Class 12 :
X-ray binaries and the discovery of black holes

ASTR350 Black Holes (Spring 2022)

Cole Miller

RECAP

- Development of radio astronomy (1960s) led to the discovery of pulsars
  - Very regular and rapid pulses of emission
  - Soon identified as the rotation of a magnetized neutron star
- Neutron stars
  - Exotic objects!
  - Average density comparable to that of atomic nucleus
  - Much of the interior has been “neutronized” (most but not all protons converted to neutrons)
  - some have very strong magnetic fields
  - importance of GR

This class

- Neutron Stars continued
- Discovery of black holes!
- Story of X-ray astronomy…

Muddiest points

General astro questions

I : Atmospheric Windows

- The atmosphere blocks many wavelengths of electromagnetic radiation. Essentially, we can just see from the ground
  - Optical/near IR
  - Microwave (from high dry places!)
  - Radio

- So how do we do X-ray astronomy?
  - why should we care?

Why X-rays ??

- Neutron stars born VERY hot in SN

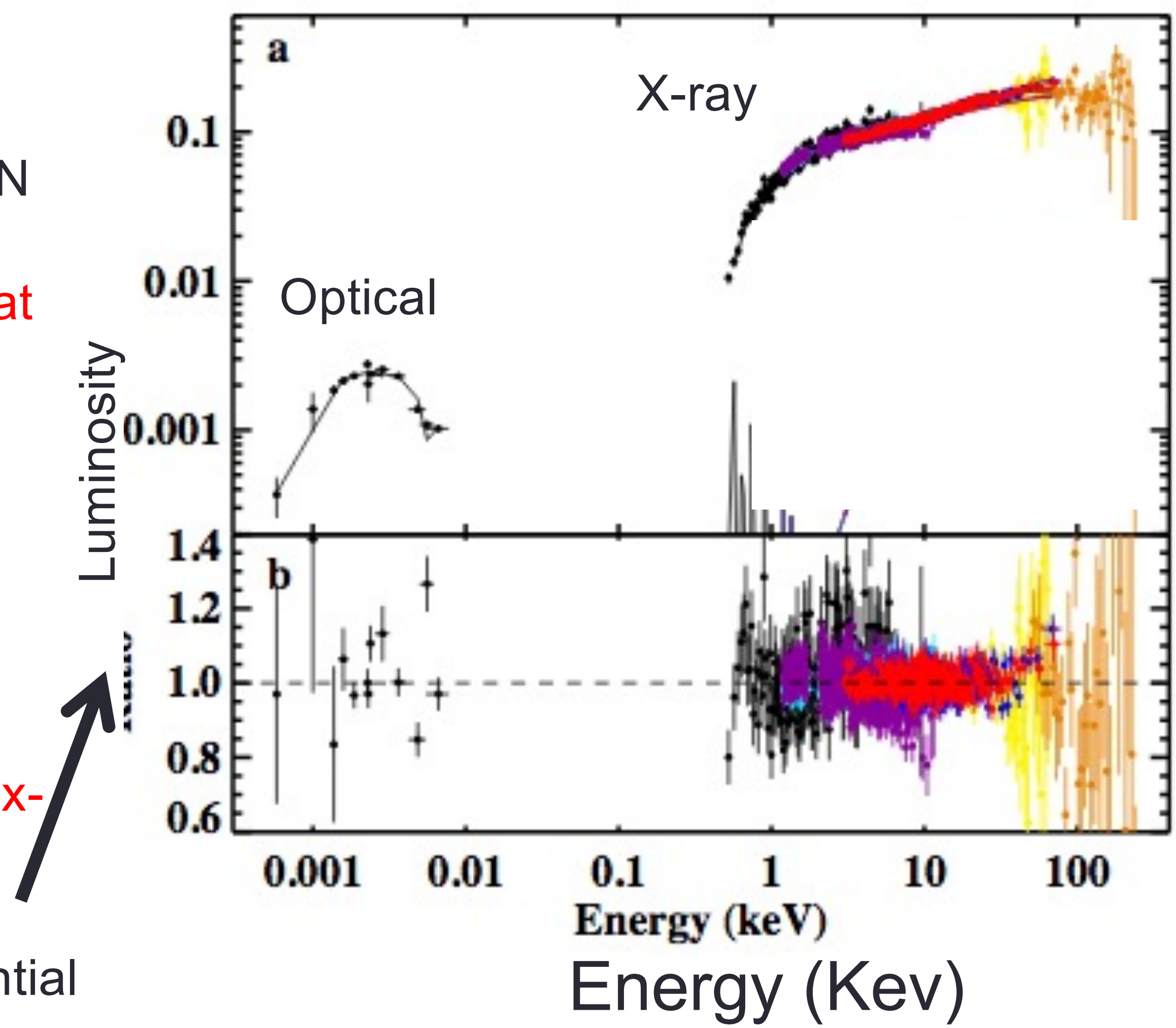
Cool off with time

After about 1000 years T~10^6 K emit at x-ray wavelengths

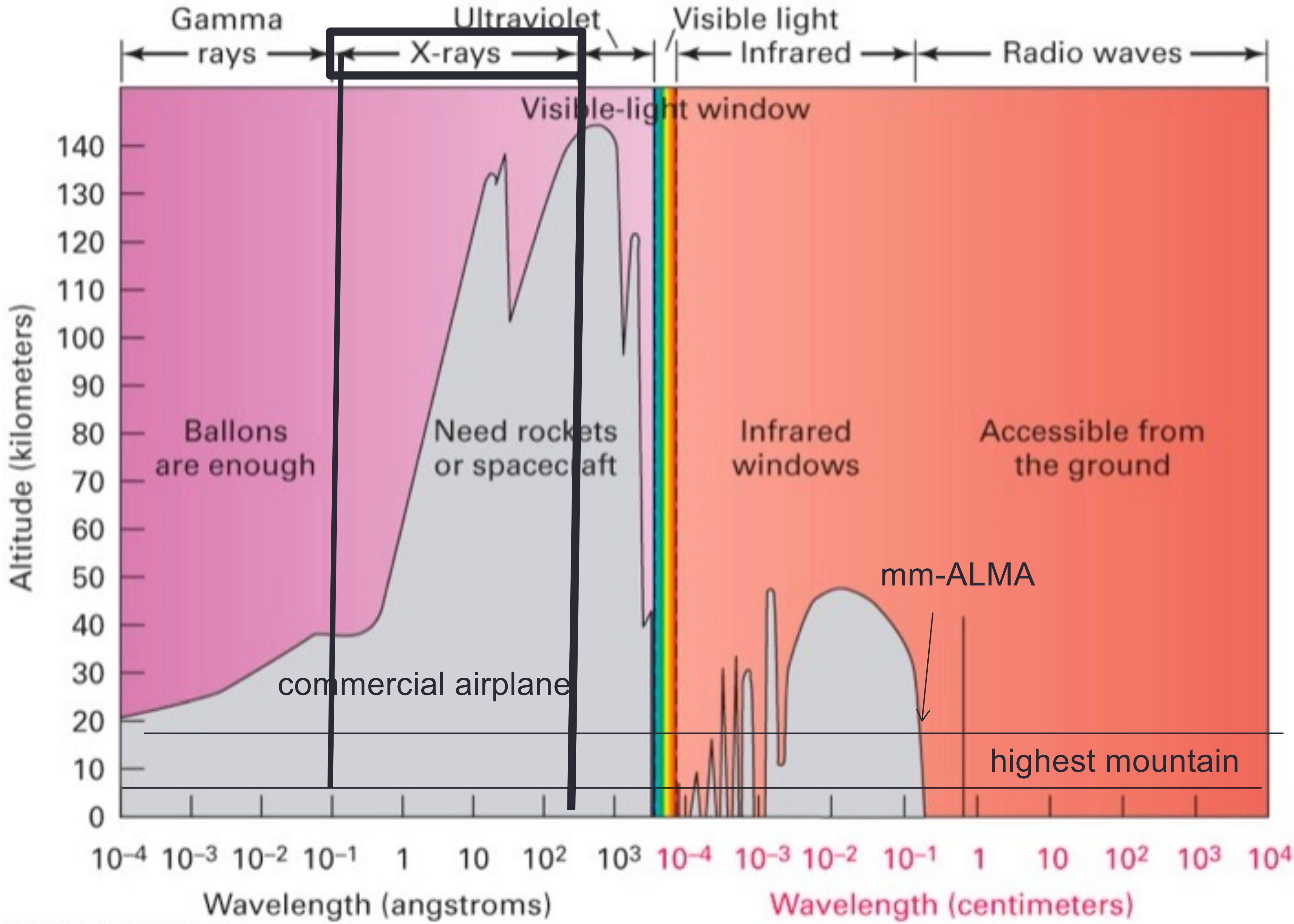
- Most accreting neutron stars emit most of their energy at x-ray wavelengths

- Most accreting stellar mass black holes emit most of their energy at x-ray wavelengths

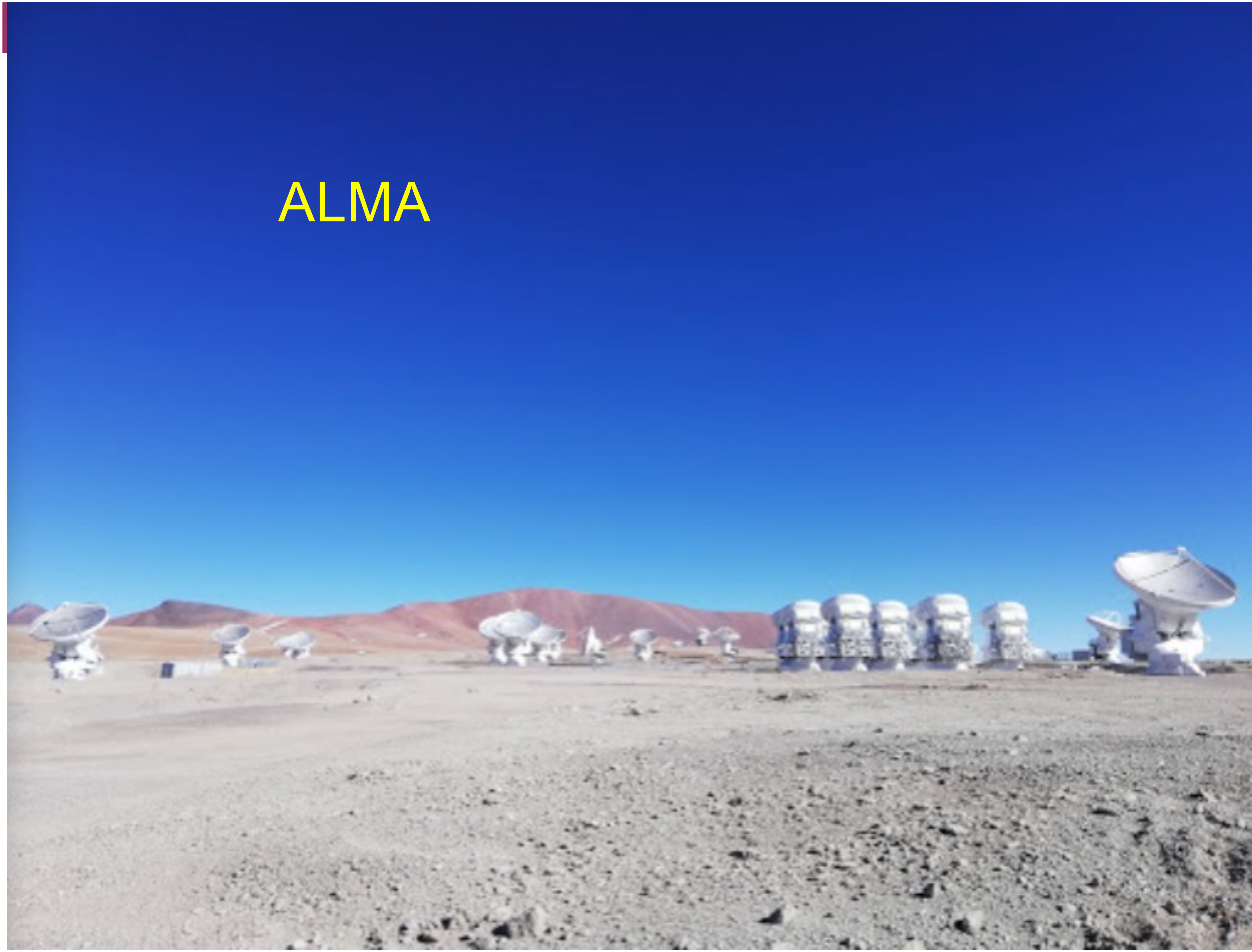
- Supermassive BHs emit a substantial amount of their energy in the x-rays

