Summary of Class

- Main topics
- Introductory Lectures – what is High Energy Astrophysics
- Physical Processes
- X-ray Detectors +Telescopes
- Cluster Lectures
- SuperNova and SNR lectures
- NS Lectures
- Black Hole Lectures
- AGN
- Summary

- Unifiying theme: high energy processes in high energy objects
- *Going over the slides there were ~30 slides per lecture and 25 lectures- 800 slides! Lots of material !*

Basic physical processes
Black body radiation
Synchrotron radiation
Compton scattering
Line emission
Photoelectric absorption

Observational results strongly influenced by the properties of telescopes and detectors and need to get above the atmosphere (observatories need to be in space)
wide variety of detectors
can focus in the x-ray
γ-rays cannot be focused.

FINAL EXAM

Tuesday, Dec 17 10:30-12:30

- Exam is in this room
- Cumulative, but with emphasis on material after the midterm
- No notes or books allowed
- **<u>Bring calculator</u>**
- There will be 2 sections with choices the second will be calculations (equations will be given)

What are High Energy Objects

- Compact objects (white dwarfs, neutron stars, black holes)- M/R is very large. Effects of gravity are dominant (GR is important)
- Objects dominated by high energy (x-ray, γ-ray emission)- clusters of galaxies, supernova remnants
- Objects that have both : gamma-ray bursts.
- Ability to probe cosmology: clusters, supermassive blackholes (active galaxies), gamma-ray bursts

How are 'high energy' photons produced

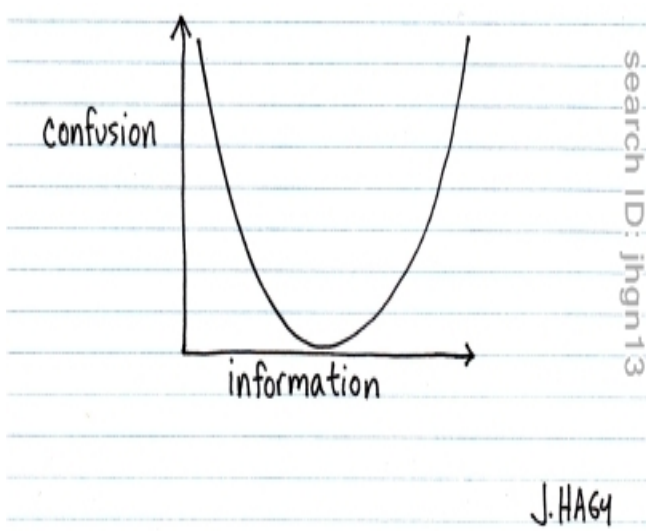
– Continuum

Thermal emission processes
- Blackbody radiation
- Bremsstrahlung

Non-thermal processes
- Synchrotron radiation
- Inverse Compton emission
- Non-thermal bremms

Line emission and absorption
- photoionization
- collisional excitation

Maybe We Had a Bit of This



How are Photons Generated/Absorbed

- Physical processes
  - **Black body radiation**- system is in equilibrium and all electromagnetic radiation falling on it is absorbed. At a particular temperature a black body emits the maximum amount of energy possible for that temperature.
  - **Synchrotron radiation**
    High energy (relativistic) particles 'spiraling' in a magnetic field (accelerated electrons)

Compton scattering
Electrons scattering of photons/photons scattering off electrons
Line Emission and absorption
Atomic transitions in atoms- x-rays mostly from K, L shell transitions
Photoelectric Absorption
Photons are absorbed by atomic transitions

•Difference between thermal (Maxwell-Boltzman distribution, equilibrium) and non-thermal (often power law distribution of particles)
•Collisional (bremmstrahlung, Compton scattering)
•Temperature sensitivities of different mechanisms give diagnostics

Synchrotron Emission

- Galactic radio emission (radiation from the halo and the disk),
- radio emission from the shell of supernova remnants
- X-ray synchrotron from PWN in SNRs
- Radio galaxies – lobes and jets
- Low Energy (radio-UV) Blazar continuum

Synchrotron

- For a power law input spectrum of particles a power law photon spectrum out to some maximum frequency is produced
- **If particle spectrum is**

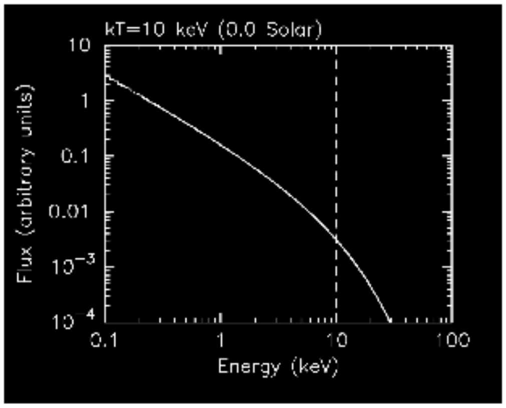
  $dN/dE \sim N_0 E^{-p}$
- **photon spectrum is $I_\nu \sim C_0 \nu^{-(p-1)/2}$**
  - **Higher energy particles radiate at higher energies $\nu \sim \gamma^2 qB/mc$**
- Where $C_0 \sim N_0 U_B \sigma_T$
  - **depends on the energy density of the B field $U_B \sim B^2$**
  - The Thompson cross section σ_T
  - and the number of particles N_0

- continuum
  - blackbody- isolated neutron stars
  - synchrotron: some SNR (e.g. Crab)
  - bremsstrahlung: Clusters of galaxies
  - Compton scattering: X-ray continuum of AGN
- lines
  - fluorescence: AGN
  - thermal: clusters
  - photoionization : AGN

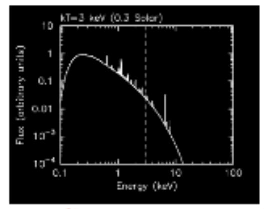
Which sources exhibit which processes and why?

BREMSSTRAHLUNG SPECTRUM

$$I(E) = AG(E,T)Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$$ exponential fall off at high E



A = normalization, G = Gaunt factor,
Z = charge of positive ions
n_e and n_i electron and ion densities
for $E << kT$ the spectrum is approximately a power law
for $h\nu >> kT$ there is an exponential cutoff



[In reality accompanied by recombination line emission]

Luminosity $L = 1.44 \times 10^{-27} T^{1/2} Z^2 n_e n_{ion} G\ V$ T = temperature, V = volume

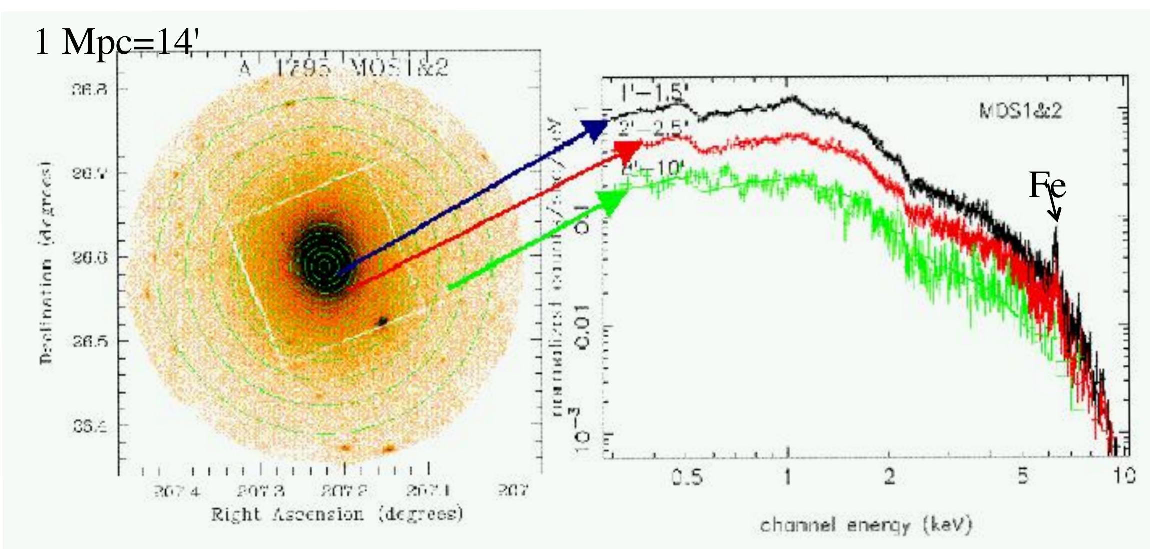


Figure 6: **Left:** Combined EPIC/MOS1&2 image of A 1795 in the [0.3 – 10]keV energy band. The circles define the

X-ray spectra of a Cluster

continuum due to bremmstrahlung - spectrum +geometry measure particle density and total mass of gas

Thompson/Compton Scattering

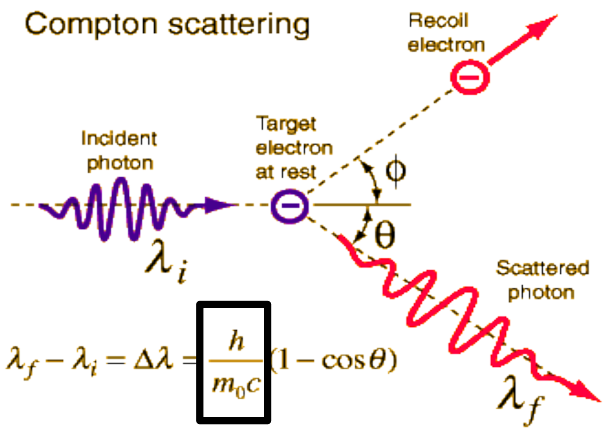
•Thomson scattering: elastic scattering of low-energy photons from low-energy electrons, with cross-section $\sigma_T = (8\pi/3)\,(e^2/m_ec^2) = 6.65\times10^{-25}\ cm^2$

