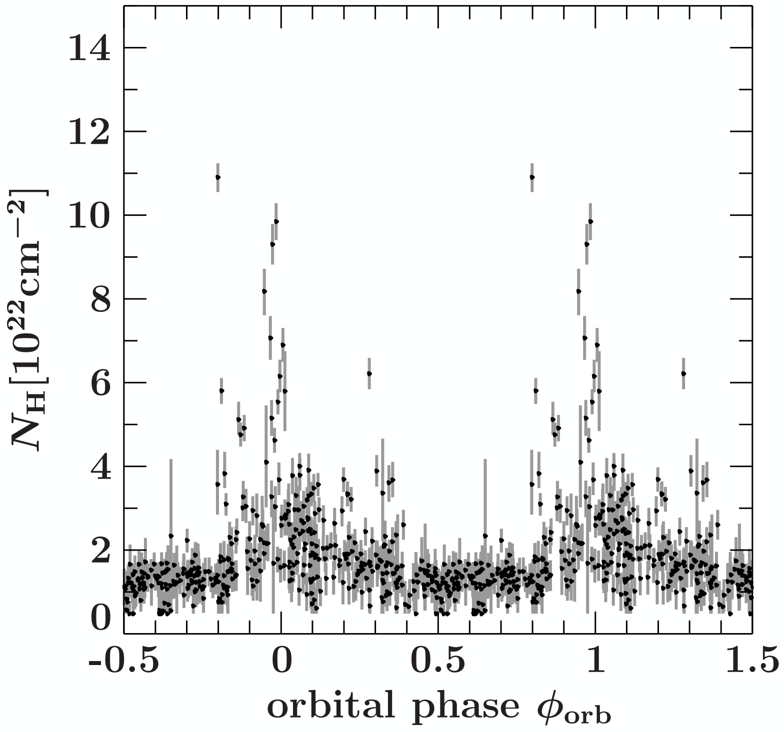
Cygnus X-1

Smooth focussed wind:

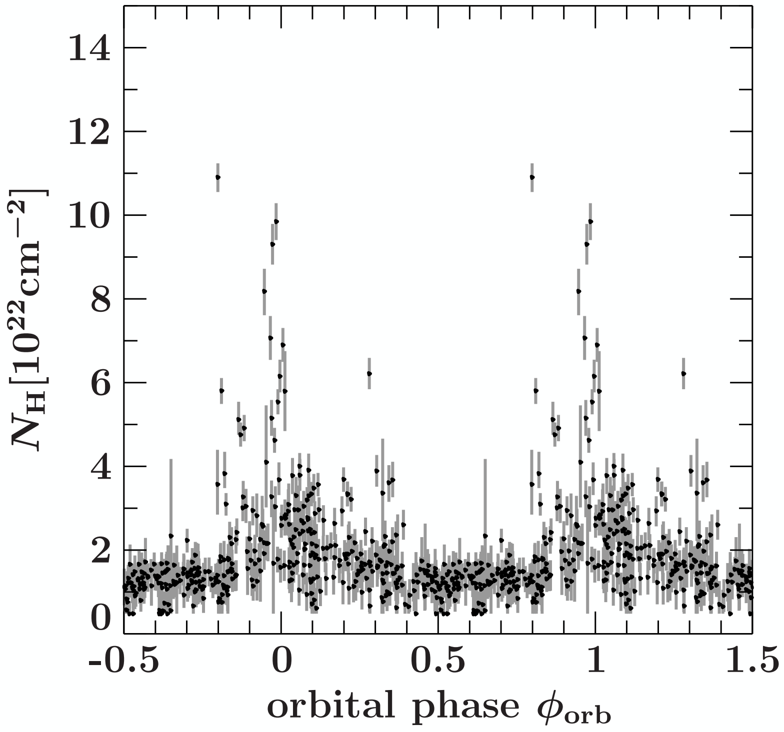


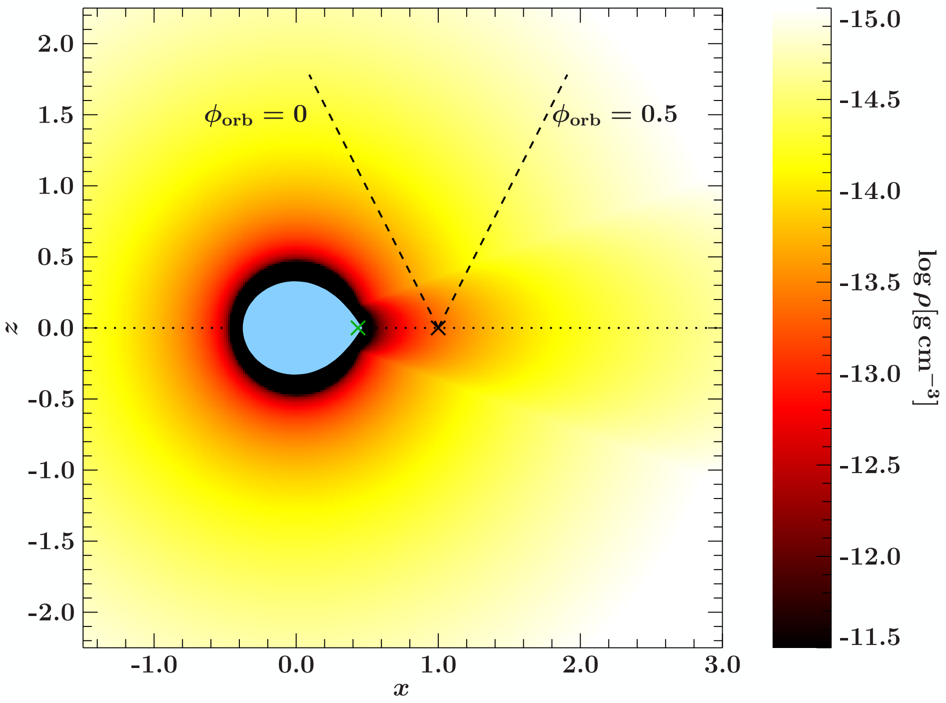
Grinberg 2015

➤ does not explain variability :(

Cygnus X-1

Smooth focussed wind:





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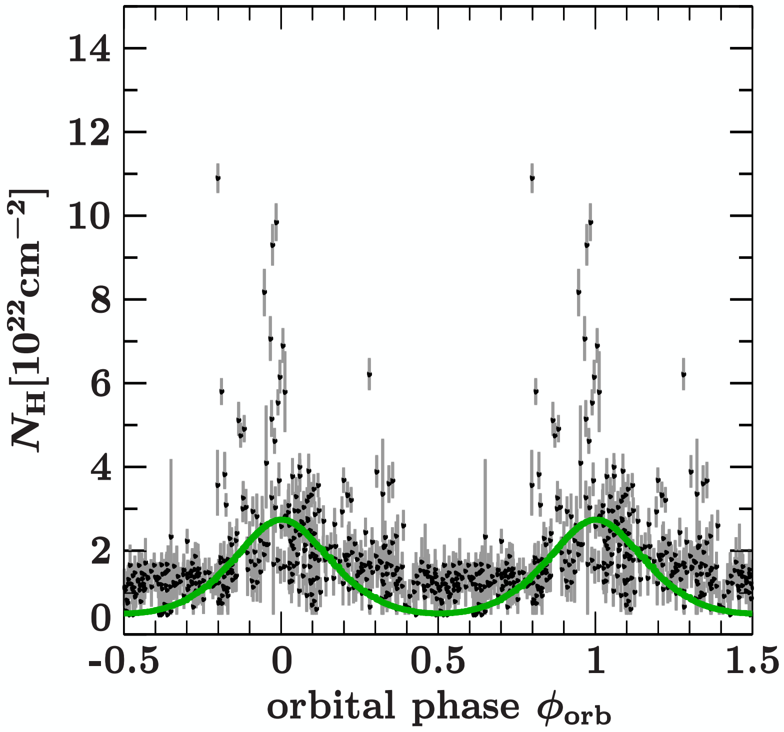
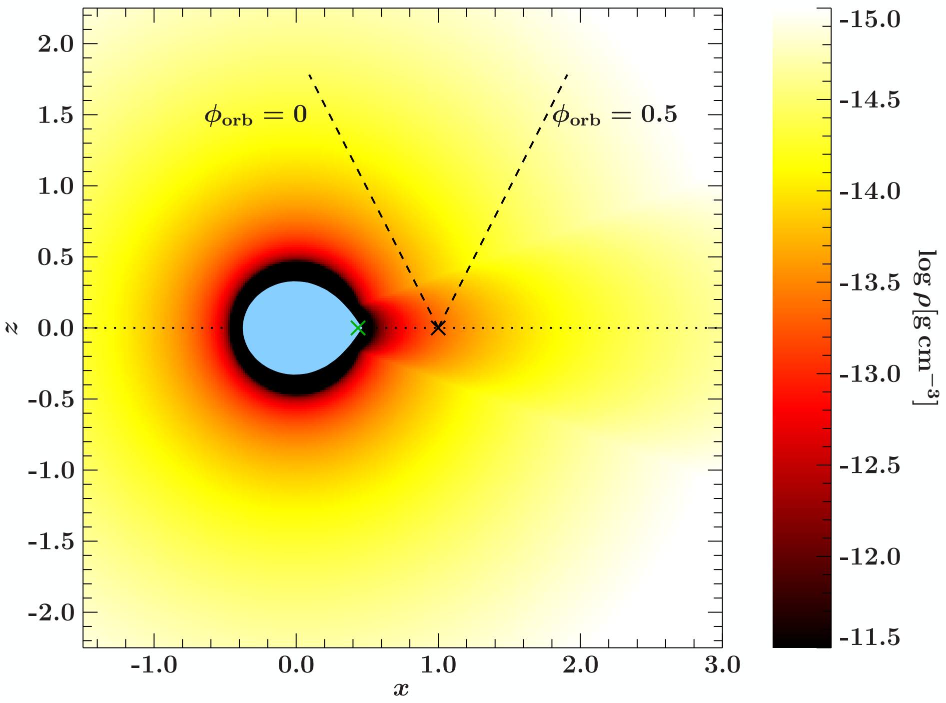
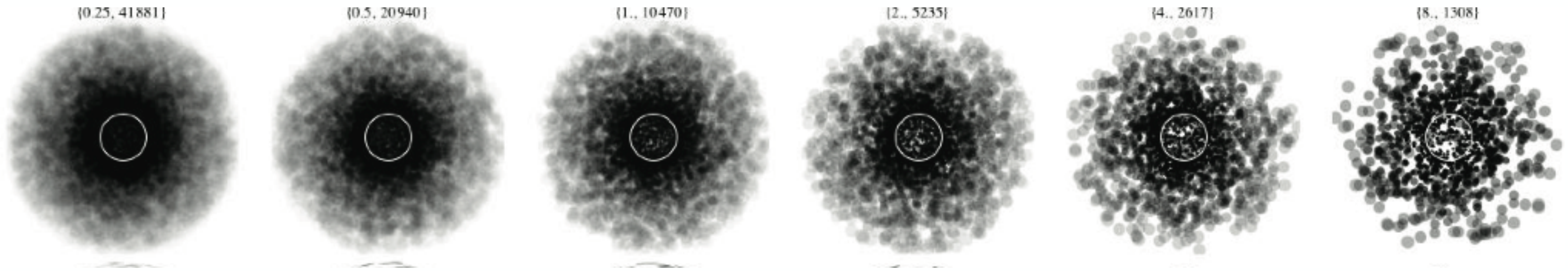