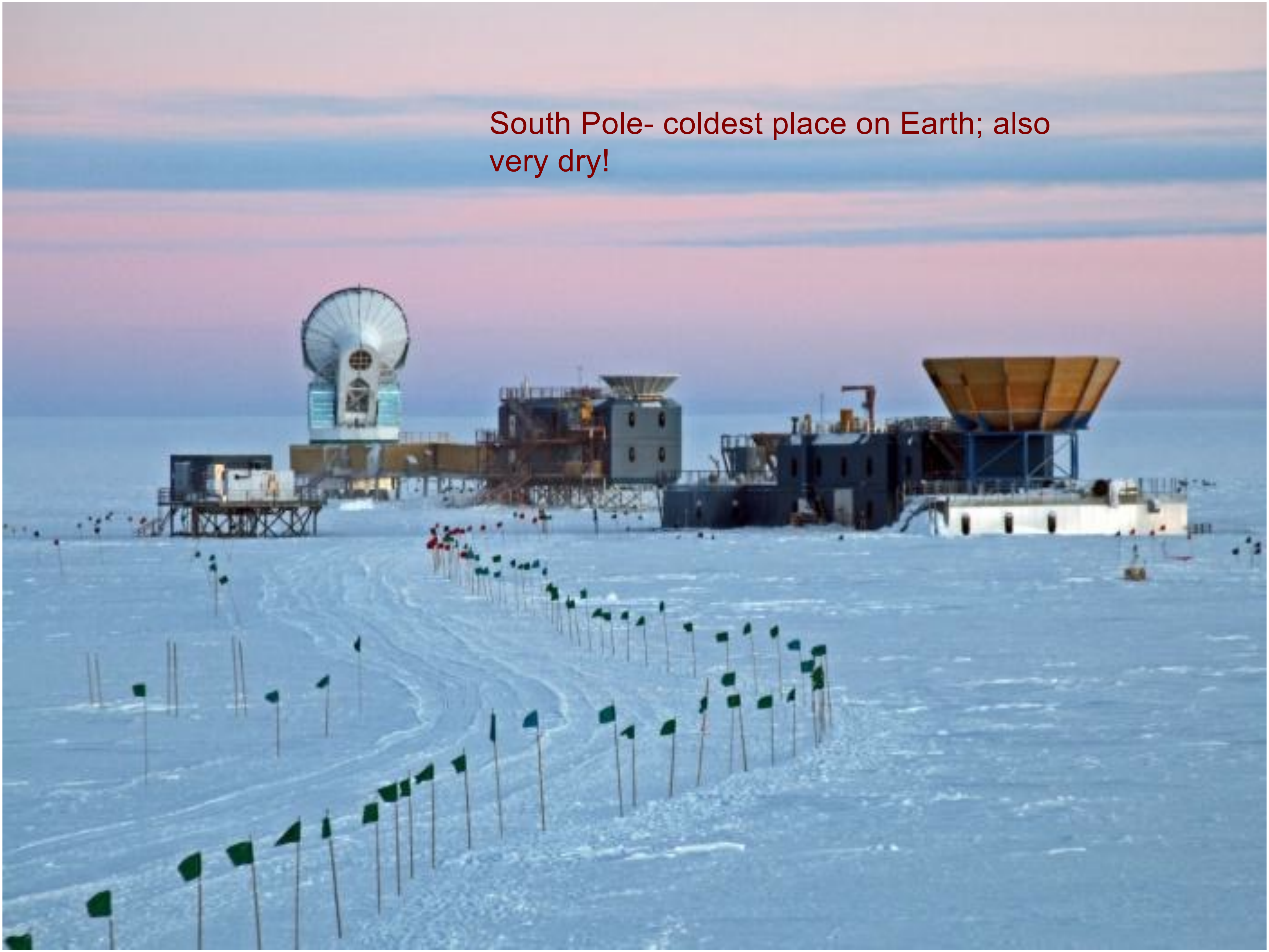


Spectrum of an accreting neutron star from optical through x-ray


Gamma rays
X-rays
Ultraviolet
Visible light
Infrared
Radio waves
Visible-light window
Altitude (kilometers)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Ballons are enough
Need rockets or spacecraft
Infrared windows
Accessible from the ground
mm-ALMA
commercial airplane
highest mountain
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³
Wavelength (angstroms)
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴
Wavelength (centimeters)