•Compton scattering: low-energy photon inelastically scatters off non-relativistic electron, *photon ends up with lower energy*

•Inverse Compton scattering: low-energy photon inelastically scatters off relativistic electron, *photon gains energy in observer rest frame*

Whether the photon gives energy to the electron or vice versa

Compton Wavelength
$=h/m_ec=0.00243$ nm for an electron

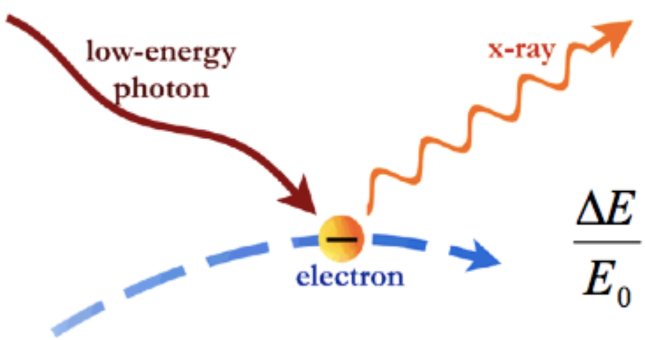


http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compton.html

INVERSE COMPTON EMISSION

Compton scattering

- Photon $E_0=h\nu$ boosted in energy by hot e^- at kT to e.g. X-rays



$$\frac{\Delta E}{E_0} = \frac{1}{m_ec^2}(4kT - E_0)$$

Examples in X-ray astronomy: active galactic nuclei (AGN), X-ray binaries

PHOTOELECTRIC ABSORPTION

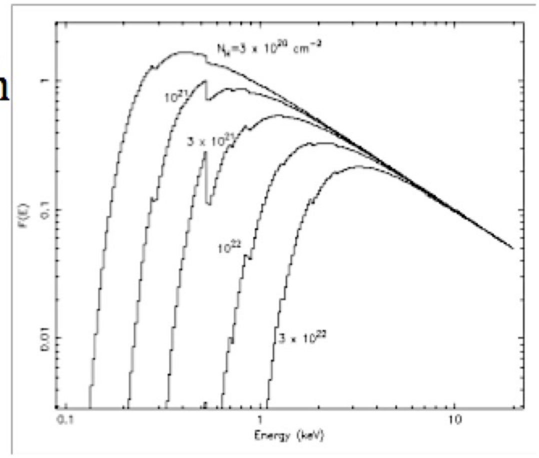
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

$\tau = \sigma(E) N_H =$ optical depth

$F(E) = A E^{-\Gamma} e^{-\sigma(E) N_H}$

$\sigma(E) \approx E^{-3}$



Profile dominated by bound-free edges of abundant elements

X-ray photoelectric absorption is important in measuring the material in the line of sight to the x-ray source

- Gas in the Milky Way towards x-ray binaries
- Material in the accretion stream in high mass x-ray binaries
- The 'torus' in AGN

X-rays are penetrating and photoelectric absorption can effectively measure column densities over 4 orders of magnitude from $\sim 10^{20}$-10^{24} atms/cm^2

How Does One Obtain Spectral/Imaging Information

How do we measure the position, energy, and arrival time of an X-ray photon?

- What we observe depends on the instruments that one observes with !
- In x and γ-ray spectroscopy we have a wide variety of instruments with different properties
- In both fields one is driven by rather low fluxes (count rates) compared to radio-UV data and so high quantum efficiency is a major goal

In the x-ray band there are numerous atomic transitions and so one wants "good" energy (wavelength) resolution in addition

- x-rays are absorbed in silicon of the CCD, resulting in the production of multiple electron-hole pairs
- Number of electrons is related to energy of photon

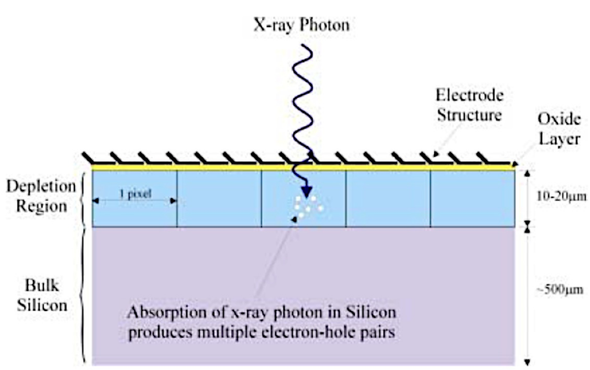


Figure 3: Schematic illustration of the direct detection of an X-ray photon.

X-ray CCD

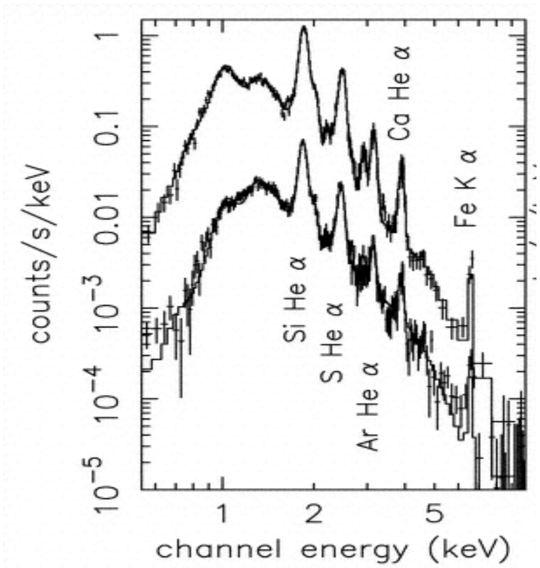
2009 Nobel Prize in Physics

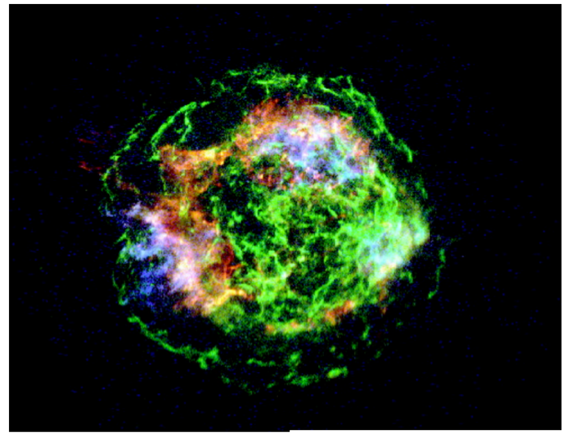
7 October 2009—Willard Boyle and George Smith, formerly of Bell Telephone Laboratories, in Murray Hill, N.J., shared half of the Nobel Prize in Physics "for the invention of an imaging semiconductor circuit-the CCD," the basis for digital imagery in everything from mobile phones to the Hubble Space Telescope.

www.lot-oriel.com/site/site_down/cc_notesxray_deen.pdf

An Elemental Map of Cas-A- Exploded in ~1670 But not seen

- Red=He-like Si, blue=Fe complex
- Bottom right- ratio of Si to Fe+Mg

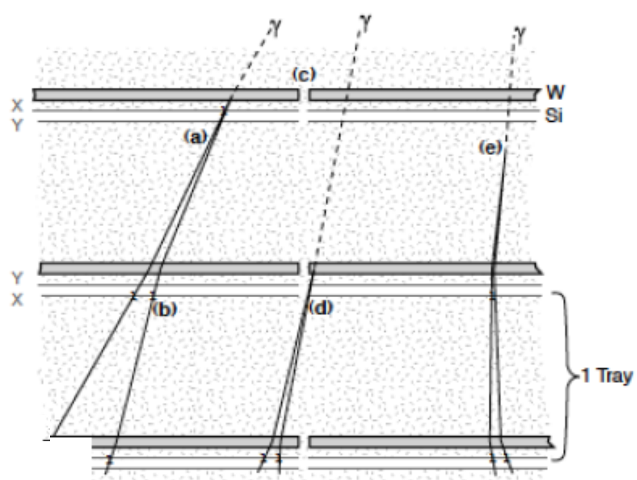


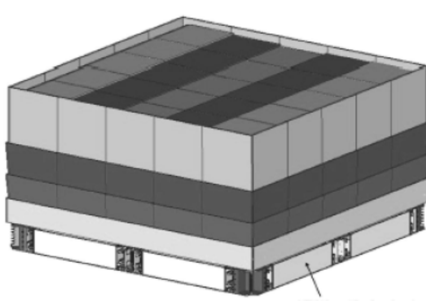


Spectrum of 2 regions in SNR

γ-ray Detectors

- High-energy γ-rays "cannot" be reflected or refracted
- they are detected at E>30 Mev by their interaction via the conversion of the γ-ray into an e^+e^- pair
- A major concern is rejecting the much larger number of cosmic rays (need 0.9997 efficiency in rejection)





Full coverage of anti-coincidence detectors

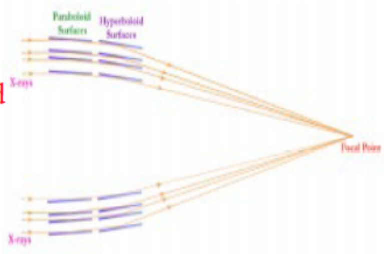
see http://imagine.gsfc.nasa.gov/science/toolbox/gamma_detectors2.html

X-Ray Reflection: Zero Order Principles:

Refs:

Gursky, H., and Schwartz, D. 1974, in "X-Ray Astronomy," R. Giacconi and H. Gursky eds., (Boston: D. Reidel) Chapter 2, pp 71-81;

Aschenbach, B. 1985, Rep. Prog. Phys. 48, 579. * very detailed



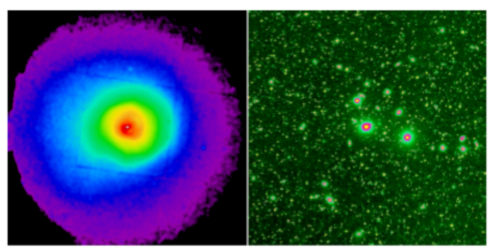
X-rays reflect at small grazing angles.