Grinberg 2015

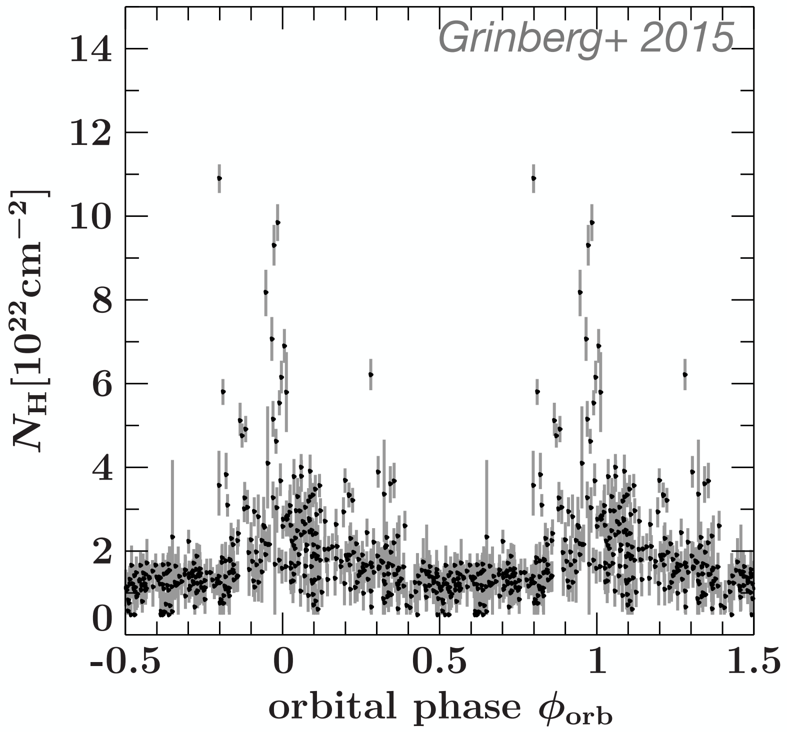
➤ does not explain variability :(

Clumpy stellar winds

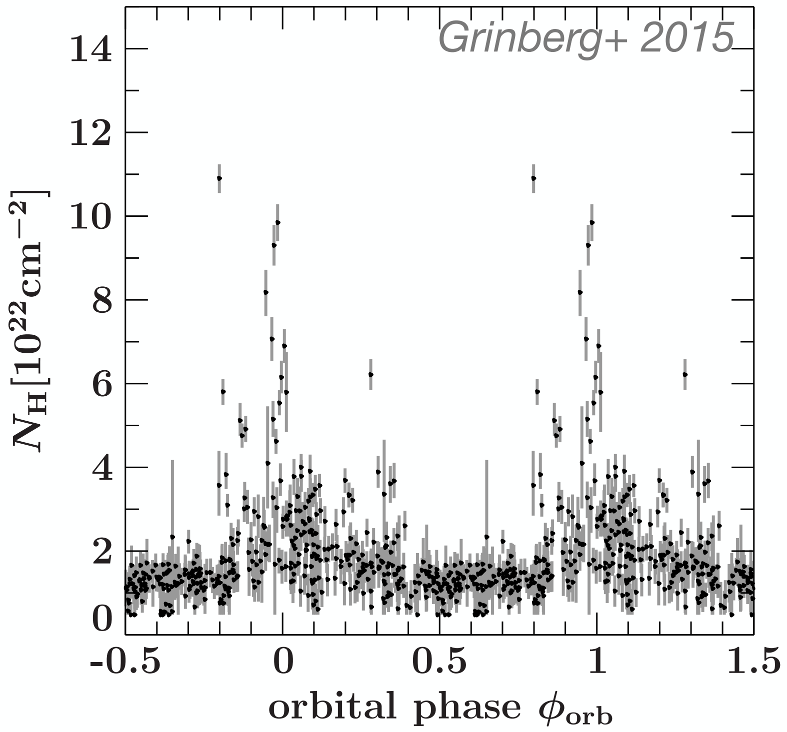


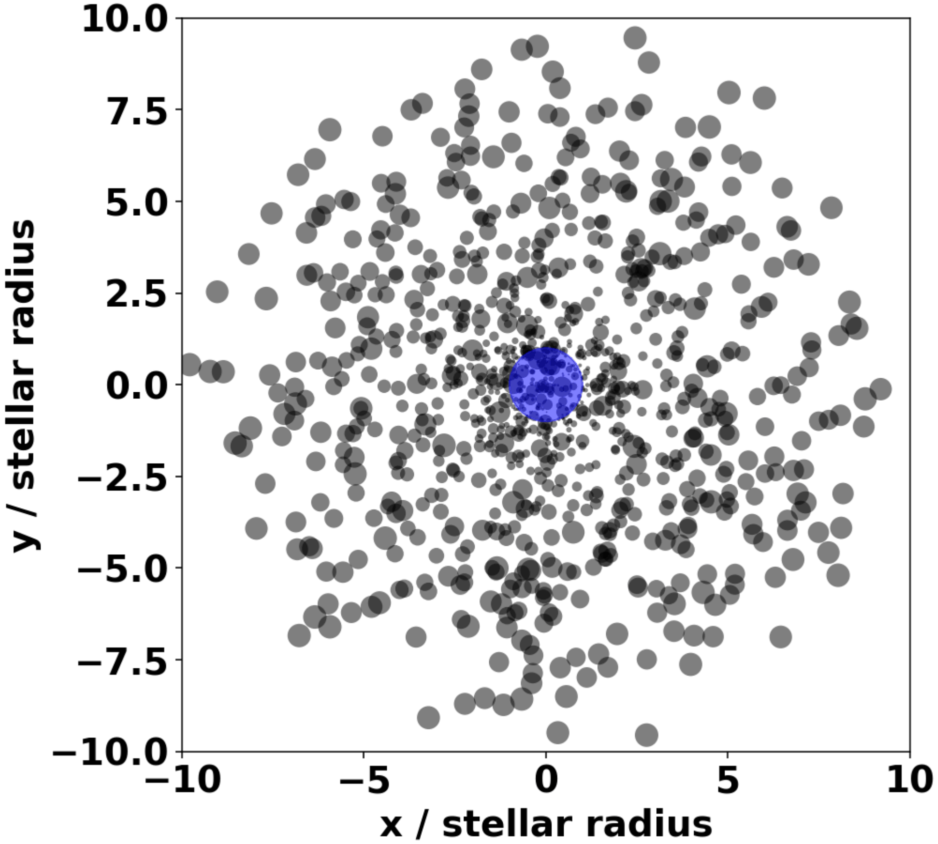
- ➤ discrete spherical clumps
- ➤ β velocity law $v = v_\infty \left(1 - R_\star / r\right)^\beta$
- ➤ no large scale wind structure
- ➤ focussed wind & (small) disk