Atacama desert- driest place on Earth


ALMA

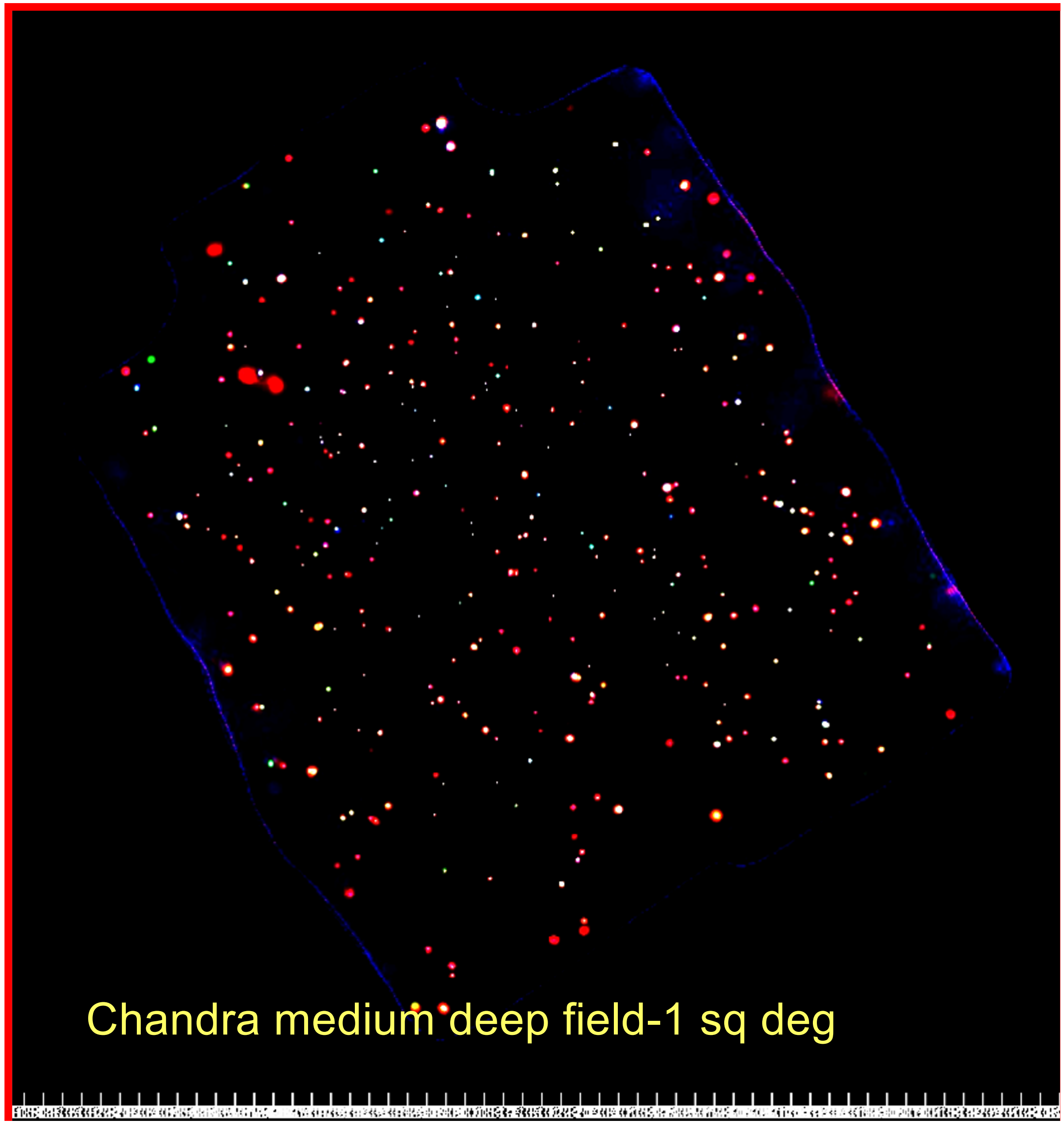

South Pole- coldest place on Earth; also very dry!

II : Early History of X-ray astronomy

- Sounding rocket flights…
  - 1949 : Launch of X-ray detector on a V2-rocket; first detection of X-rays from Sun
  - 1962 : First detection of an X-ray source from outside of the solar system (Sco-X1, Giacconi et al **Nobel prize** 2002)
  - 1964 : Detection of Cygnus X-1- **first black hole**
- Satellites
  - 1970 : Uhuru satellite launched- first survey
  - Since 1970's multiple satellites- focusing on surveys, imaging, timing, spectroscopy

Nature of Faint X-ray Sources

- Most of the faint x-ray sources are **super massive black holes** active galaxies (AGN, quasars, Seyfert galaxies)
- At a median redshift of 0.7 (D_L=4260 Mpc = 1.31×10^{28} cm)
- median x-ray luminosity ($10^{43.5}$ergs/sec =8×10^9 $L_\odot$)
  - The red 'blobs' are clusters of galaxies



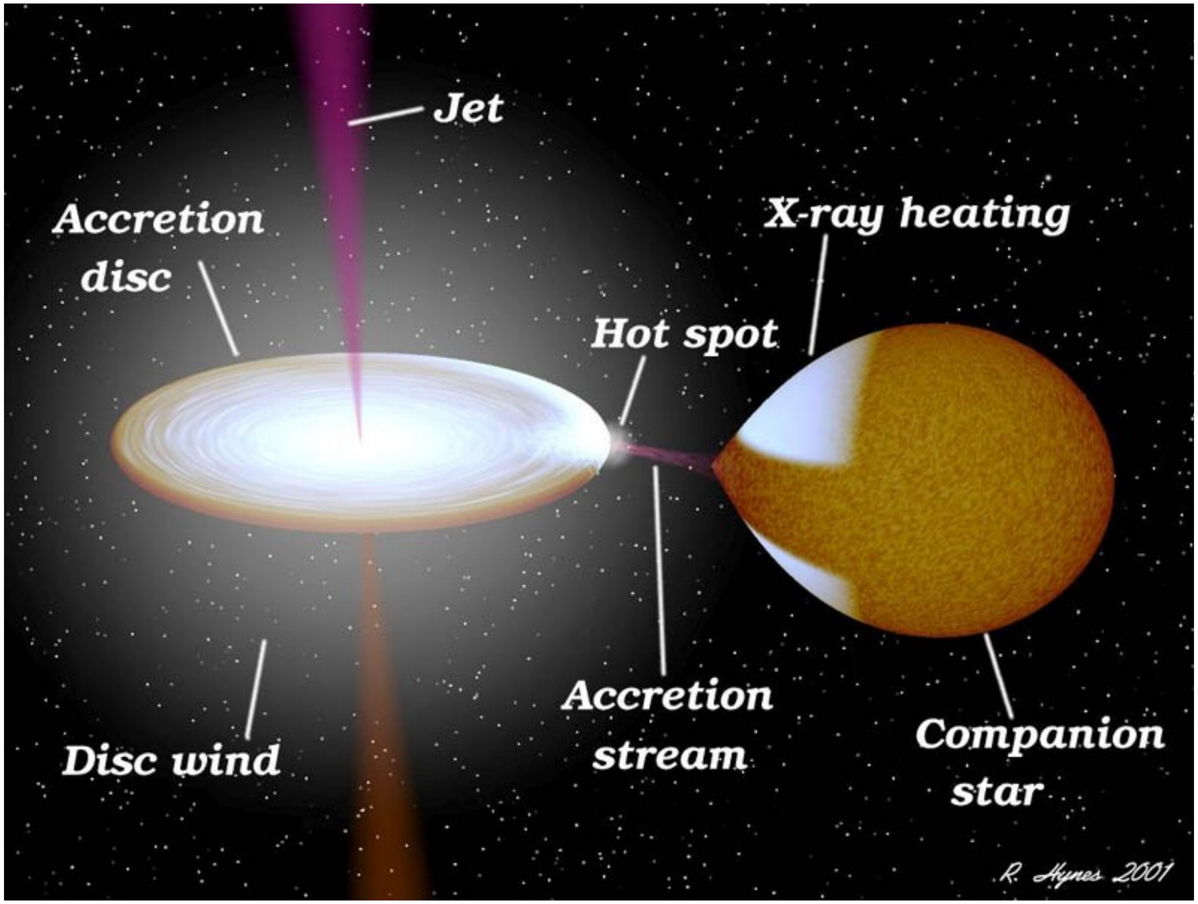
II : Neutron star X-ray binaries

- Many X-ray binaries* consist of a neutron star (rather than a black hole) orbiting a normal star
- Important new aspect…
  - Neutron stars have a magnetic field and a surface!
  - Appearance of source can depend on magnetic field