An analogy is skipping stones on water.

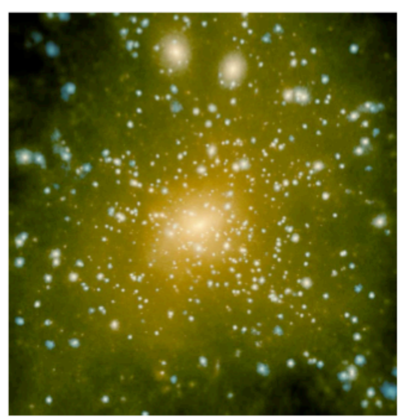
Scattering of any wave by an ensemble of electrons is coherent only in very special directions; namely, the familiar Angle of Incidence equals Angle of Reflection, $\phi_i = \phi_0$.

Clusters of Galaxies

- Clusters of galaxies are the largest gravitationally bound systems in the Universe.
- At optical wavelengths they are over-densities of galaxies with respect to the average density: 100-1000's of galaxies moving in a common gravitational potential well (a smaller assembly is defined a galaxy group).
- The typical masses ~ 10^{13}- $10^{15}M_{sun}$ (10^{46} - 10^{51} gm) and sizes ~ 1 - 4 Mpc (10^{24}-10^{25} cm).
- The combination of size and mass leads to velocity dispersions/ temperatures of 300-1200km/sec; 0.5-12 keV
- M~(kT)R; σ^2~kT



X-ray optical
Perseus cluster d~73Mpc



Dark matter simulation
V.Springel

WHY ARE CLUSTERS INTERESTING?

- Largest, most massive systems in the universe
- Probes of the history of structure and galaxy formation
  - Dynamical timescale are not much shorter than the age of the universe
  - -clusters retain an imprint of how they were formed
- Provide a history of nucleosynthesis in the universe
  - - as opposed to galaxies, clusters probably retain all the enriched material
- The gravitational potential is dominated by dark matter on all scales
- Most of the baryons are in the hot gas (80%)

Theoretical Tools

- Physics of hot plasmas
  - Bremmstrahlung
  - Collisional equilibrium
- Formation of structure -mergers
- How to use lensing to measure gravitational potential (mass)
- Measurement of dark matter, total mass and their distribution via hydrostatic equilibrium
- Determination of chemical abundances

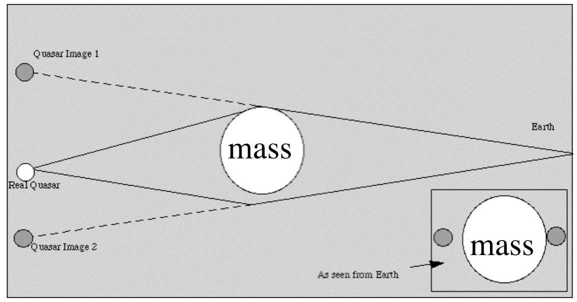
Basics of Gravitational Lensing

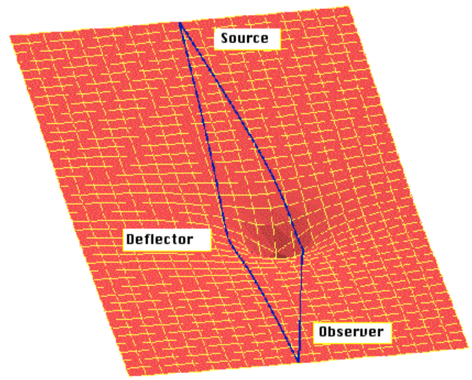
Massive clusters can produce **giant arcs** when a background galaxy is aligned with the cluster core.

- Every cluster produces weakly distorted images of large numbers of background galaxies.
  - These images are called arclets and the phenomenon is referred to as weak lensing.
- The deflection of a light ray that passes a point mass M at impact parameter b is

$$\Theta_{def} = 4GM/c^2 b$$

Also important for studies of AGN





Lensing

- Einstein radius is the scale of lensing
- For a point mass it is
- $\theta_E = ((4GM/c^2)(D_{ds}/D_d D_s))^{1/2}$

- or in more useful units
- $\theta_E = (0.9'')M_{11}^{\ 1/2}\ D_{Gpc}^{\ -1/2}$

- Lens eq

$\beta\ = \theta - (D_{ds}/D_d D_s)4GM/\theta c^2$.

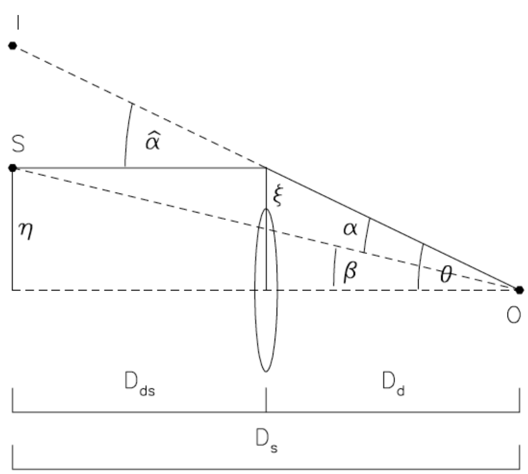
or

$\beta\ = \theta - \theta^2_E/\theta$

2 solutions for θ_E

Any source is imaged twice by a point mass lens

Gravitational light deflection preserves surface brightness because of the Liouville theorm



What can be measured with X-ray Spectra

- Temperature profile, redshift, and abundances of the most common elements (heavier than He).
- Using symmetry assumptions the X-ray surface brightness can be converted to a measure of the ICM density.
- Using the assumption of hydrostatic equilibrium the cluster total mass (dark+baryonic) can be estimated.

Deriving the Mass from X-ray Spectra

For spherical symmetry eq of hydrostatic equilibrium reduces to

$(1/\rho_g)\, dP/dr = -d\phi(r)/dr = GM(r)/r^2$

With a little algebra and the definition of pressure - the total cluster mass can be expressed as

$$M(r) = kT_g(r)/\mu G m_p)\mathbf{r}\ (d\ln T/d\ln r + d\ln \rho_g/d\ln r)$$

k is Boltzmans const, μ is the mean mass of a particle and m_H is the mass of a hydrogen atom

Every thing is observable

The temperature T_g from the spatially resolved spectrum

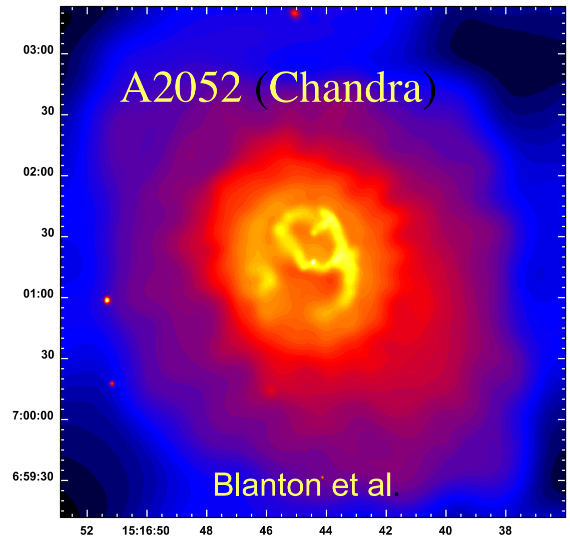
The density ρ_g from the knowledge that the emission is due to bremmstrahlung

And the scale size, **r**, from the conversion of angles to distance

Effects of Feedback

the hot gas can apparently be strongly affected by AGN activity- direct evidence of the ability of SMBHs to influence environment on large scales

"Holes" in x-ray emitting gas caused by energy from central AGN



How do Clusters Form- Mergers

- As time progresses more and more objects come together- merge
- Hierarchical growth of structure in ΛCDM universe
- Clusters as most massive objects tend to form late

Now

10^{10} yrs ago

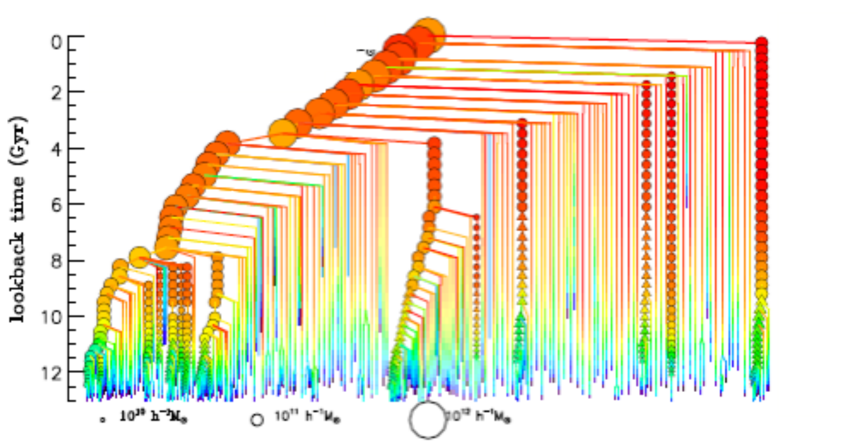


Figure 1. BCG merger tree. Symbols are colour–coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than 10^{10} $M_{\odot}$ h^{-1} are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. Triangles show galaxies that have not yet joined this FOF group.