Clumpy stellar winds

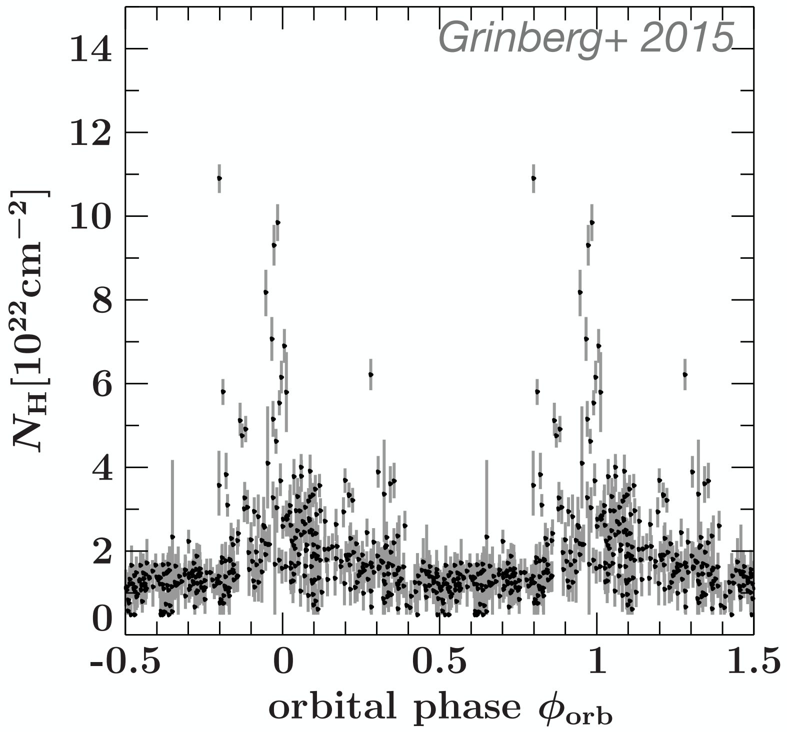


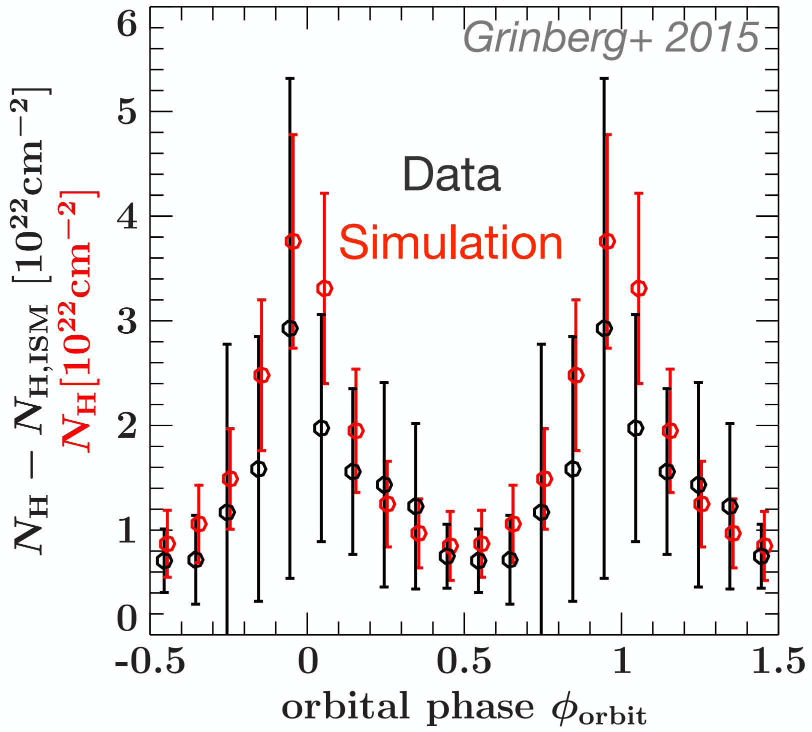
Clumpy stellar winds





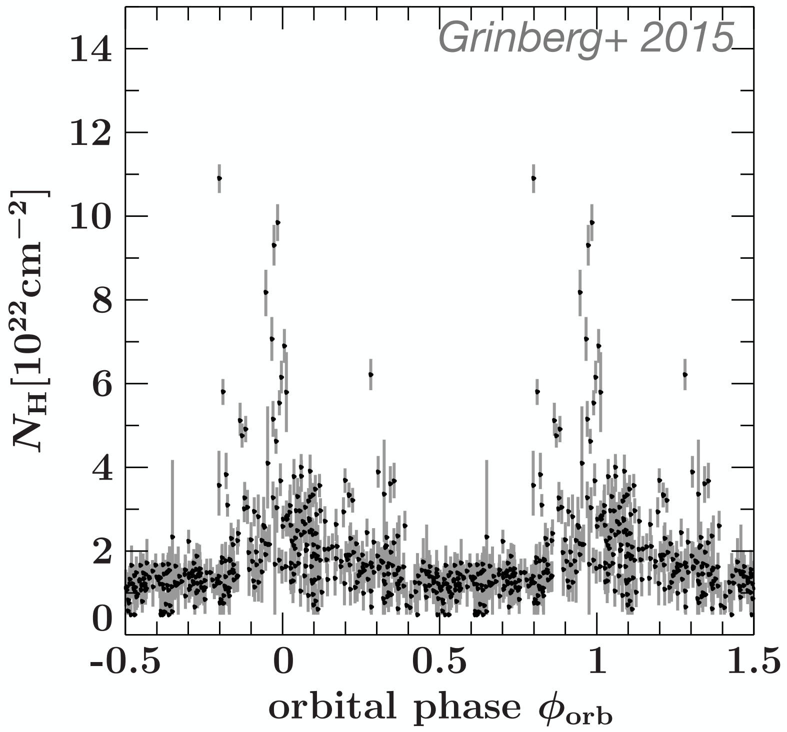
Clumpy stellar winds

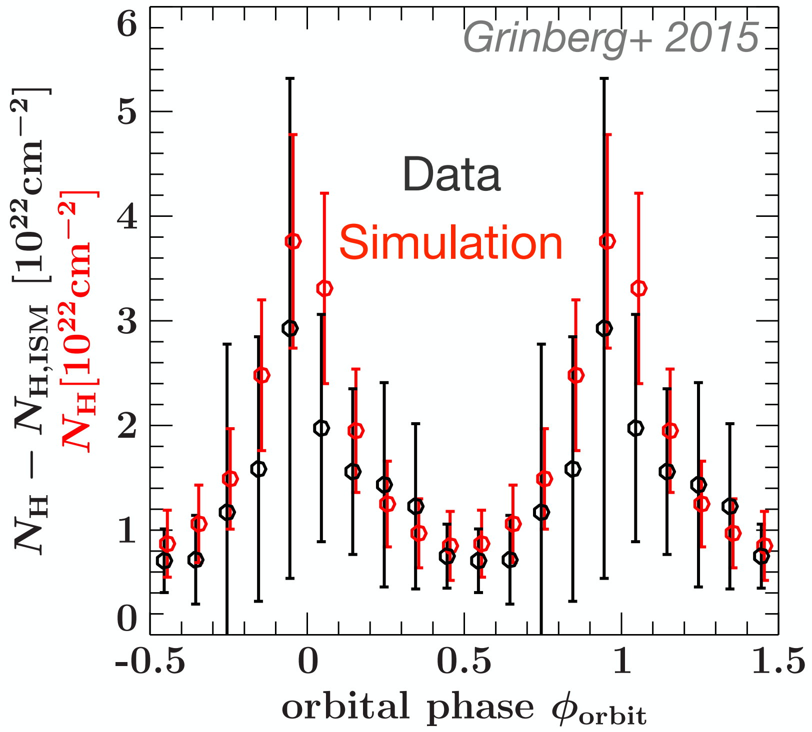




Averages & standard deviations

Clumpy stellar winds



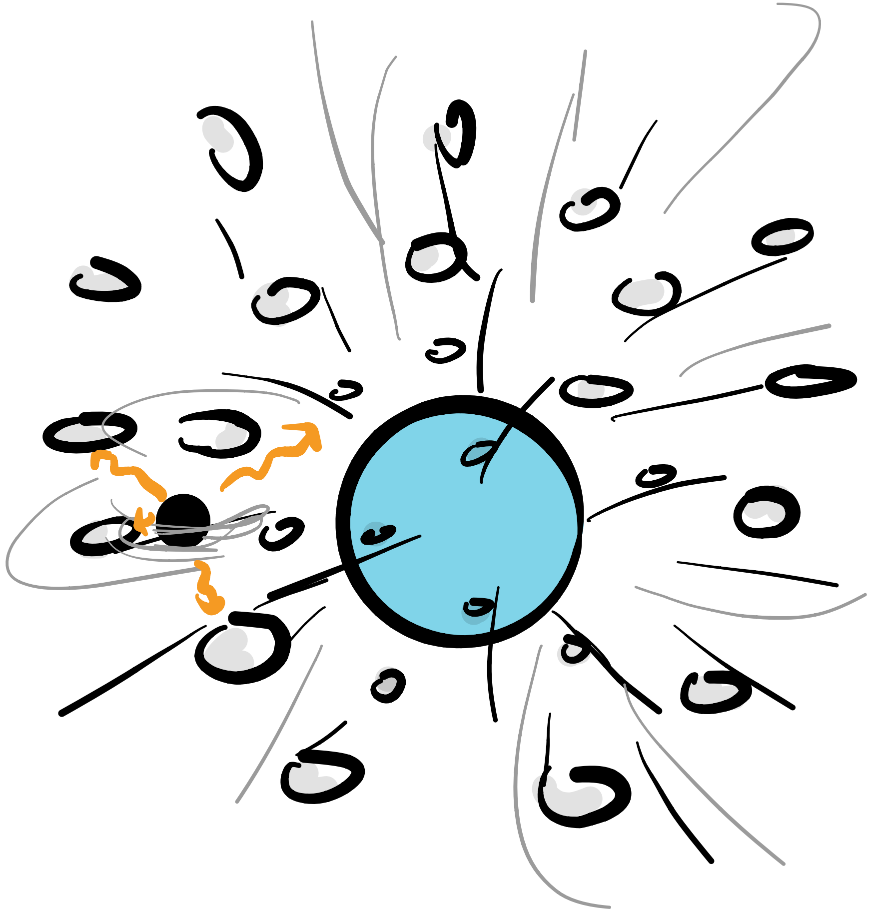


Averages & standard deviations

➤ explains dips and some (not all!) variability; constrains on wind porosity

SHORT TERM VARIABILITY & CLUMPINESS

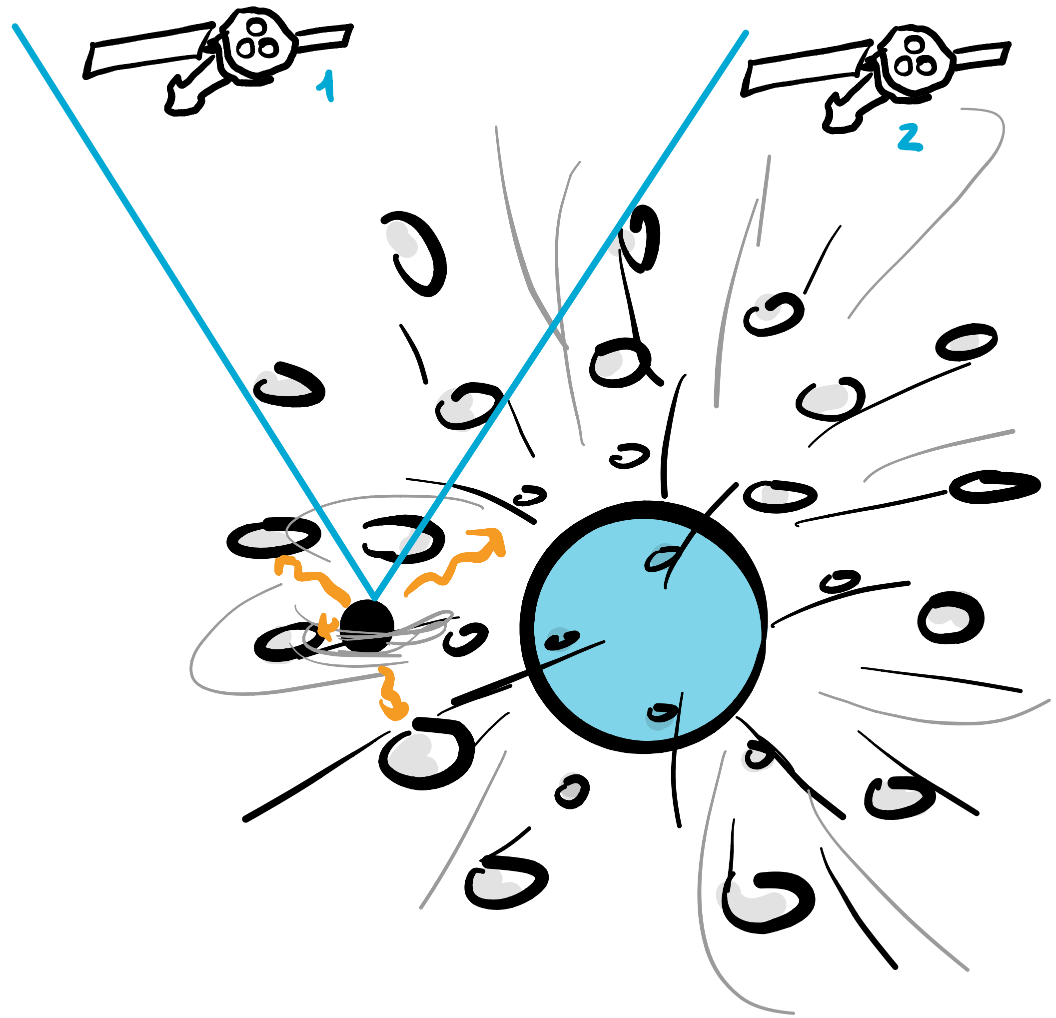
DEPENDS ON



SHORT TERM VARIABILITY & CLUMPINESS

DEPENDS ON

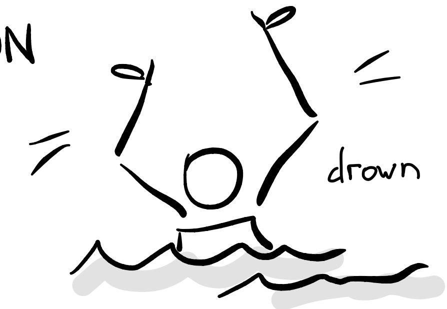
- LINE OF SIGHT (1 vs 2)