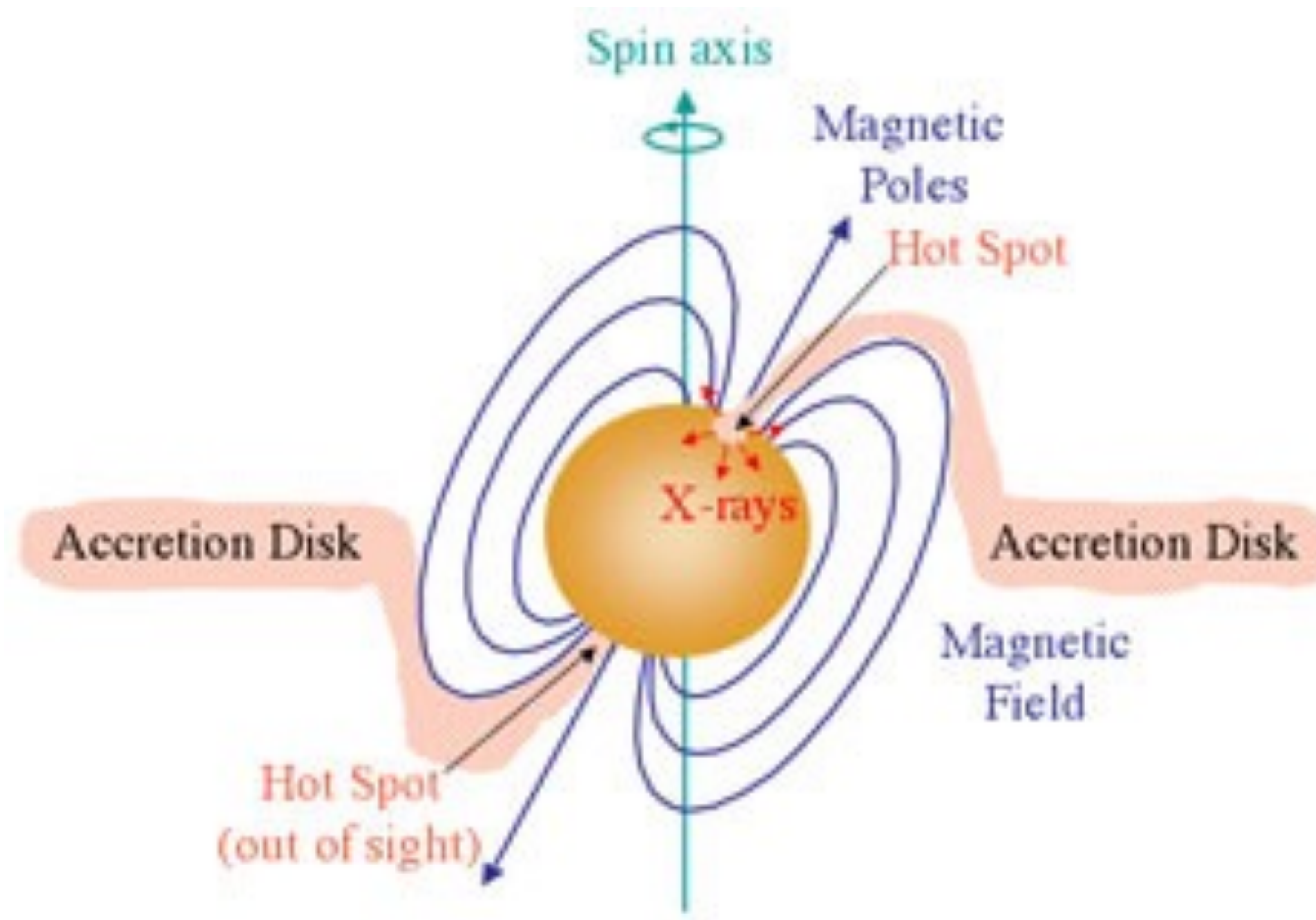
*x-ray binary: a binary stellar system consisting of a main sequence star or white dwarf and a compact object (NS or BH) which is accreting material and produces copious x-ray emission

Accreting Neutron Stars

- Two types- based on mass of companions (high mass (O/B stars); low mass (mainly K, M) stars)
  - Low mass x-ray binaries-NS star tends to have low magnetic field-
  - High mass-NS tends to have high magnetic field
  - Reason for difference is not clear; “burial” of magnetic field by accreting matter is a possibility but isn’t easy in detail



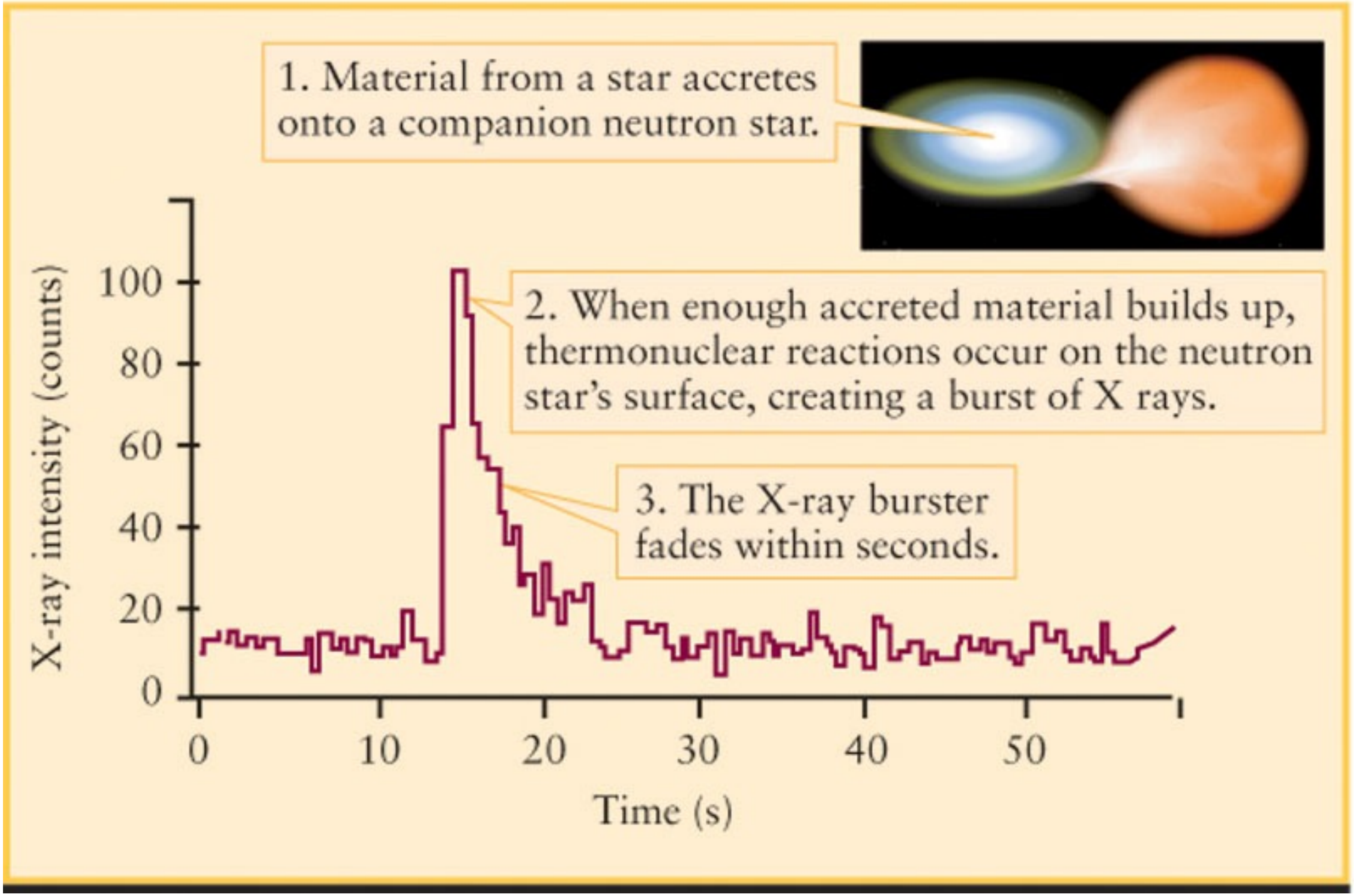
- Strongly magnetized neutron star X-ray binaries…
  - Matter flows from a companion star and forms an accretion disk
  - Magnetic field disrupts accretion disk
  - Matter flows down field lines and strikes neutron star surface at magnetic poles… get “hot spots”
  - In hotspots, temperatures get high enough to fuse the incoming hydrogen to helium (continuously)
  - As poles spin around (due to NS rotation), the hot-spots flash in and out of view… get an **accretion-powered X-ray pulsar**.
  - Luminosities range from 10^{32}-$4x10^{38}$ ergs/sec, ~ 100 in Milky Way more luminous that 10^{36} erg/sec; for reference, Sun is ~$4x10^{33}$ erg/sec total
  - Unlike case of the radio pulsars these are **spinning-up** due to the action of the accretion disk