Neutron Stars

- Predicted theoretically by Volkoff and Oppenheimer (1939)
- First 'discovered' by Hewish et al 1967 (Noble prize) as the counterparts to radio pulsars
  - short period from radio pulsars (<1s) can only be obtained from a compact object via either rotation or oscillations; period derivatives are small and for radio pulsar periods always increase (slow down)
    - All characteristic timescales scale as $\rho^{-1/2}$ (ρ is density)

      rotation frequency ω=sqrt(GM/r^3) =sqrt($G\rho$)
    - Shortest periods ~1.5ms- light travel time arguments give a size (ct~ 500km)

White dwarfs with $\rho \sim 10^7$–10^8 gmcm^{-3} max rotation periods $P = 2\pi/\Omega \sim 1$–10 s

- **To get periods of ~1ms need $\rho \sim 10^{14}$ gmcm^{-3} much denser than normal stars or white dwarfs**
- What are the sources of energy?
  - Spin down
  - accretion

Supernova and Remnants

SNRs are probes both of their progenitor star (and of their pre-supernova life) and of the medium into which they explode (the ISM)

They are also cosmic accelerators (cosmic rays).

Birth places of neutron stars and stellar mass black holes.

laboratories for study of magnetic fields, shock physics, jets, winds, nuclear physics etc

- SNR evolution (and their appearance now) depends on many factors:
  - age
  - environment (density)
  - total energy of the explosion
  - progenitor star (mass, type of SN associated..)

Why Study Supernova Remnants?

Supernova explosion:
How is mass and energy distributed in the ejecta?
What was the mechanism of the supernova explosion?
What and (how much) elements were formed in the explosion, and how?
What are the characteristics of the compact stellar remnant?

Shock physics:
How is energy distributed between electrons, ions, and cosmic rays in the shock?
How do electrons and ions share energy behind the shock?

Interstellar medium:
What is the structure of the interstellar medium, and how does the shock interact with that structure?
How is the ISM enriched and ionized

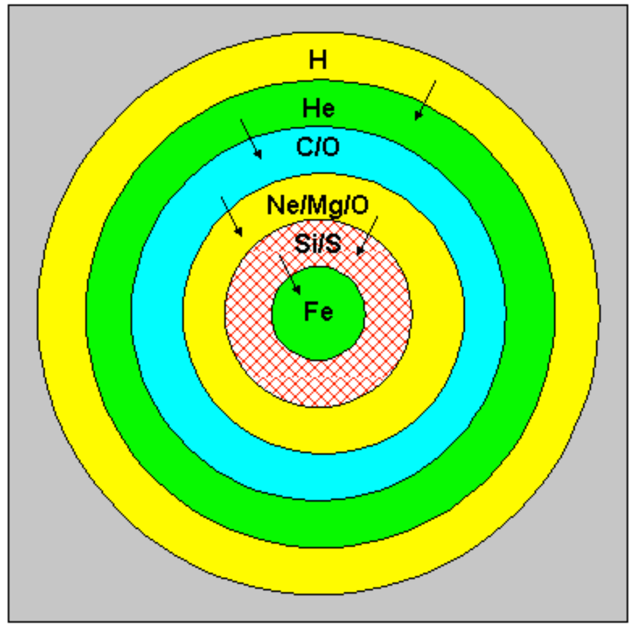
Supernova- Types

- Supernova come in two types (I and II)
  - Type Ia is the explosion of a white dwarf pushed over the Chandrasekar limit- details are not understood
    - However they are used as a 'standard candle' for cosmology
  - Type Ib and II is the explosion of a massive star after it has used up its nuclear fuel
- Type I supernovae do not show hydrogen in their spectra. Type Ia supernovae reach peak luminosities of about
  2×10^{43} erg/s
- Type II supernovae show hydrogen in their spectra. Their light curves are rather diverse, and their peak luminosities are around 10^{42} erg/s

II/Ib/Ic Core-Collapse of Massive Progenitor

- Massive progenitor core forms neutron star or black hole
- Explosive nucleosynthesis products near core (Si and Fe) plus hydrostatically formed outer layers (O, Ne) are expelled
- **Most of the explosion energy is carried away by neutrinos-** Detection of neutrinos from SN 1987A confirmed basic physics (kT sensitive) Nobel prize 2002 (Cardall astro-ph 0701831)
- Uncertain explosion mechanism details involve neutrinos, probably large-scale shock instabilities, rotation, possibly magnetic fields

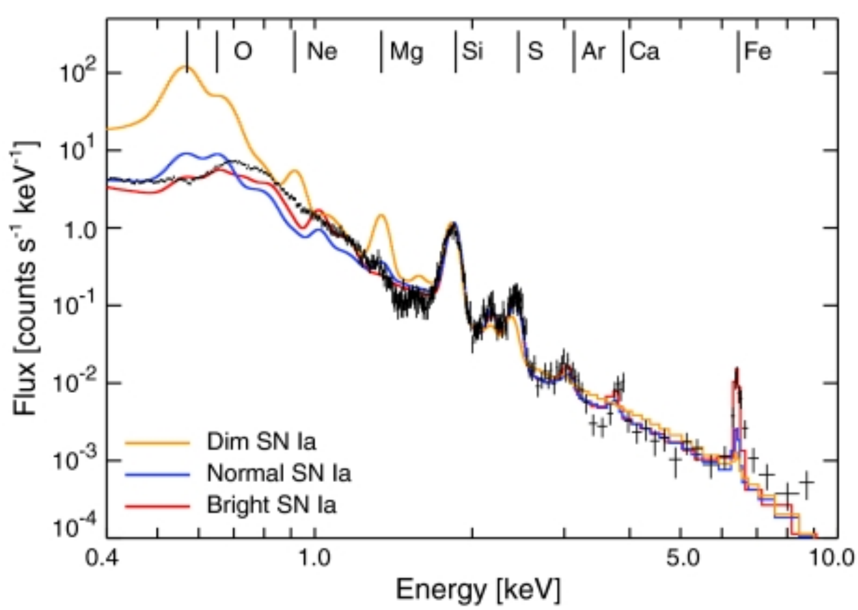
Supernova Explosions



Initially in core-collapse supernovae (type II) the energy comes from the gravitational energy freed in the collapse- later times from radioactive decay

Comparison of Yields From Different Type Ia Models with X-ray Spectral data

See strong lines in x-ray spectrum from elements synthesized in the SN



Remnant Evolution

Free Expansion

Ejecta expand without deceleration r~t - Core collapse SN have initial velocities of ~5000km/sec and several $M_\odot$ of ejecta , SN Ia ~10,000 km/sec, ~1 $M_\odot$

Adiabatic (Sedov-Taylor, or “atomic bomb”)

Ejecta are decelerated by a roughly equal mass of ISM- $r \sim t^{2/5}$

Energy is conserved-(Cooling timescales are much longer than dynamical timescales, so this phase is essentially adiabatic e.g. net heat transfer is zero).

Evolution of density, pressure is self-similar

Temperature increases inward, pressure decreases to zero

Radiative

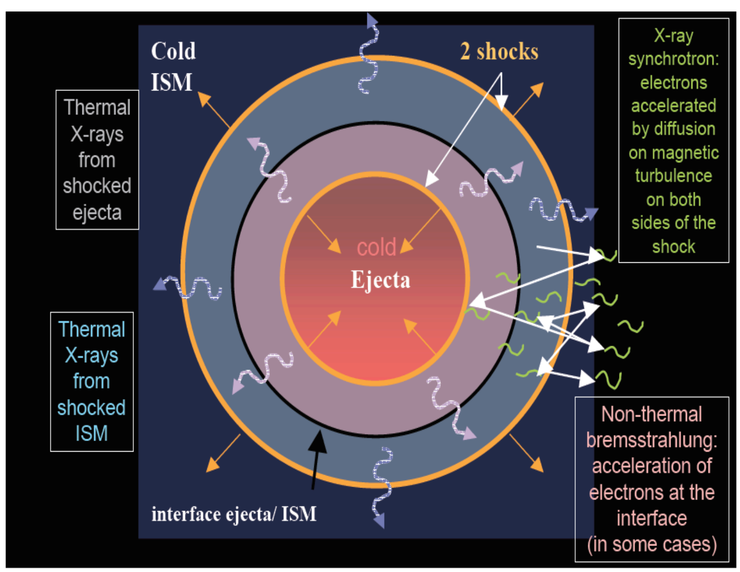
Dissipation of remnant energy into ISM

Remnant forms a thin, very dense shell which cools rapidly

Interior may remain hot- typically occurs when shock velocities vs drop to around 200 km/sec