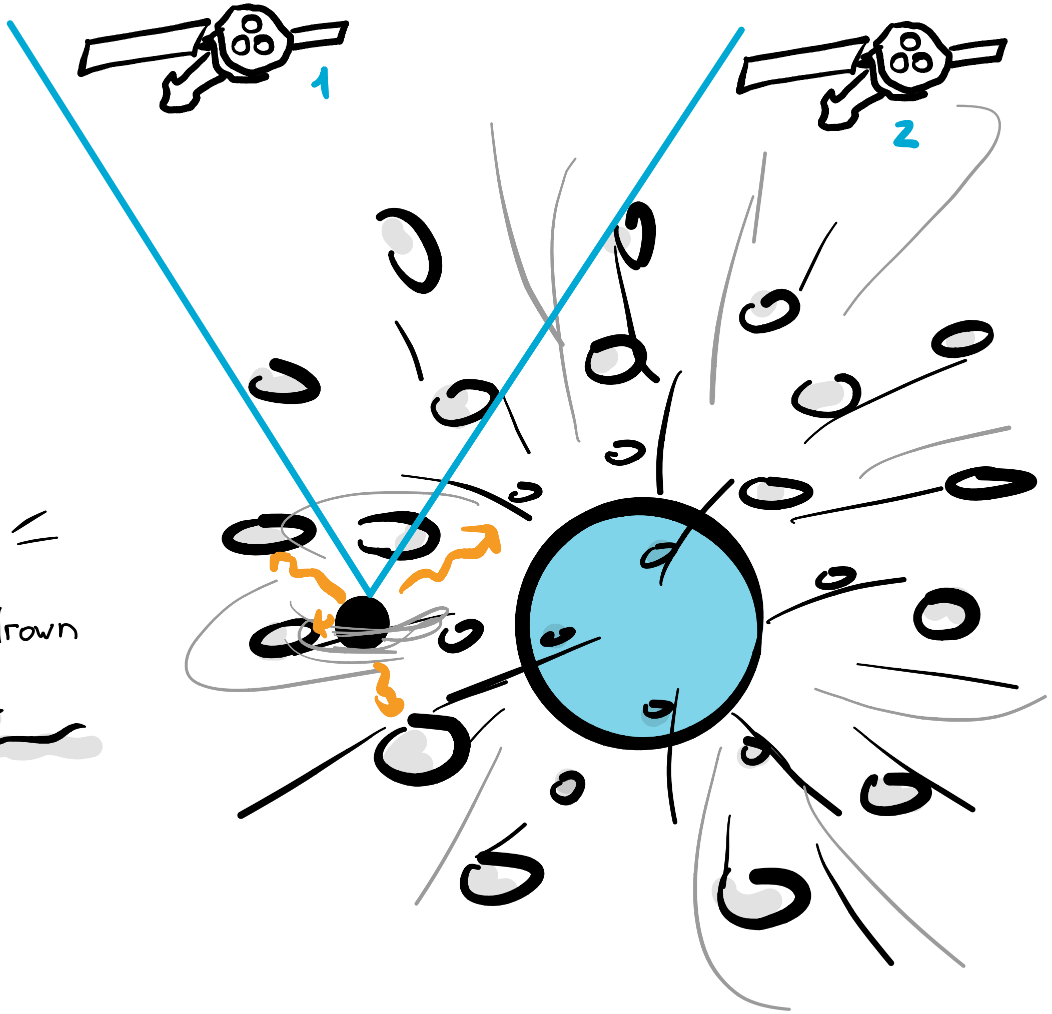


SHORT TERM VARIABILITY & CLUMPINESS

DEPENDS ON

- LINE OF SIGHT (1 vs 2)
- CLUMP PROPERTIES (MASS, RADIUS)
- CLUMP MOVEMENT
- WIND IONIZATION





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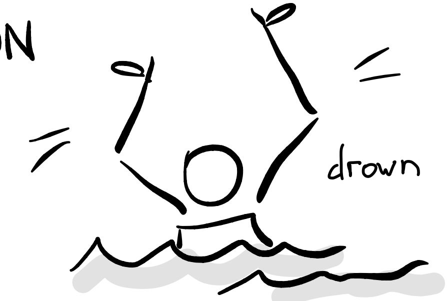
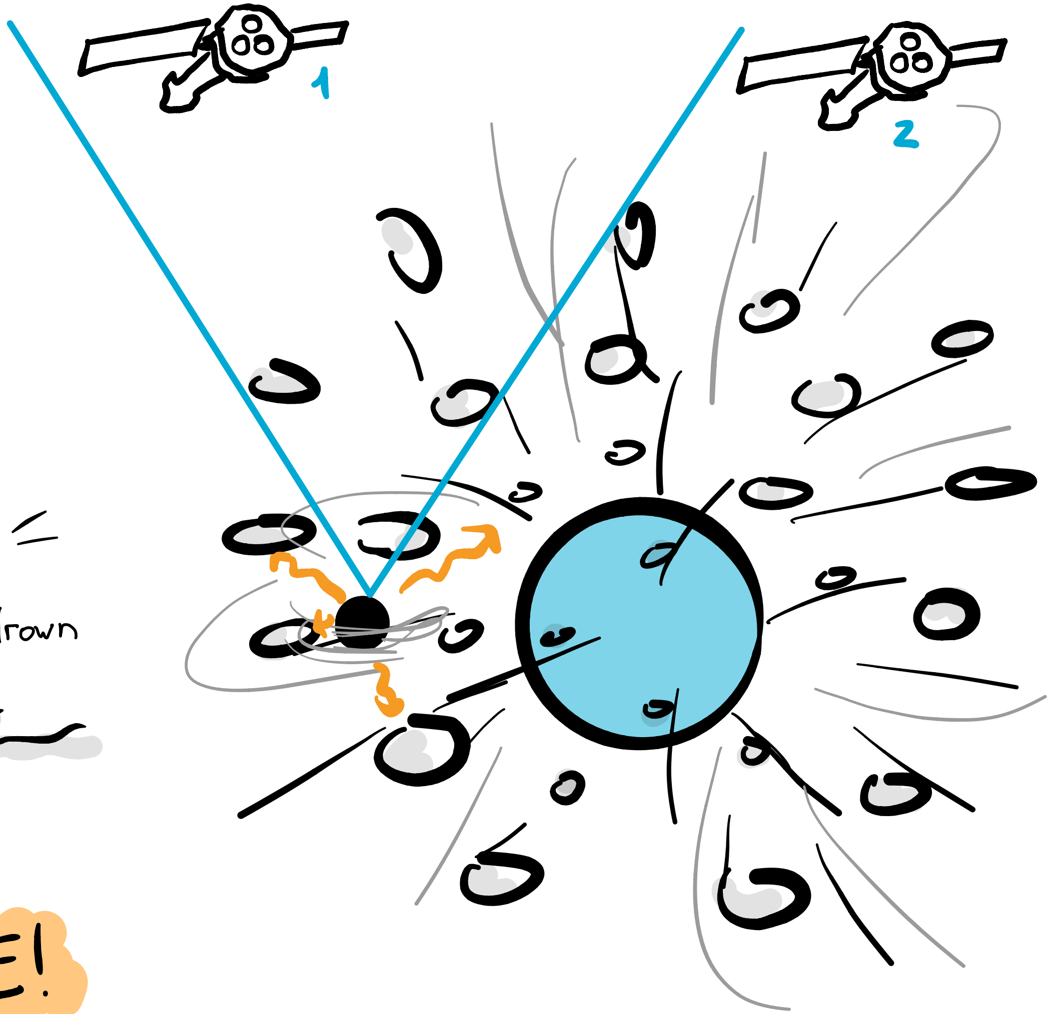
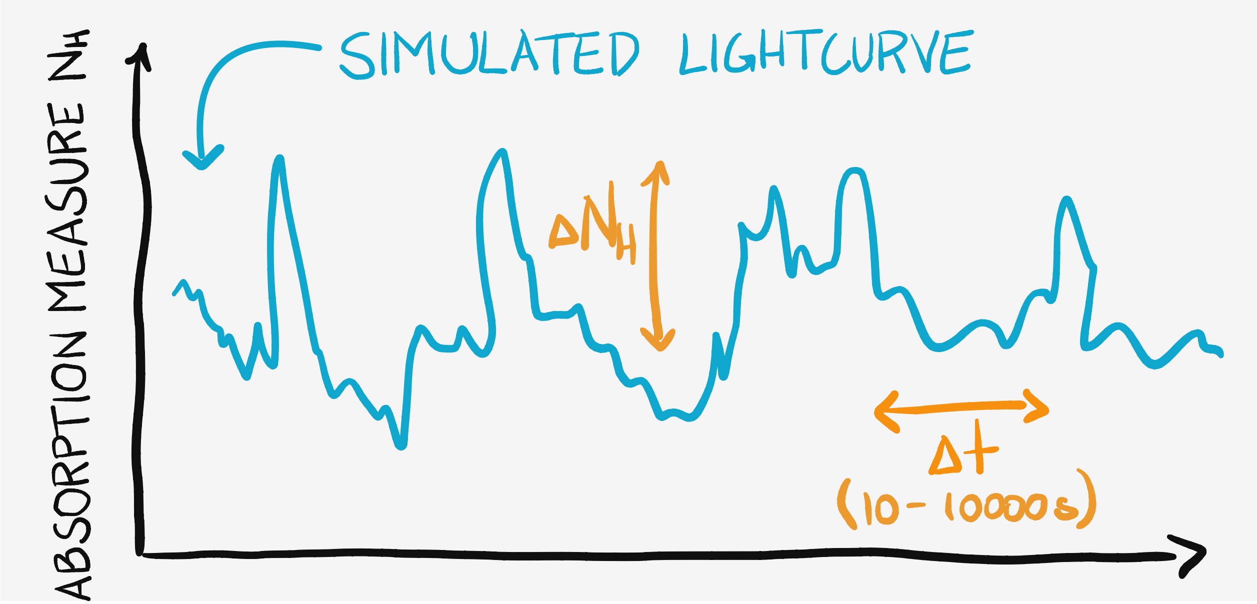


SIMULATE!