From http://astronomy.swin.edu.au/cosmos/X/X-ray+Pulsar

X-ray Bursters

- Weakly magnetized neutron star X-ray binaries
  - Accretion disk extends all of the way to the neutron star surface… hydrogen gas is dumped onto surface and spreads around.
  - So… there's a growing layer of hot hydrogen gas on surface
  - Once layer grows thick enough, runaway **fusion** starts at base of layer… layer explodes!
  - Explosion lasts about 10s and blows most of the layer into space… "**X-ray burst**"

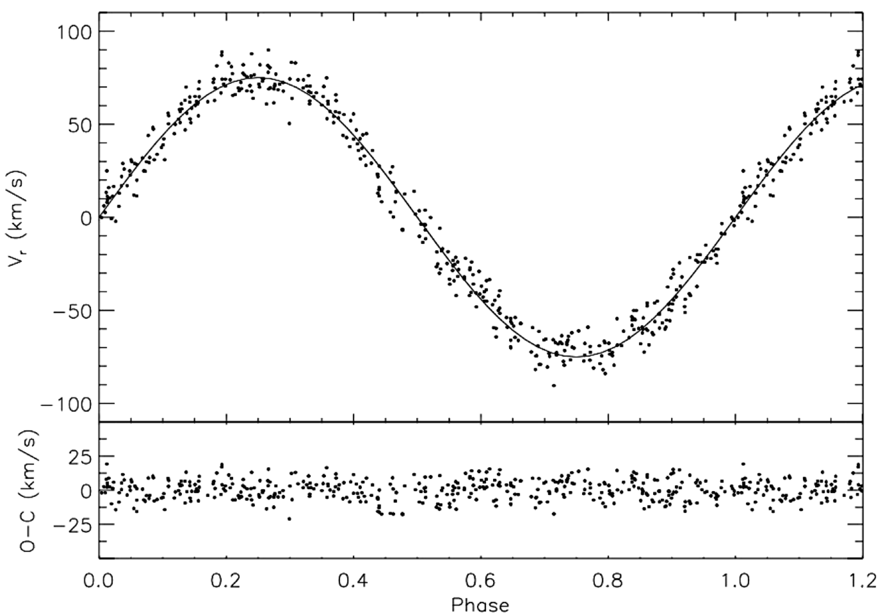

1. Material from a star accretes onto a companion neutron star.
2. When enough accreted material builds up, thermonuclear reactions occur on the neutron star's surface, creating a burst of X rays.
3. The X-ray burster fades within seconds.
X-ray intensity (counts)
100
80
60
40
20
0
0
10
20
30
40
50
Time (s)

III X-ray astronomy

- X-ray surveys (Uhuru satellite) found ~300 new sources in the early 1970's
  - One of them was very strange
- Properties of Cygnus X-1
  - Associated with a massive star 6000 ly away
  - Powerful X-ray source… 10^5x power of Sun!
  - Rapidly variable X-ray source

III : Figuring out Cygnus X-1

- Once companion star identified, intense study began
- Companion is a blue supergiant with mass of $40M_{sun}$
- Star found to wobble…
  - Period 5.6 days
  - Velocity ±75km/s
  - Clearly a binary star… *something* is orbiting the star, causing it to swing around
  - Analysis of orbit says that the companion must be $7\text{-}20M_{sun}$
- Nature of companion
  - Must be very small (X-ray variability)
  - **Too massive for neutron star**
  - **… hence a black hole!**

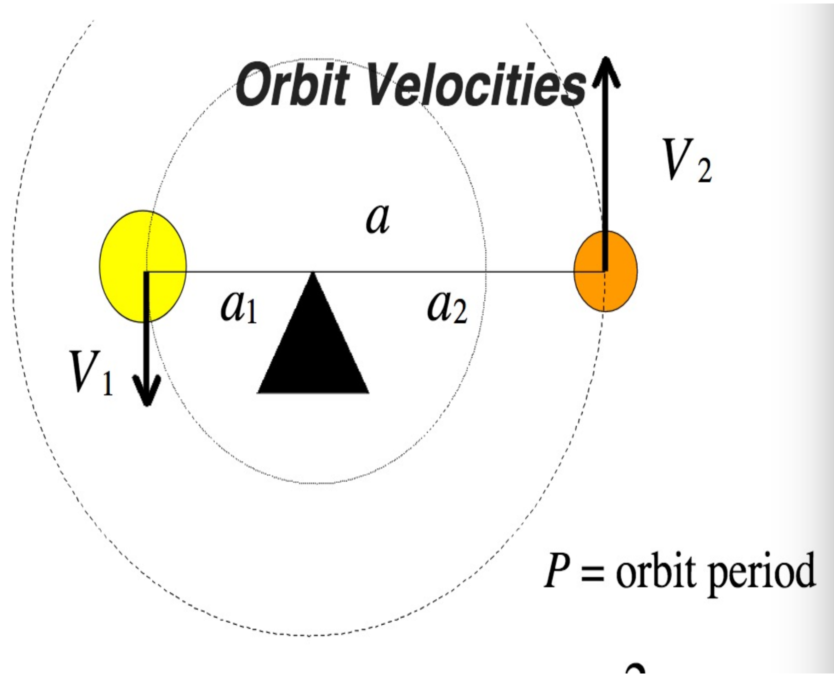


Velocity of companion star vs phase of 5.6d period

Brocksopp et al. (1999)