- Fermi acceleration- 1949:
- charged particles being reflected by the moving interstellar magnetic field and either gaining or losing energy, depending on whether the "magnetic mirror" is approaching or receding. energy gain per shock crossing is proportional to velocity of shock/ speed of light - spectrum is a power law

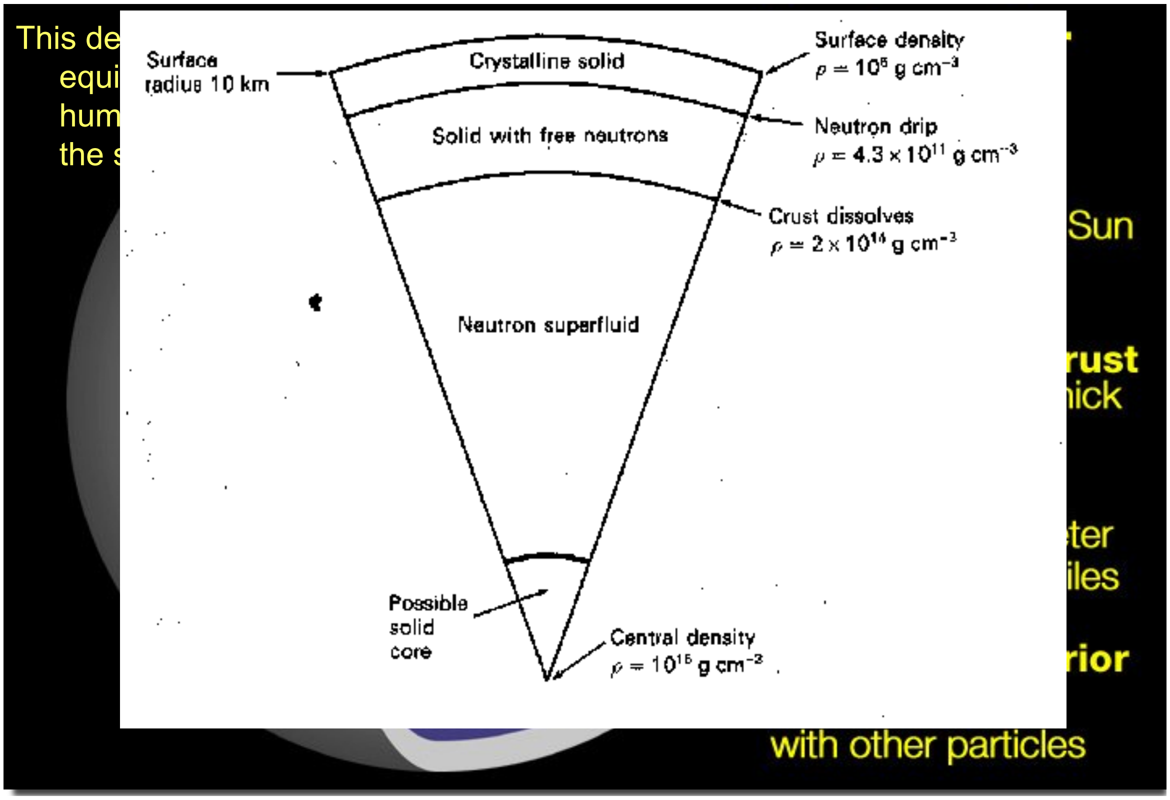
See Melia sec 4.3



DeCourchelle 2007

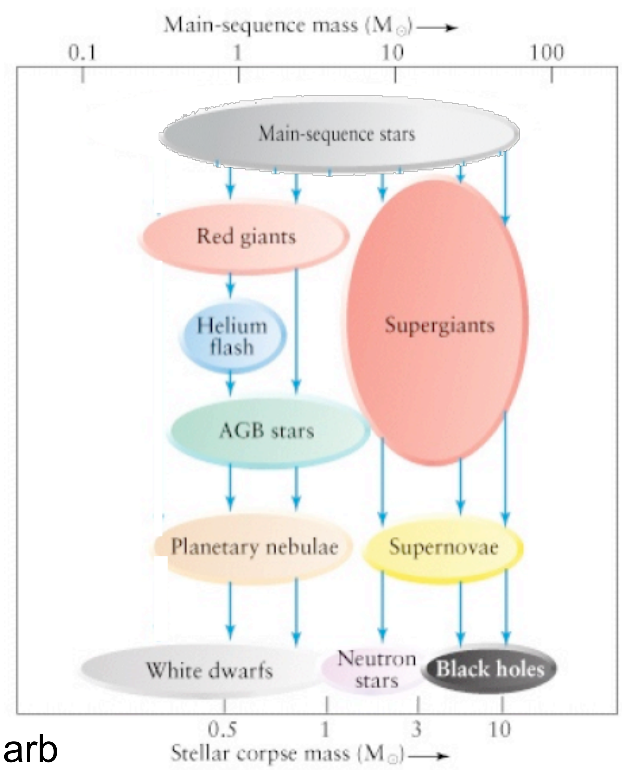
Nice analogy- ping pong ball bouncing between descending paddle and table

Inside Neutron Stars

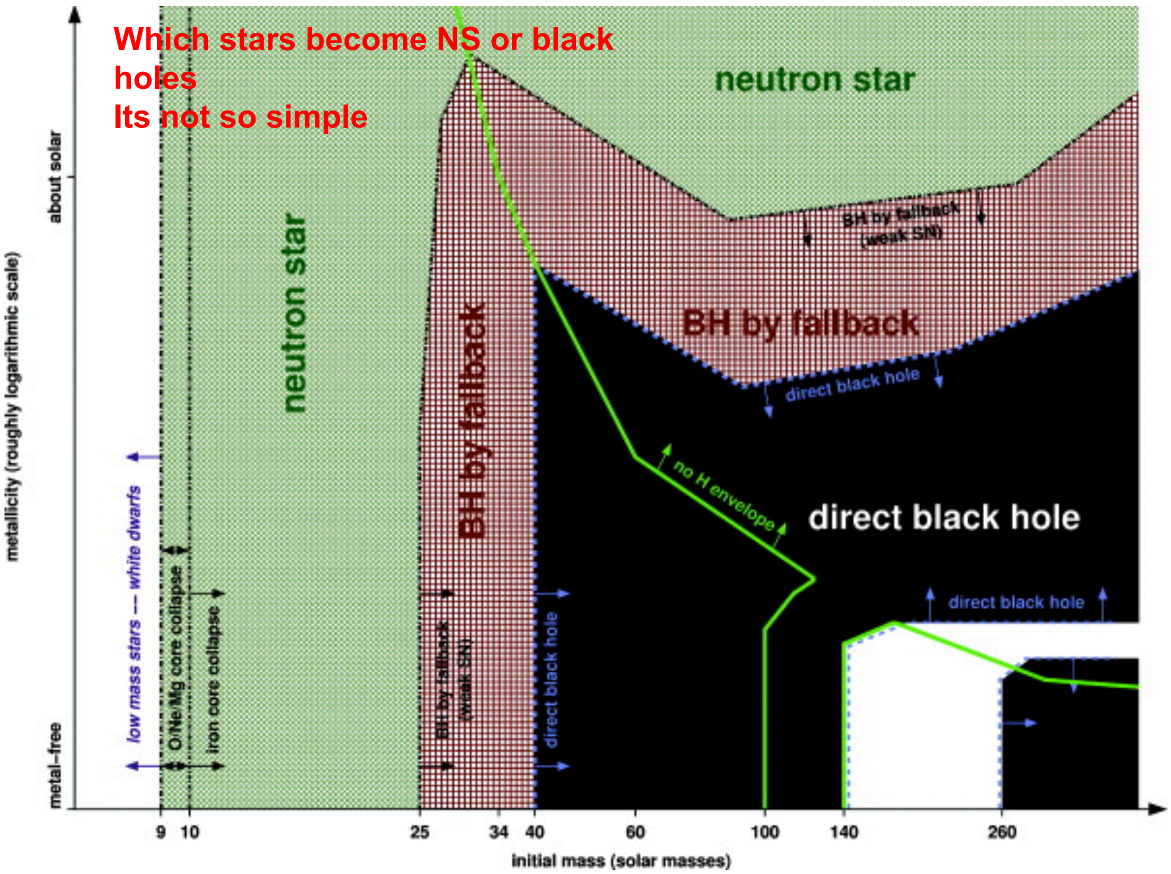


Progenitors of Compact Objects

- Main sequence stars evolve and at the end of their 'life' (period of nuclear burning) end up as compact objects
- $t_{MS}/t_{sun} \sim (M/M_{sun})^{-2.5}$
- The most massive end up as black holes ?
- The least massive as white dwarfs (the main sequence lifetime of stars less than 1/2 M_{sun} is greater than the Hubble time so they never get to white dwarfs)



Samar Safi-Harb



Degneracy and All That- Longair pg 395 sec **13.2.1**

- In *white dwarfs*, internal pressure support is provided by **electron degeneracy pressure** and their masses are roughly the mass of the Sun or less
- the density at which degeneracy occurs in the non-relativistic limit is proportional to $T^{3/2}$
- This is a quantum effect: Heisenberg uncertainty says that $\delta p \delta x > h/2\pi$

For Neutron stars

– $\varrho \approx 10^{16}$ kg/m^3 - Neutron degeneracy pressure starts to become important