El Mellah, Grinberg + 2020

SHORT TERM VARIABILITY & CLUMPINESS



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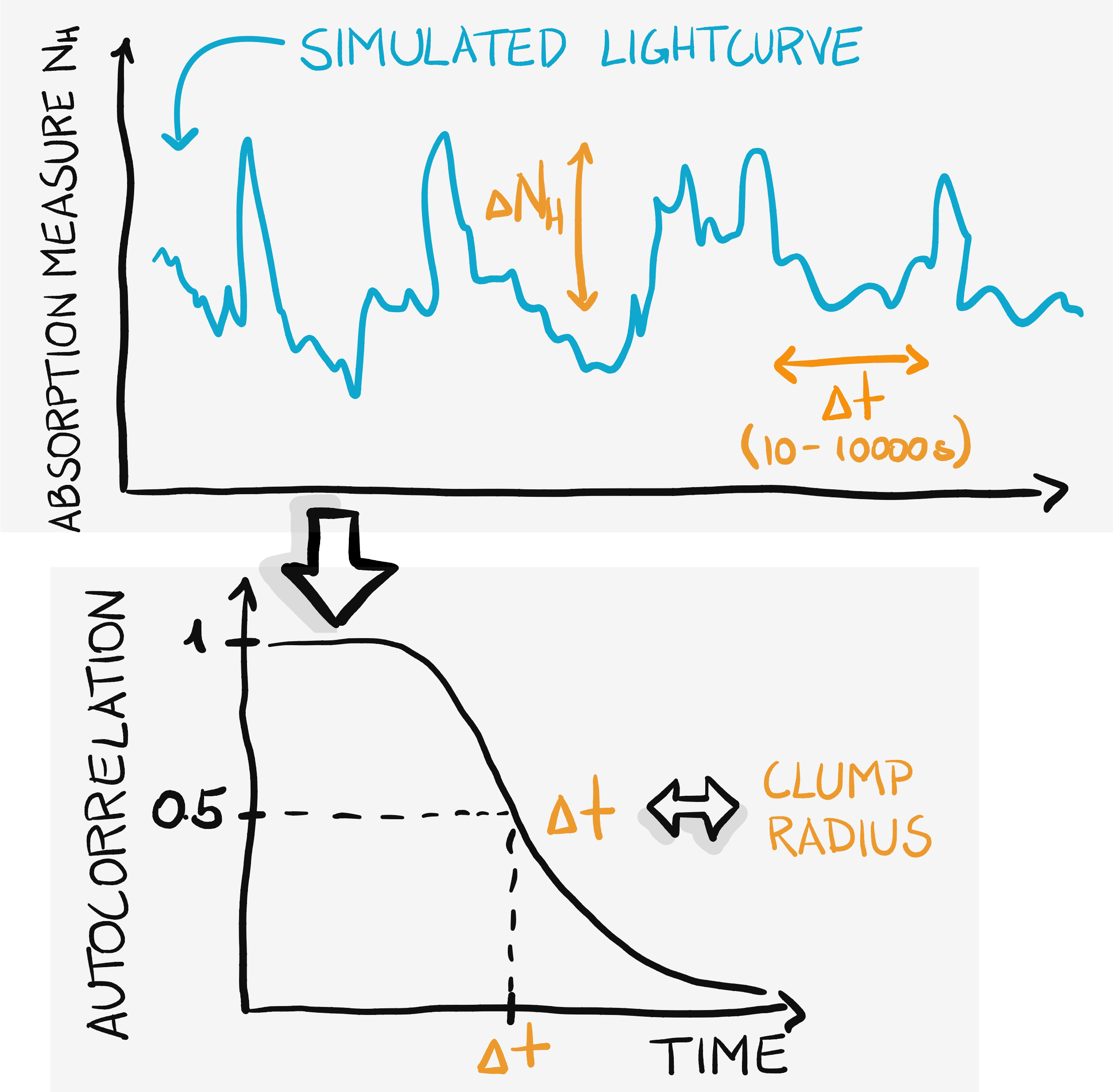

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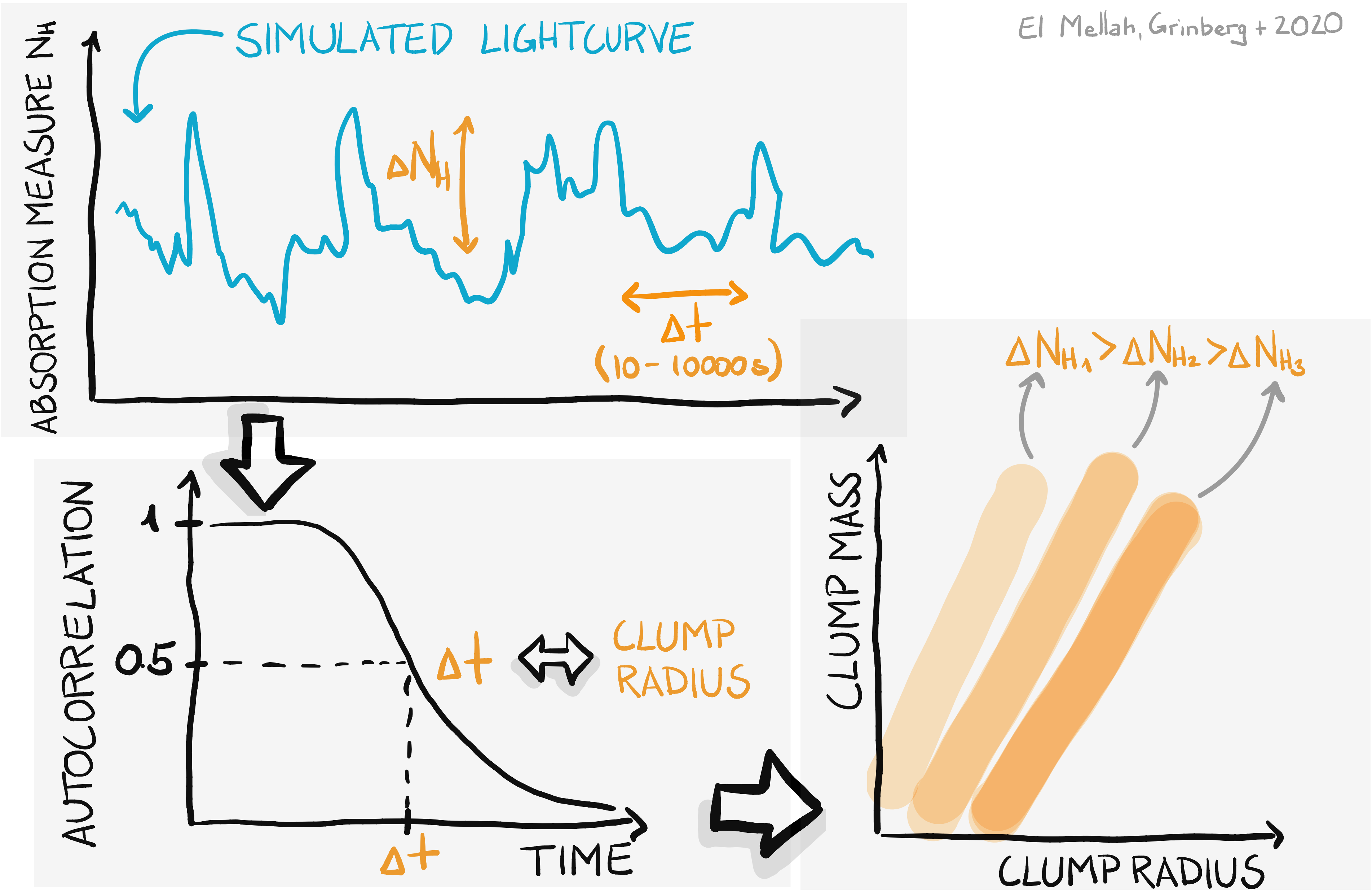
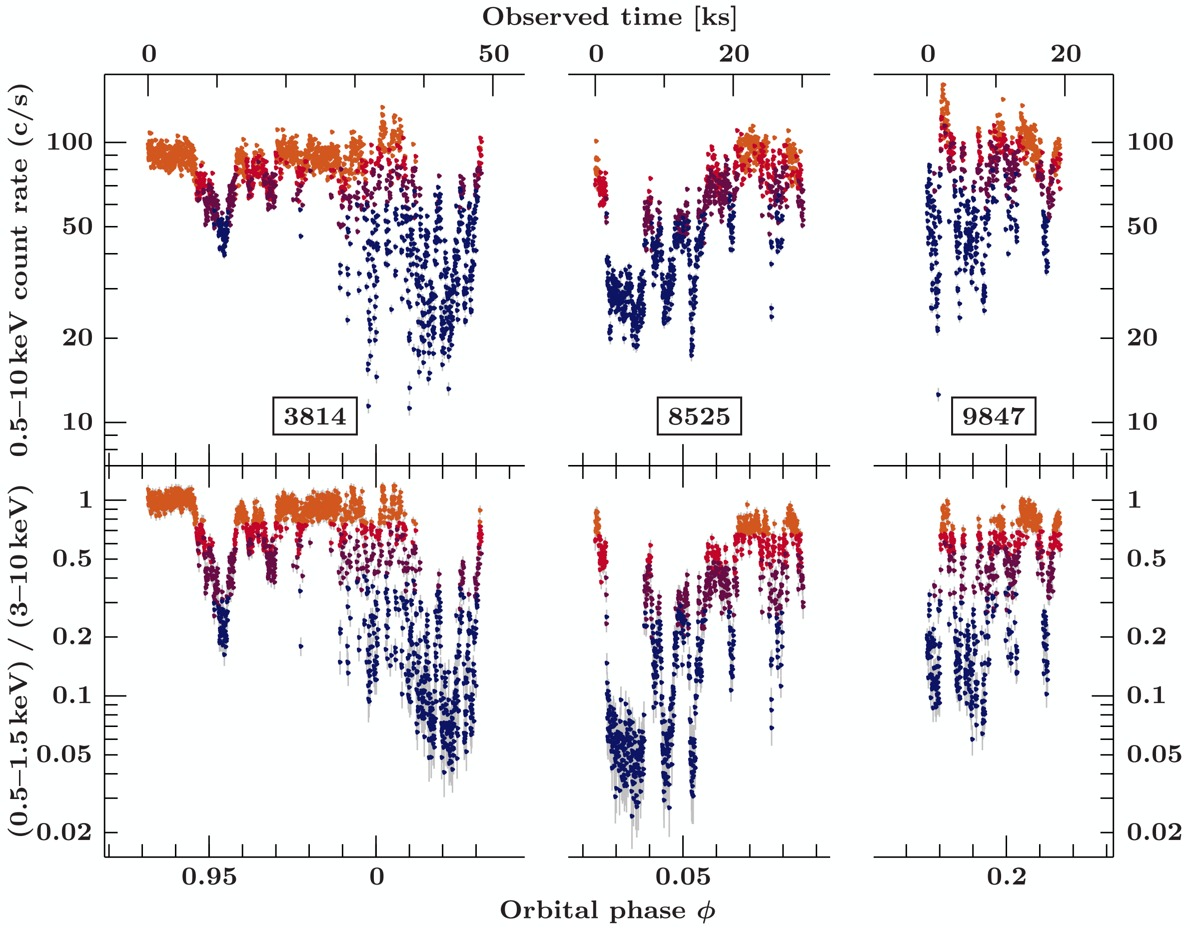