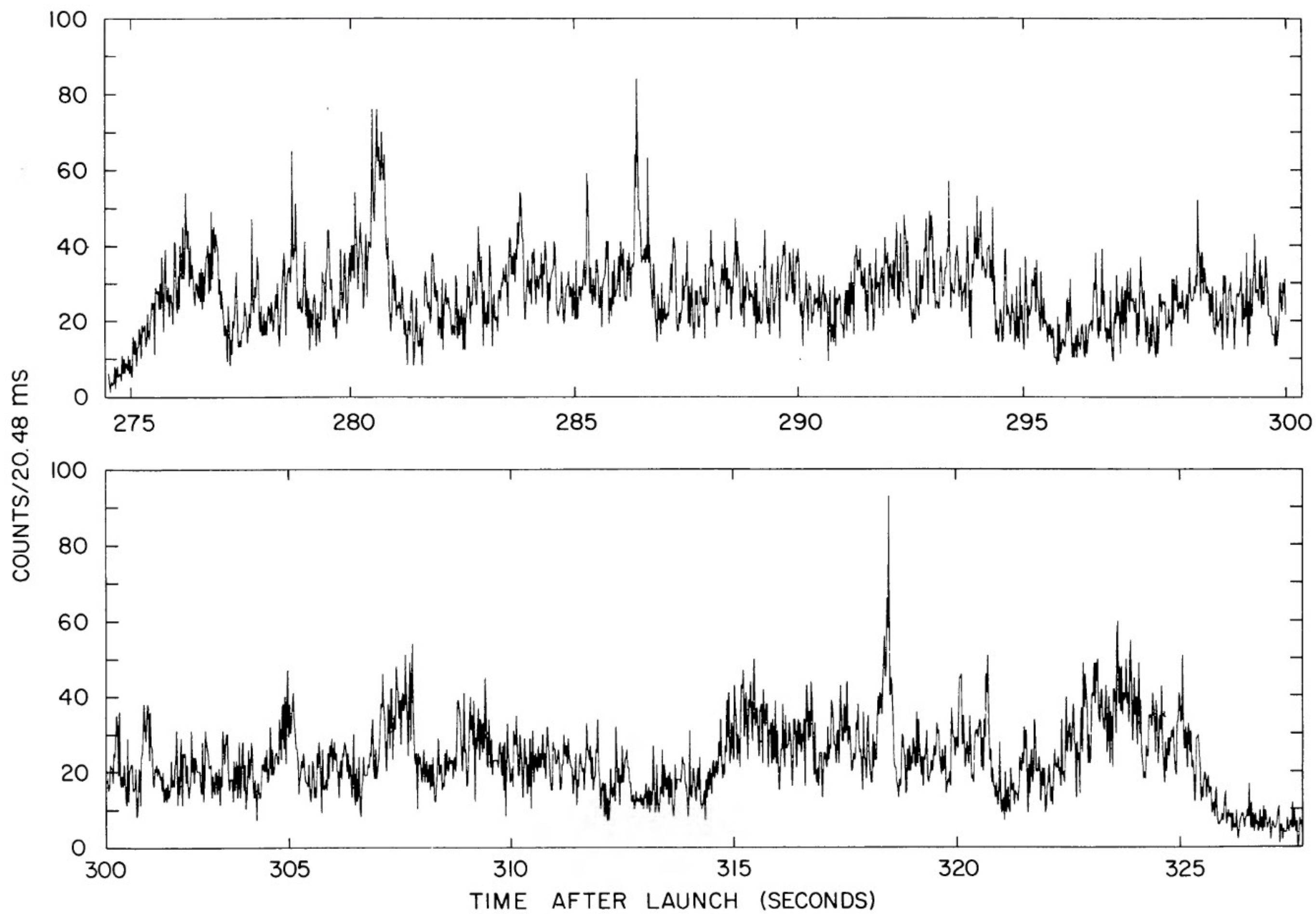
III : Figuring out Cygnus X-1

- Observable velocities $K_1 = V_1$**sini** and $K_2 = V_2$sini
- and the minimum mass M is
  - $M\sin^3 i = P(K_1+K_2)^3/2G\pi$
  - If we only have velocity information for the star (and not the compact object) the minimum mass is $P_{orb}K_2{}^3/2\pi G$



III : Figuring out Cygnus X-1

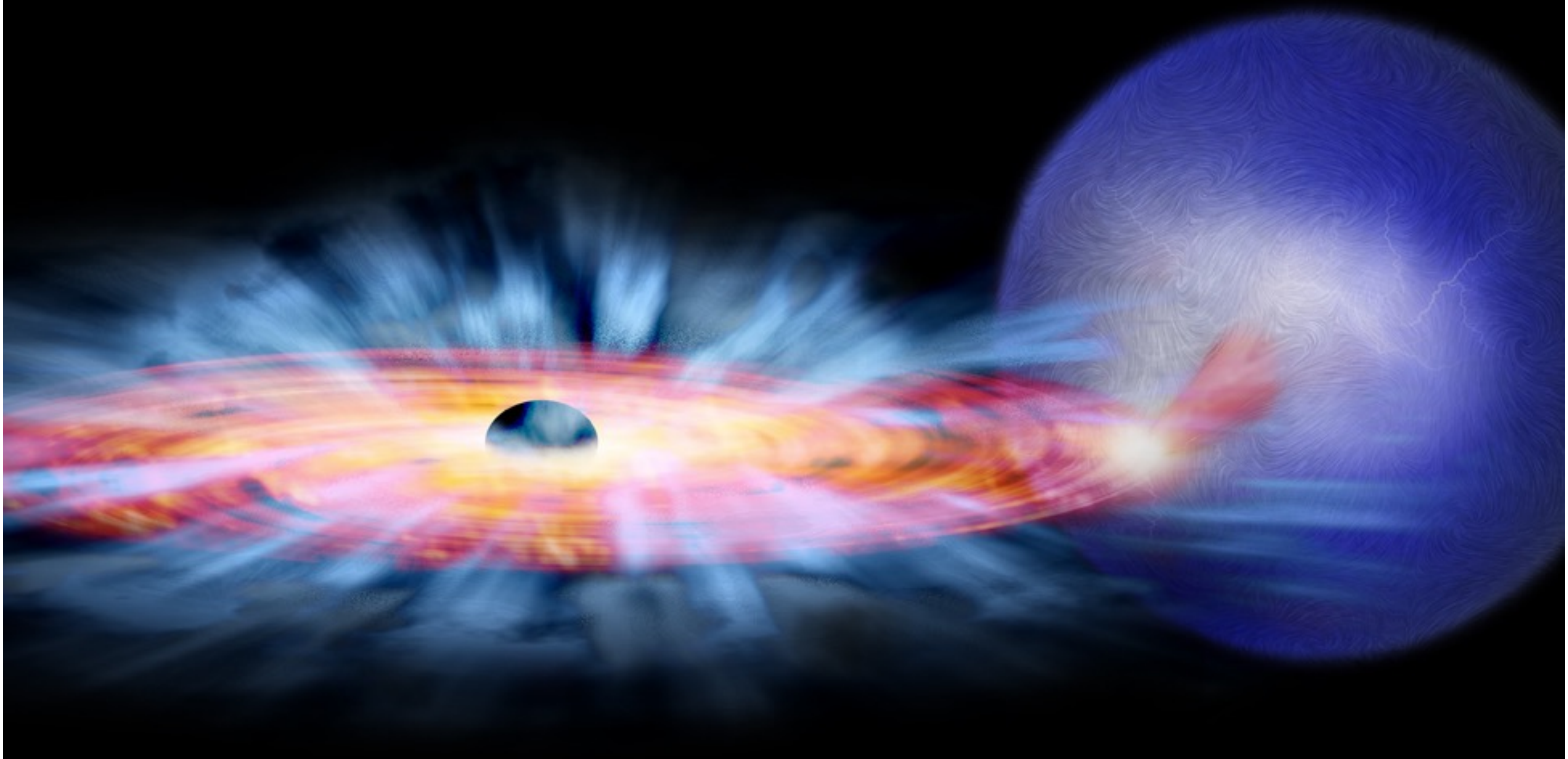
- Very rapid (millisecond), high intensity variability
- Generic argument that size of source R~cΔt- e.g 1 ms=3x10^{5}m- much smaller than sun