– $\varrho \approx 10^{18}$ kg/m^3 - Neutron degeneracy finally halts the collapse provided that $M<3M_{sun}$

– End up with a neutron star… typical mass of $1.4M_{sun}$ with a radius of 10km- theoretical mass radius relation is not well understood due to the effects of QCD

Radius of NS

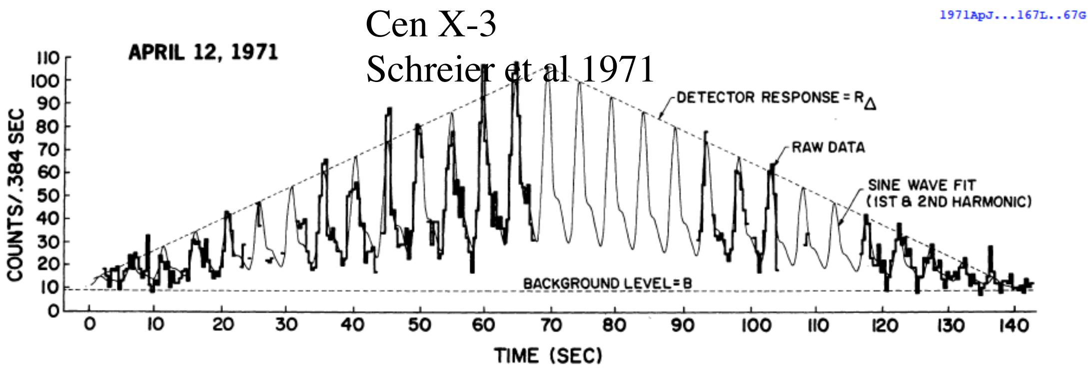
- Use the 'known' density of nuclear matter

($\varrho_{Neutron}$~$1.2x10^{14}$g/cm^3) and the Chandrasekar mass gives a radius

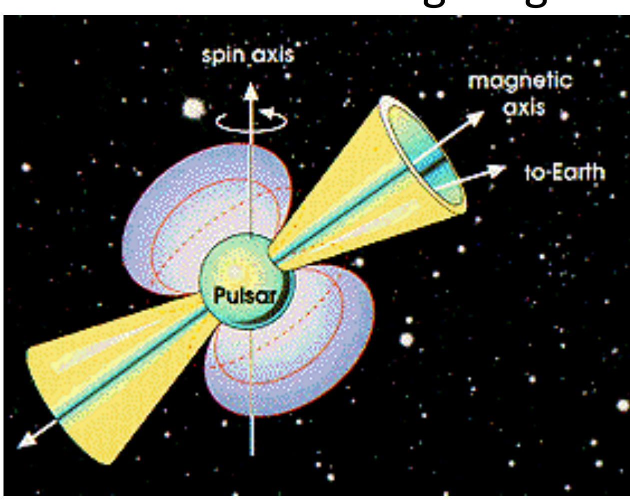
- R_{NS}~$(3M_{Chandra}/4\pi\varrho_{Neutron})^{1/3}$ ~10km

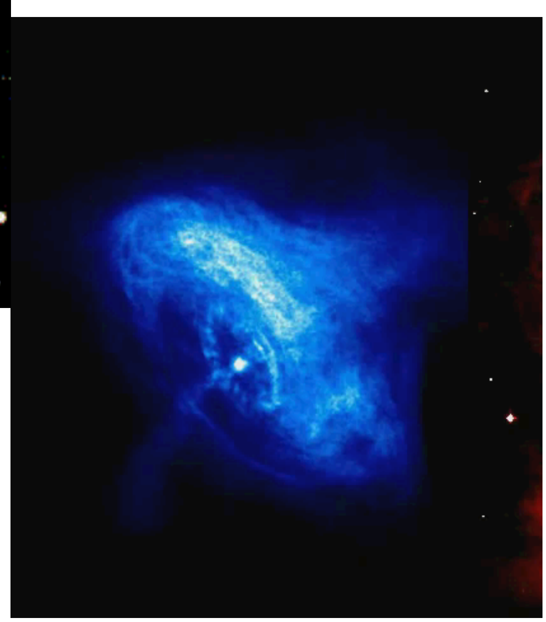
consistency between the observed spin periods, and neutron stars

Cen X-3
Schreier et al 1971



Rotating magnetic field model





- Emission from isolated, non-accreting neutron stars

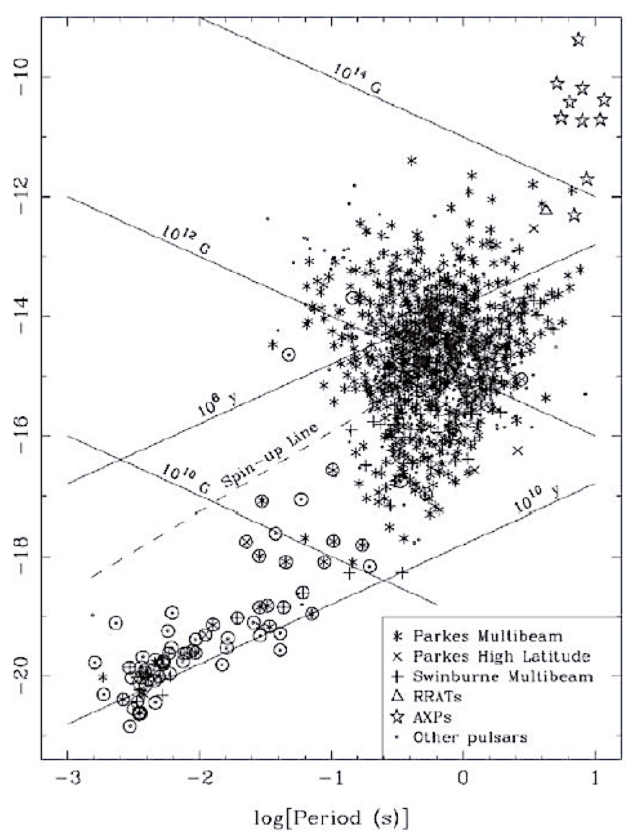
Radiation Mechanism

a magnetic dipole with magnetic dipole moment p_m radiates electromagnetic radiation at a rate

$-dE/dt \sim [\ \Omega^4\ p^2_{m0}]/[6\pi c^3\ ]$.eq 13.33

- Where p_{m0} is the magnetic moment is the component of the magnetic dipole perpendicular to the rotation axis
- Magnetic dipole radiation extracts rotational energy from the neutron star.
- If I is the moment of inertia of the neutron star,
- $-d/dt[I\Omega^2]=I\Omega d\Omega/dt= \Omega^4 p^2_{m0}/6\pi c^3$ and so $d\Omega/dt \propto \Omega^3$
- The age of the pulsar can be estimated if it is assumed that its deceleration can be described by a a law $d\Omega/dt \propto \Omega^n$ if n is constant throughout its lifetime It is conventional to set $n = 3$ to derive the age of pulsars **τ;** so **$\tau = P/(2\ dP/dt\ )$**.
- Using this relation the typical lifetime for normal pulsars is about 10^5–10^8 years.

- Where radio pulsars lie in the P,dP/dt plot.
  - the lines correspond to constant magnetic field and constant age.
- If magnetic braking mechanism slows-down of the neutron star then (see eqs 13.40-13.42)
- $B_s \approx 3\text{x}\ 10^{15}(PdP/dt\ )^{1/2}$ T .



Basics of Accretion

Is there a limit on accretion?

If the accreting material is exposed to the
radiation it is producing it receives a force due to radiation pressure

The minimum radiation pressure is
(Flux/c)xσ (σ is the relevant cross section)
Or
$L\sigma_T/4\pi r^2 m_p c$ (σ_T is the Thompson cross section ($6.6\text{x}10^{-25}$ cm^2) m_p is the mass of the proton)

The gravitational force on the proton is GM_x/R^2

Equating the two gives the Eddington limit

$L_{Edd}=4\pi M_x G m_p c/\sigma_T = 1.3\text{x}10^{38} M_{sun}$ erg/sec

Frank, King & Raine, "Accretion Power in Astrophysics",

Accretion -Basic idea

- Viscosity/friction moves angular momentum outward (viscosity is due to magnetic fields)
  - allowing matter to spiral inward
  - Accreting onto the compact object at center

gravitational potential energy is converted by *friction* to heat
Some fraction is radiated as light

Very efficient process Energy ~GM/R=$1.7\text{x}10^{16}$ (R/10km) $^{-1}$ J/kg**~1/2mc^2**

Nuclear burning releases ~$7\text{x}10^{14}$J/kg (0.4% of mc^2)

Two Modes of Accretion- Longair 14.5.2

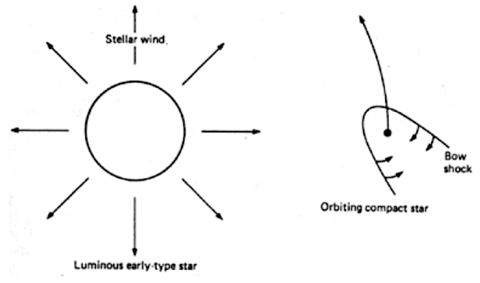


Figure 9: Accretion from a stellar wind.[23]