Clumps structure in Cygnus X-1

Chandra HETG observations



Hirsch+ 2019

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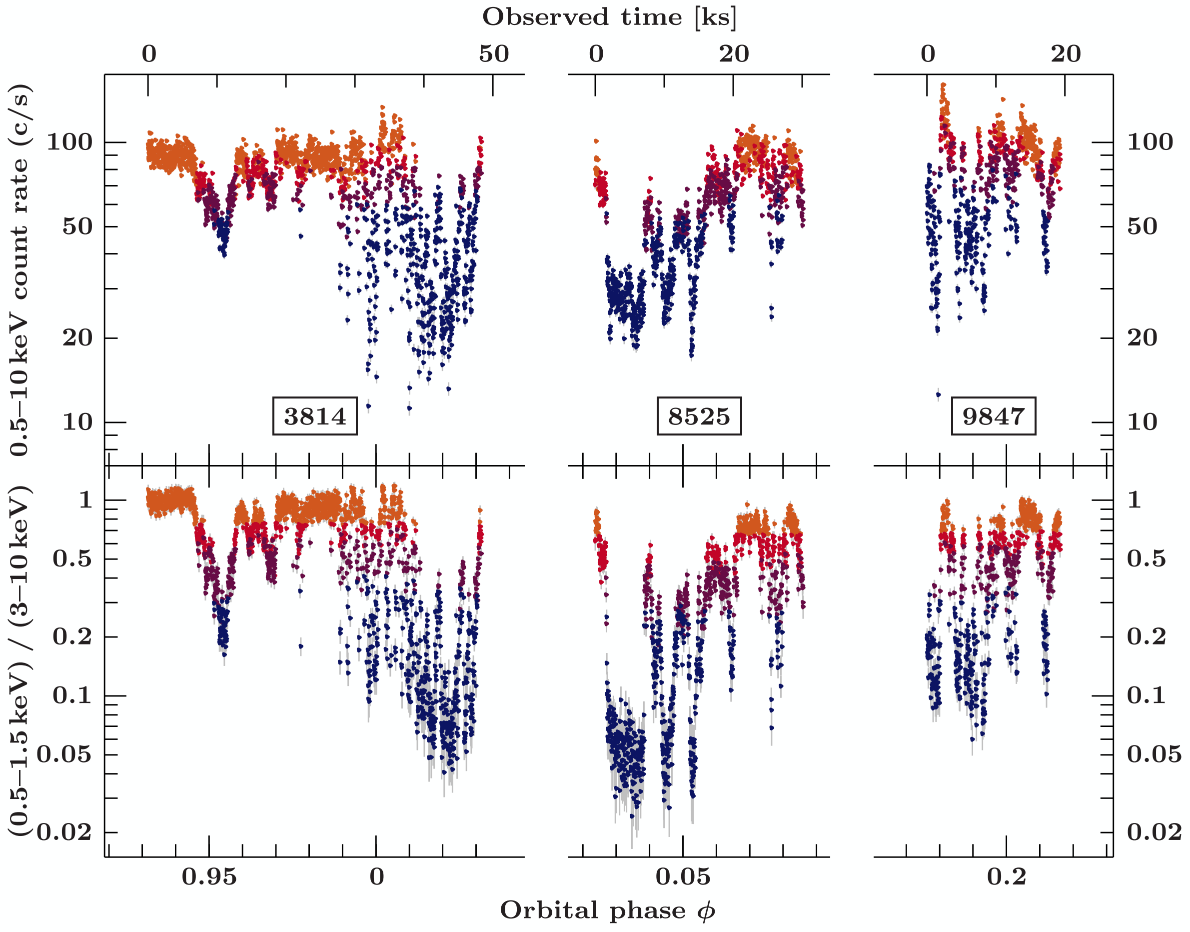

➤ divided in four absorption stages

Hirsch+ 2019

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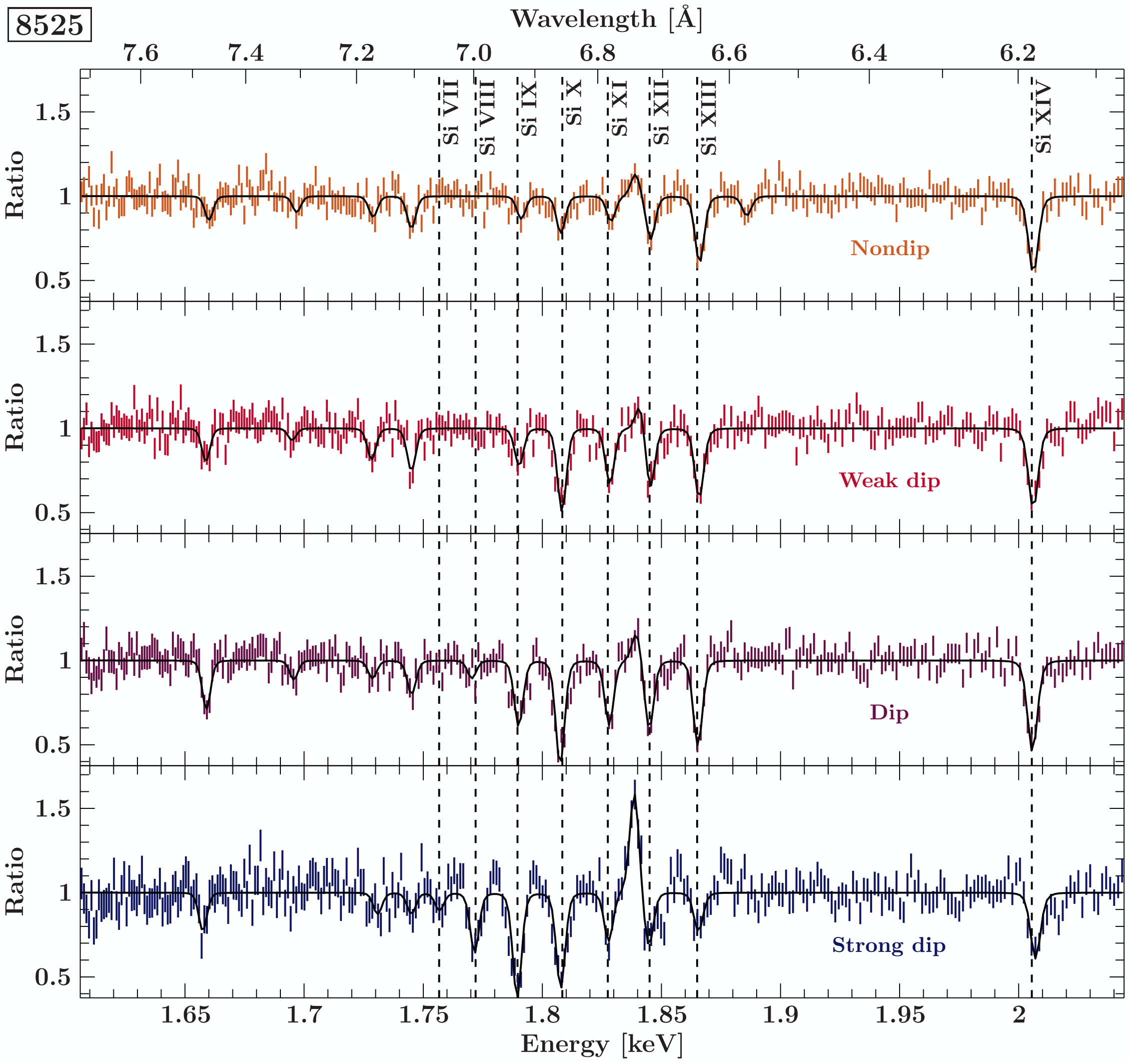

Hirsch+ 2019

- divided in four absorption stages
- stronger absorption $\Longrightarrow$ lower ionization stages (of Si & S)

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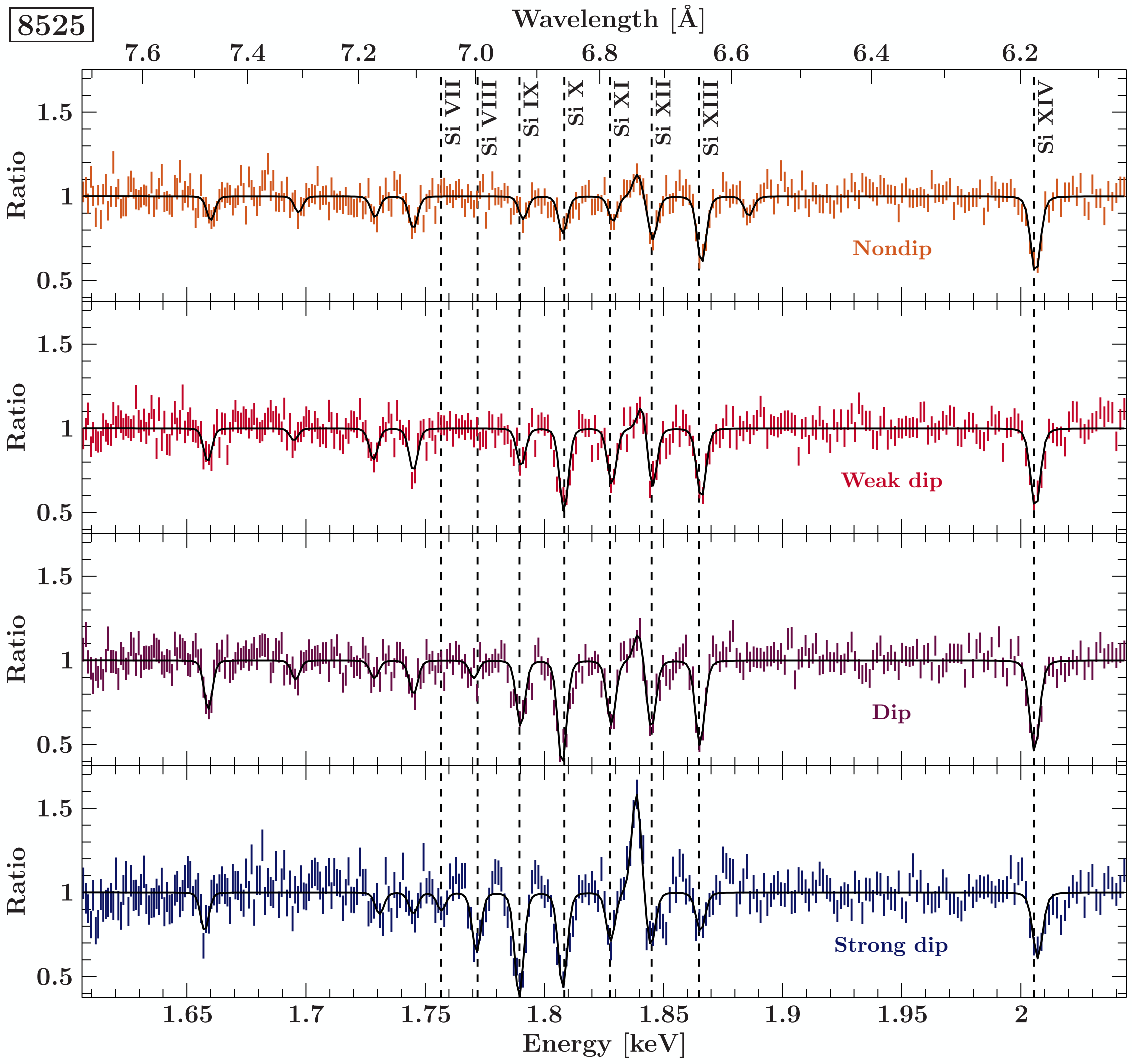