Rothschild et al. (1974)

- So… why the X-rays?
  - Gas from star flows towards black hole
  - Forms an accretion disk around black hole
  - Inflowing/spirally gas gives up gravitational potential energy and heats up to 10^{7-8}K
  - Hence X-rays!
  - Physics of accretion disks can be probed via x-ray spectroscopy and timing- also signatures of strong gravity (for stellar mass black holes x-ray observations are the only way to measure this set of properties)

Accretion from a Companion Star



Why Accretion Into a Black Hole is Different

- Neutron stars have a magnetic field and a surface- they can be pulsars and bursters
- Black holes have an event horizon and not a surface and do not have a strong magnetic field associated with them – cannot be pulsars or bursters (no surface to accumulate material to explode)
  - spinning black holes have an ergosphere which NS do not have
  - Black holes have a ISCO (innermost stable circular orbit) and NS do not
- Both can have companion stars with a wide range of mass from which accretion can occur
- HOWEVER: it is difficult in detail to find behavior which happens in all accreting black holes and no accreting neutron stars.

Downward to Black Holes!-

- A neutron star has a maximum mass $M<3\ M_{sun}$
  - If this mass is exceeded one has a complete gravitational collapse to a black hole
- **How Can We Observe Black Holes**
- If a black hole is a 'place' where radiation cannot escape to infinity then how can they be observed ?
  - Dynamical effects on 'nearby' material
  - "Shining" black holes- a black hole can be a place where accretion occurs and the process of accretion around a compact object can produce huge amounts of energy and radiation- making the black hole 'visible

Observations to Determine Nature of Object

If it bursts or pulses it's most likely a neutron star
(presence of a magnetic field or a surface)

If its mass is >3$M_{\odot}$ it's most likely a black hole
maximum mass of a NS is ~3 $M_{\odot}$

Stellar Mass Black Holes

- What do you mean 'black holes' ?
- We know of objects whose mass (derived from observations of the lines from the companion objects and Newton's (Einstein) laws) which are larger than possible for a NS or white dwarf.
- *They have other unusual properties (related to their x-ray spectrum and timing behavior)*
- **Big differences- no surface, no (?) magnetic field, higher mass, stronger GR effects**.

Table 4.3. *Candidate black hole binaries*[a]

Source	RA(2000)	DEC(2000)	r_x[b]	BH trait[c]	Grade[d]	Referen
1354–645 (BW Cir)	13 58 09.74	-64 44 05.2		LH,HS	A	1,2,
1524–617 (KY TrA)	15 28 16.7	-61 52 58		LH,HS	A	5,
4U 1630–47	16 34 01.61	-47 23 34.8		LH,HS	A	8,9,10,11
XTE J1650–500	16 50 01.0	-49 57 45		LH,HS,VH	A	12,13,14,15
SAX J1711.6–3808	17 11 37.1	-38 07 06		LH,HS	B	17
GRS 1716–249[e]	17 19 36.93	-25 01 03.4		LH	B	19,20
XTE J1720–318	17 19 59.06	-31 44 59.7		LH:,HS	C	22,23
KS 1730–312	17 33 37.6	-31 13 12	30″	LH,HS	C	25
GRS 1737–31	17 40 09	-31 02.4	30″	LH	B	27,28
GRS 1739–278	17 42 40.03	-27 44 52.7		LH,HS,VH	A	30,31,32,33
1E 1740.7–2942	17 43 54.88	-29 44 42.5		LH,HS,J	A	35,36,37,38
H 1743–322	17 46 15.61	-32 14 00.6		HS,VH	A	40,41,42,80,81
A 1742–289	17 45 37.3	-29 01 05		HS:	C	43,44,45
SLX 1746–331	17 49 50.6	-33 11 55	35″	HS:	C	47,48
XTE J1748–288	17 48 05.06	-28 28 25.8		LH,HS,VH,J	A	50,51,52,53
XTE J1755–324	17 55 28.6	-32 28 39	1′	LH,HS	B	55,56,57
1755–338 (V4134 Sgr)	17 58 40.0	-33 48 27		HS	B	59,42,60,61
GRS 1758–258	18 01 12.67	-25 44 26.7		LH,HS,J	A	63,38,64,65
EXO 1846–031	18 49 16.9	-03 03 53	11″[f]	HS	C	
XTE J1908+094	19 08 53.08	+09 23 04.9		LH,HS	B	68,69,70
1957+115 (V1408 Aql)	19 59 24.0	+11 42 30		HS	C	72,42,73,74
XTE J2012+381	20 12 37.70	+38 11 01.2		LH,HS	B	76,77,78

~20 black holes with a dynamical measurement of the mass

Black Holes in the Milky Way

- Over the last 40 years ~25 BHs have been discovered as the counterparts to x-ray sources
- New ones are discovered at the rate of 1-2 per year as the counterparts to 'x-ray transients'
- Based on supernova rates expect ~10^7-10^8 in the MW
  So can only see these in rare circumstances!

Observational Evidence for Black Holes