Accretion from a stellar wind

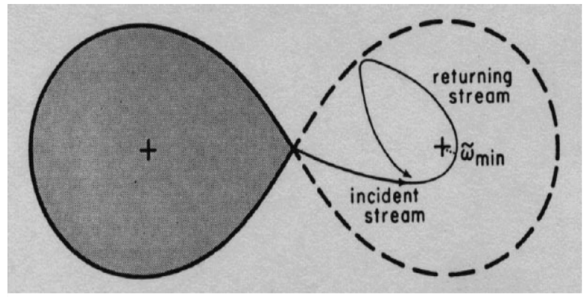


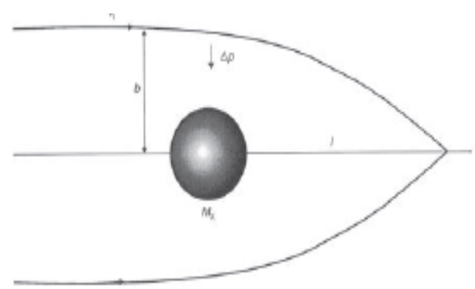
Figure 6: Roche lobe geometry, showing the incident mass stream through the inner Lagrangian point and the intersection of the returning stream with the newly arriving material. The low mass companion on the left hand side completely fills its Roche lobe, while the position of the compact object is denoted by a plus sign (+) inside the right hand lobe.[24]

Accretion from Roche Lobe Overflow

Cominsky (2002)

Accretion From a wind – Following Longair

- $L_X \approx [\,\eta \dot{m}_P / 4]\,(2GM_X/R_P)^2 \mathbf{v_w}^{-4}$
- $\dot{m}_P$ the mass loss rate from the donor star
- accretion rate is ~$(\dot{m}_P/4)(R_c/R_p)^2$
- R_p is the distance of the compact object from the donor star
- R_c is the critical (capture radius)
- **Wind velocity v_w>> orbital velocity v_x**

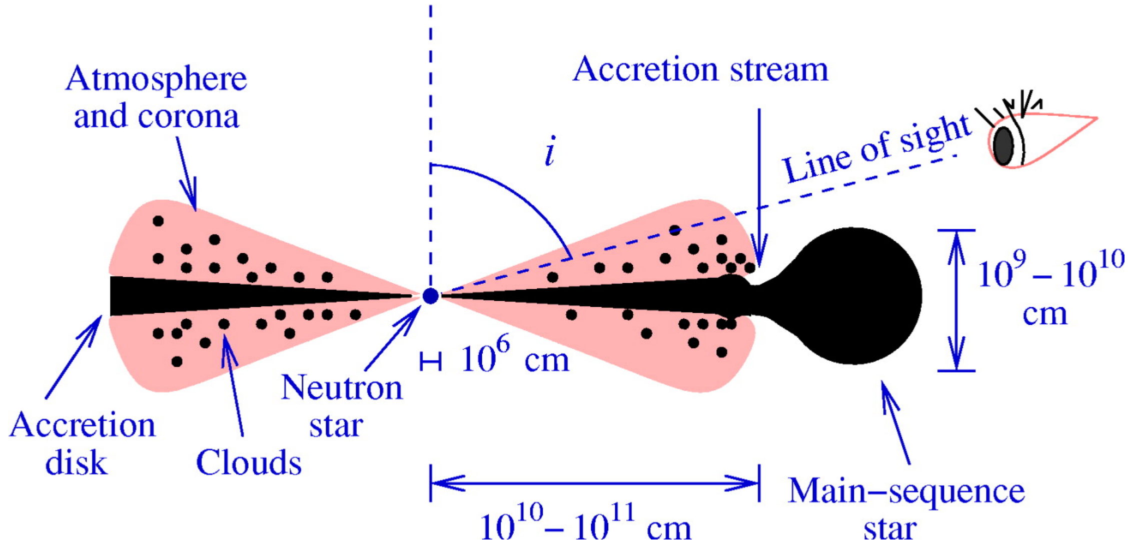


s of accretion by a star of mass M_X in a stellar wind of velocity v_1.

So X-ray luminosity is directly proportional to the mass-loss rate of the donor star, $\dot{m}_P$, and is very sensitive to the wind velocity

Geometry of heated accretion disk + coronal in LMXB

Viewing angle is important additional parameter



Jimenez-Garate et al. 2002

Basics of Accretion

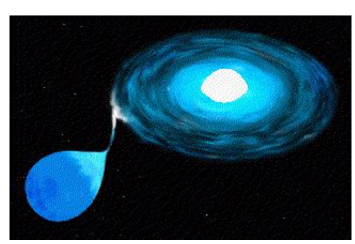
- Because of angular momentum considerations an accretion disk, **almost** always forms
- Matter is thought to form a physically thin (but optically thick* disk) which has Keplerian rotation
- Matter falls into by losing angular mometum via viscosity

the angular velocity is $\Omega_k = \text{sqrt}(GM/r^3)$

The binding energy of a parcel of the disk is $E = GM_{disk}M_x/2R = 1/2\ L_{acc}$

The other half of L_{acc} is released very close to the star surface (the boundary layer) as matter in the disk tries to co-rotate with the NS (what happens for a black hole??)

If the star spins more slowly than the innermost part of the accretion disk (angular speed $\omega_{k)}$, the BL must release a large amount of energy as the accreting matter comes to rest at the stellar surface. Some of this is used to spin up the star, but there remains an amount $G\mathcal{M}M_x/2R(1-\omega_{k/}\Omega_k)^2$ which is radiated



* Optically thick means that a photon emitted inside the disk always interacts with matter at least once before 'escaping'

- Energy released by an element of mass in going from r+dr to r

Gravitational potential energy is (M is the mass of the accreting object)

E_p =-GMm/2r so energy released is

E_g =-GMmdr/r^2.

the luminosity of this annulus, for an accretion rate $\mathscr{M}$, is

dL ~ GM$\mathscr{M}$ dr/r^2.

assuming the annulus radiates its energy as a blackbody

L = $\sigma A T^4$. The area of the annulus is $2\pi r dr$, and since

L=M$\mathscr{M}$ dr/r^2 we have

- T^4 ~M$\mathscr{M}r^{-3}$, or
- **T ~(M$\mathscr{M}$/r^3)$^{1/4}$**

Thin accretion disks

Accretion disks form due to angular-momentum of incoming gas

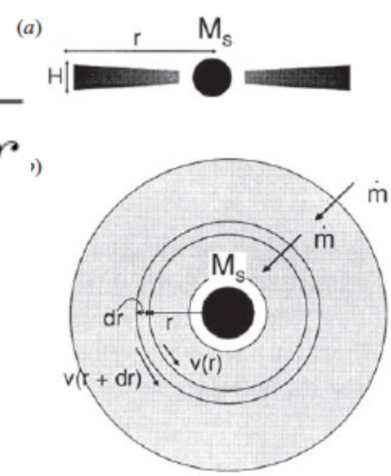
Once in circular orbit, specific angular momentum (i.e., per unit mass) is

$$J = vr = \sqrt{GMr}$$

So, gas must shed its angular momentum for it to actually accrete…

Releases gravitational potential energy in the process!

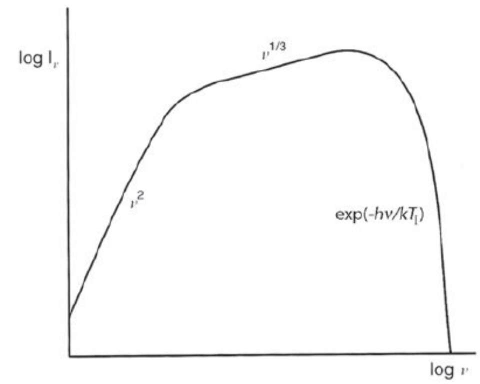
Matter goes in, angular momentum goes out!



Total Spectrum

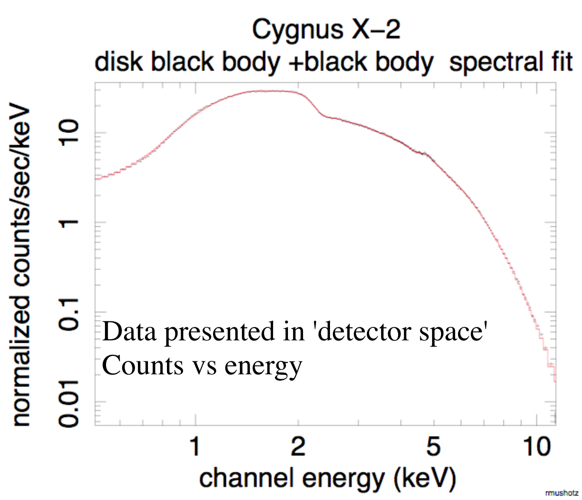
- If each annulus radiates like a black body and the temperature scales as $T \sim r^{-3/4}$ (Longair 14.54)
- The emissivity scales over a wide range of energies as $I(\nu) \sim \nu^{1/3}$
- At lower frequencies the spectrum has a Raleigh-Jeans ν^2 shape and at higher energies has a exponential cutoff corresponding to the maximum temperature $(e^{-h\nu/kT_{inner}})$
- Thus the spectrum from a disc is a sum of blackbody components, with increasing temperature and luminosity emitted from a decreasing area as the radius decreases.