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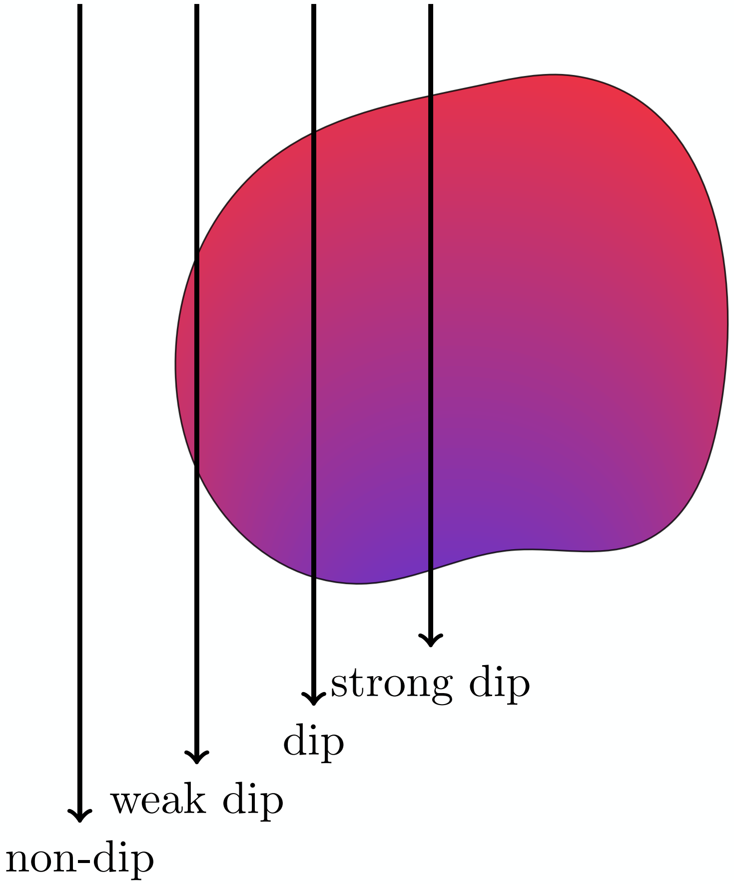
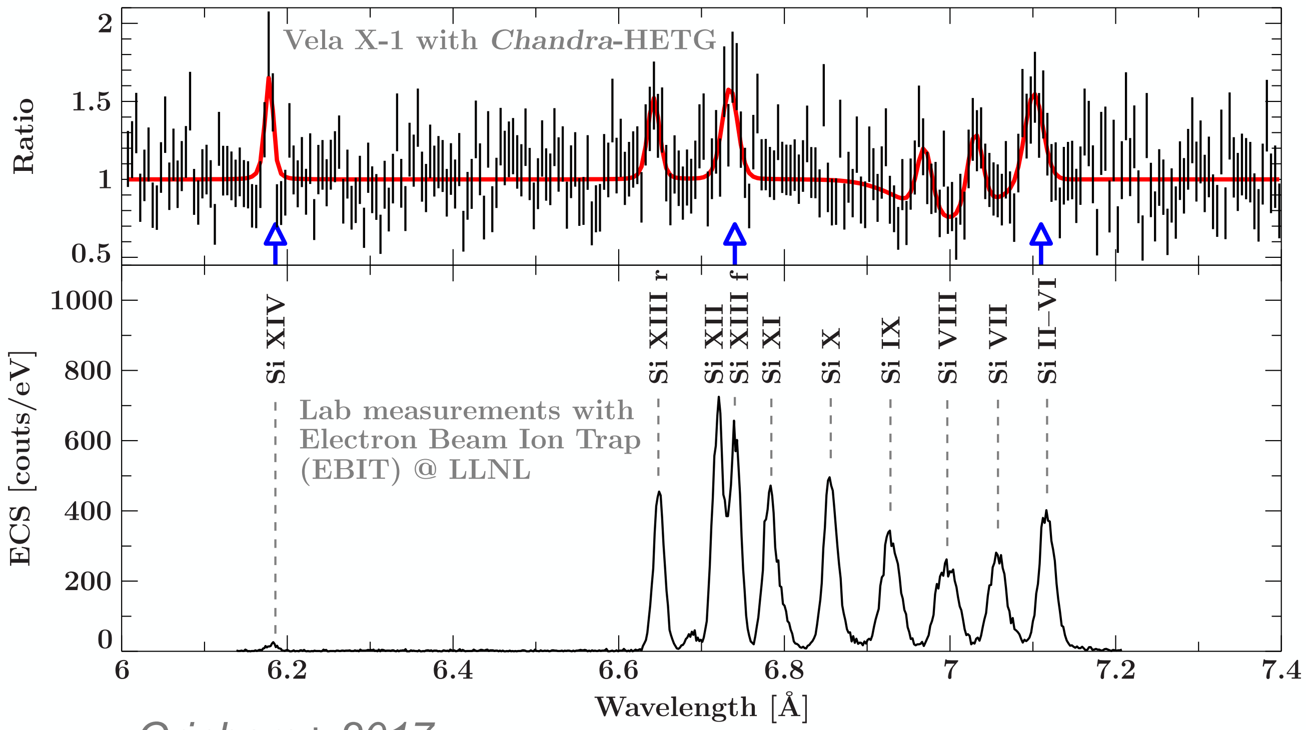


- ➤ divided in four absorption stages
- ➤ stronger absorption $\Longrightarrow$ lower ionization stages (of Si & S)
- ➤ same Doppler shift for all lines (using the newest lab measurements)

$\Longrightarrow$ structured clumps with cold cores

Hirsch+ 2019

Multiphase medium in Vela X-1: dips



Grinberg+ 2017

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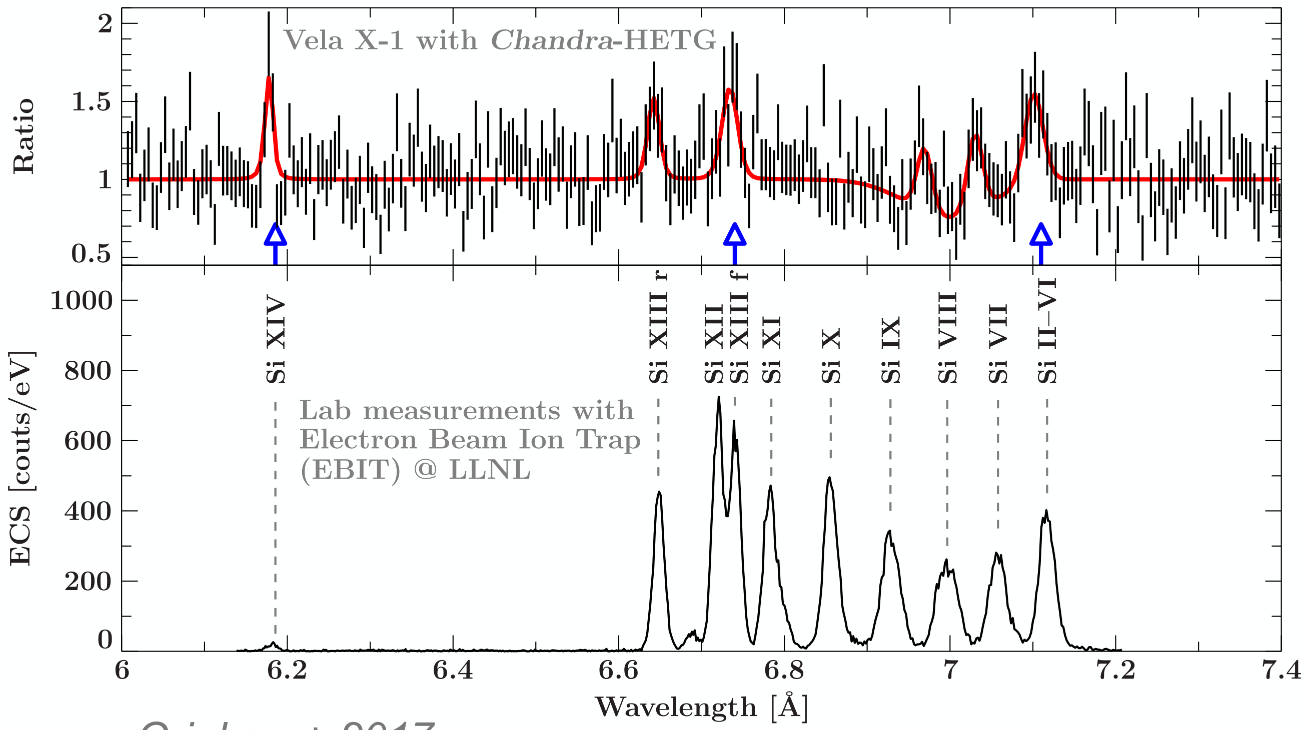

Grinberg+ 2017

- ➤ high & low ionization ions

$\Longrightarrow$ hot & cold has present

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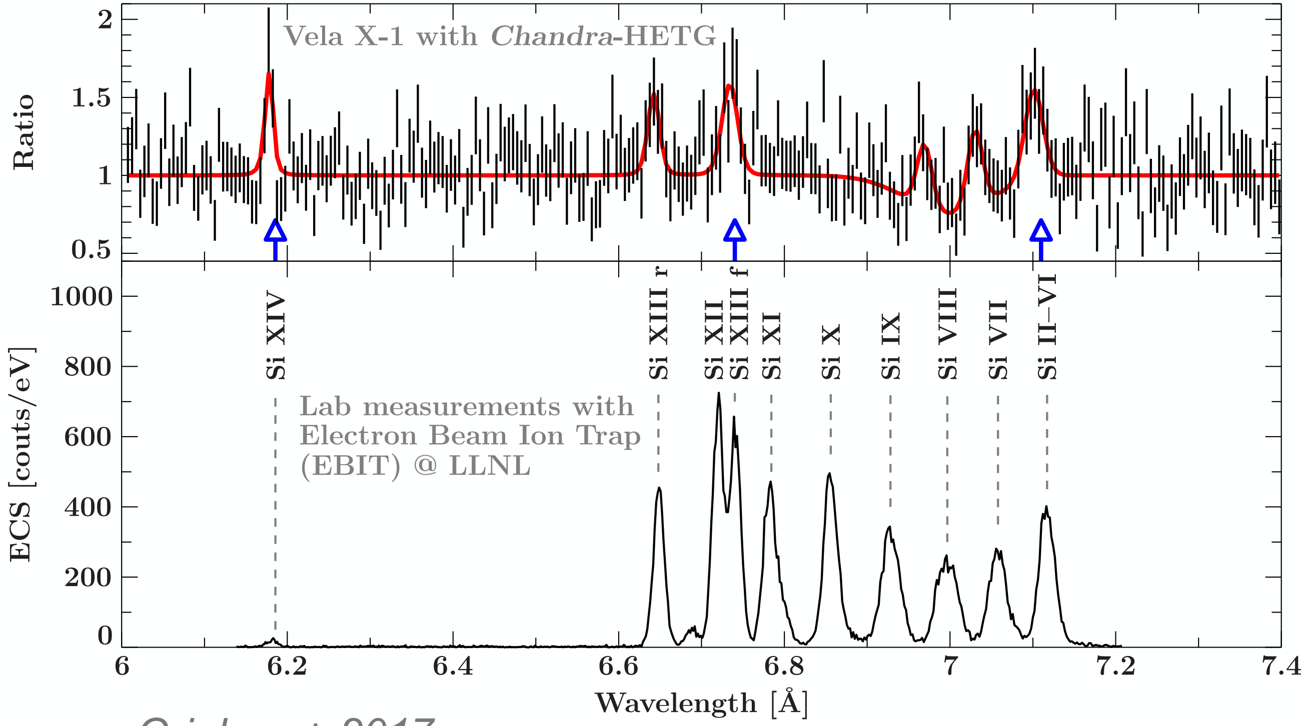


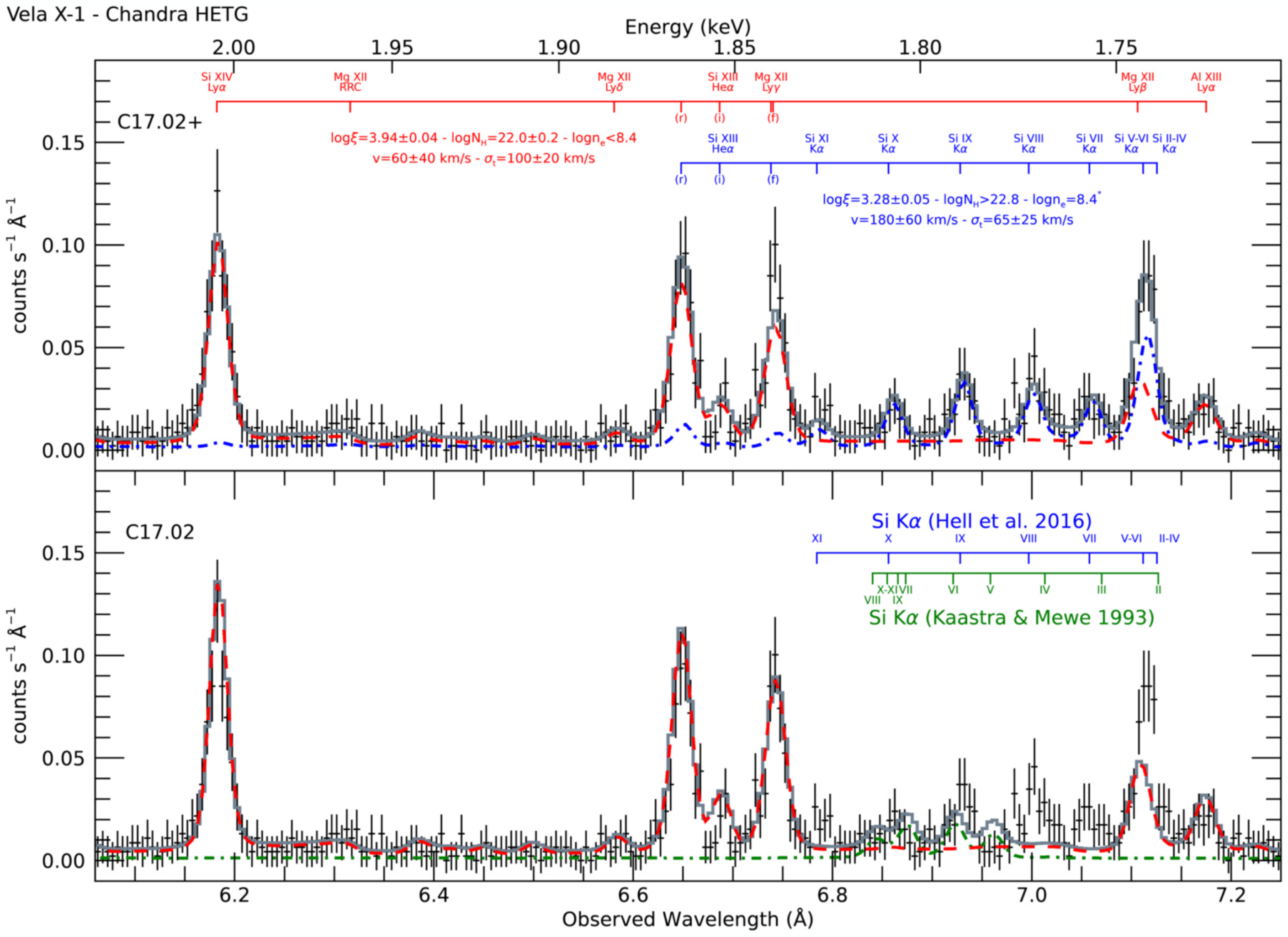
Grinberg+ 2017

➤ high & low ionization ions

⟹ hot & cold has present

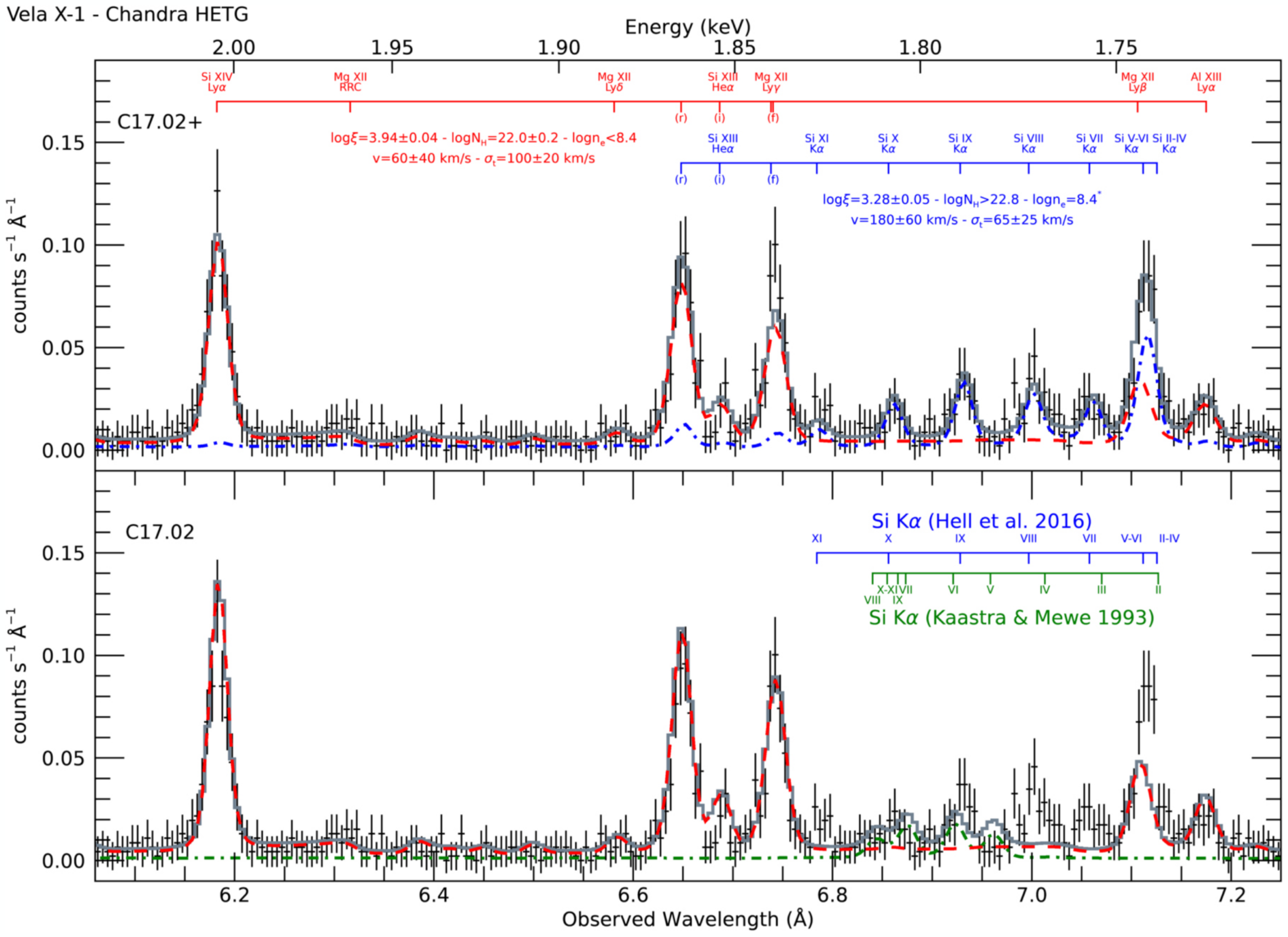
⟹ highly ionized part of the wind vs. clumps - shocks? clump in the wind? clump interaction with the compact object?

Multiphase medium in Vela X-1: wakes



Camilloni+ 2021; see also Amato 2020

Multiphase medium in Vela X-1: wakes



Camilloni+ 2021; see also Amato 2020

- looking through the photoinization wake ⟹ reasonable description with SPEX/Pion or Cloudy

But: problems at low ionization stages!

Solution: implement better atomic data!

Now: hints of different dynamics of cold + hot gas

Accretion & ejection processes

- labs for physics under extreme conditions
- AGN on fast-forward
- probes for material in their direct environment (esp. stellar winds in high mass stars)

Populations & evolution

- compact object merger progenitors (or not)
- probes for stellar and compact object evolutionary pathways

Questions?