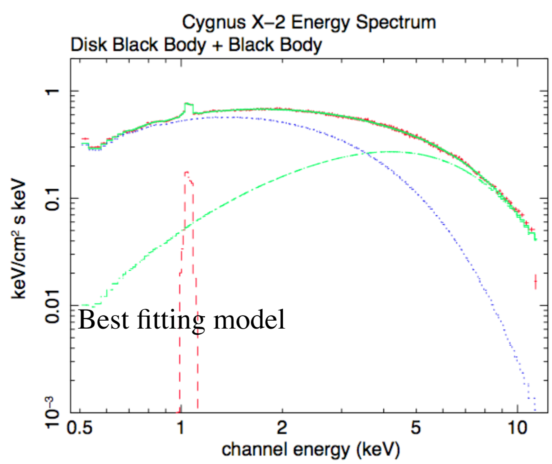
If the disk 'cuts off' at some radius r_{inner} then the temperature profile is
$T(r) = 3GM\dot{m}/8\pi\sigma r^3[1 - (r_{inner}/r)^{1/2}]^{1/4}$
eq in 14.7.1.



the emission spectrum of an optically thick accretion disc.
The exponential cut-off at high energies occurs at frequency $\nu = kT_l/h$,
where T_l is the temperature of the innermost layers of the thin accretion disc.
At lower frequencies the spectrum tends towards a Rayleigh–Jeans spectrum $I \propto \nu^2$.

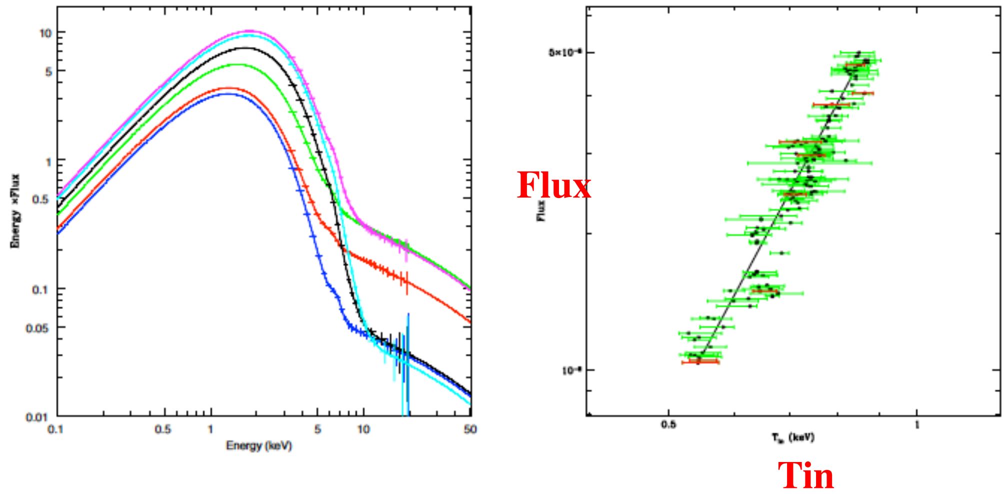
Fit to Real Data





The data is of very high signal to noise
Simple spectral form fits well over a factor of 20 in energy
Emitted energy peaks over broad range from 2-6 kev

Do They Really Look Like That



- X-ray spectrum of accreting Neutron star at various intensity levels- notice the good fit to a black body spectrum at E<7 keV and the 'extra' high energy powerlaw
- **Right panel is $T(r_{in})$ vs flux - follows the T^4 law**

If the Magnetic Field is Strong (As In NS Pulsars)

- If magnetic pressure dominates over thermal pressure the magnetic field channels the accretion flow and matter flows along field lines that connect to the magnetic polar regions:
- Thus the accretion energy is released in a "hot spot" near the two magnetic poles.
  - If the magnetic axis is not aligned with the rotational axis, then as the star rotates we see more or less of the hot spot, and hence pulsations in the X-rays.

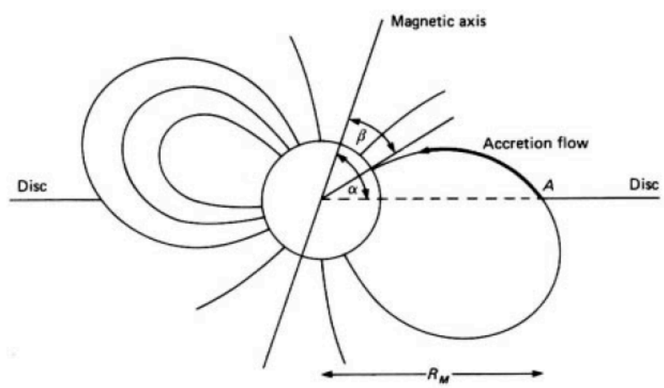


Figure 8: Accretion in a strong ($\sim 10^{12}$ Gauss) magnetic field. Note that the accretion disk is held off the neutron star surface by the centrifugal barrier formed by the rotating magnetosphere.[23]

Cominsky (2002)

- Putting in typical numbers, the radius where magnetic and material stresses are equal (called the Alfven radius)

$$r_A = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7} = 3.2 \times 10^8 \dot{M}_{17}^{-2/7} \mu_{30}^{4/7} \left(\frac{M}{M_\odot}\right)^{-1/7} \text{cm} .$$

M_{17} is the accretion rate in units of 10^{17} gm/sec- Eddington limit for 0.7M object

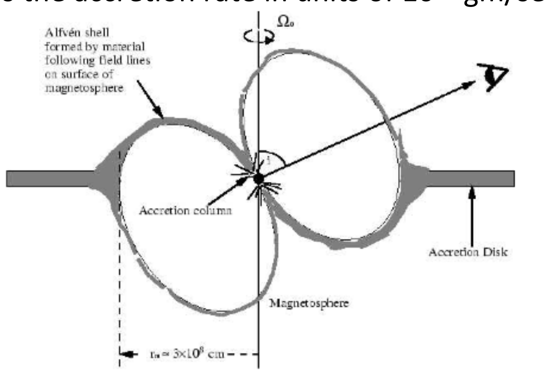
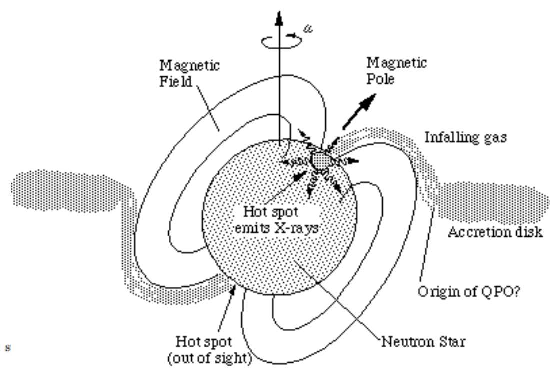


Fig. 1.— Rough sketch of the accretion flow in a disk being picked up by a strong neutron s magnetic field. From http://lheawww.gsfc.nasa.gov/users/audley/diss/img203.gif



Mass of the NS Star

- In order to measure the mass of the neutron star and its optical companion we need to measure the mass function. For a circular orbit it can be shown that this is defined

$$M_X = K^3{}_O P / 2\pi G \sin^3 i \, (1 + K_X/K_O)^2$$

- M_O and M_X are the mass of the optical component and the X-ray source, respectively,
- K_X , K_O are the semi-amplitude of the radial velocity curve for the x-ray and optical companion, respectively
- P is the period of the orbit and i is the inclination of the orbital plane to the line of sight.

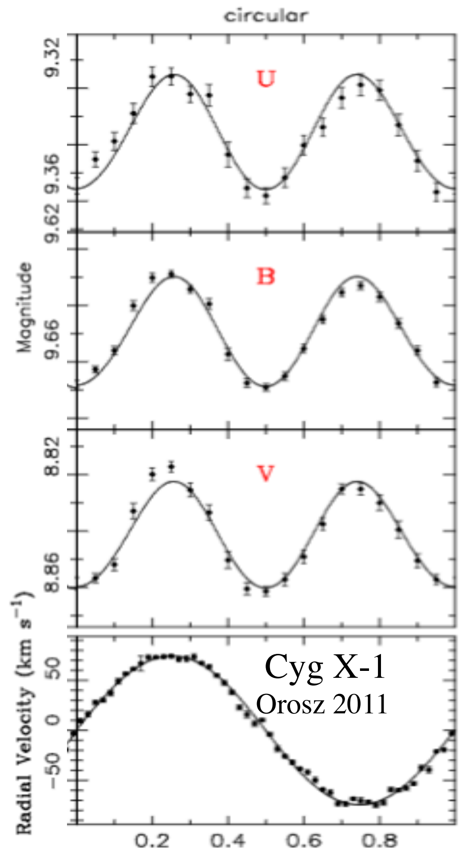
•K_X and P can be obtained very accurately from X-ray pulse timing delay measurements and K_o is measured from optical spectra of the companion

Evidence for black holes

- Galactic black hole candidates – the same sort of dynamical evidence we have for neutron stars! ~20 known
- Black hole mass from orbit of companion star- Cyg X-1 first galactic black hole discovered
  - Period 5.6 days
  - K = V sin i = 75km/s
  - Analysis of orbit shows that

$$f = \frac{K^3 P}{2\pi G} = \frac{M_1^3 (\sin i)^3}{(M_1 + M_2)^2}$$

  - “Mass function” f can be measured…
  - $M_{BH} > f$



<u>So what is the actual size ?</u>

$R_G \sim 1.5\ (M / M_\odot)$ km

<u>So how close are neutron stars to being black holes ?</u>

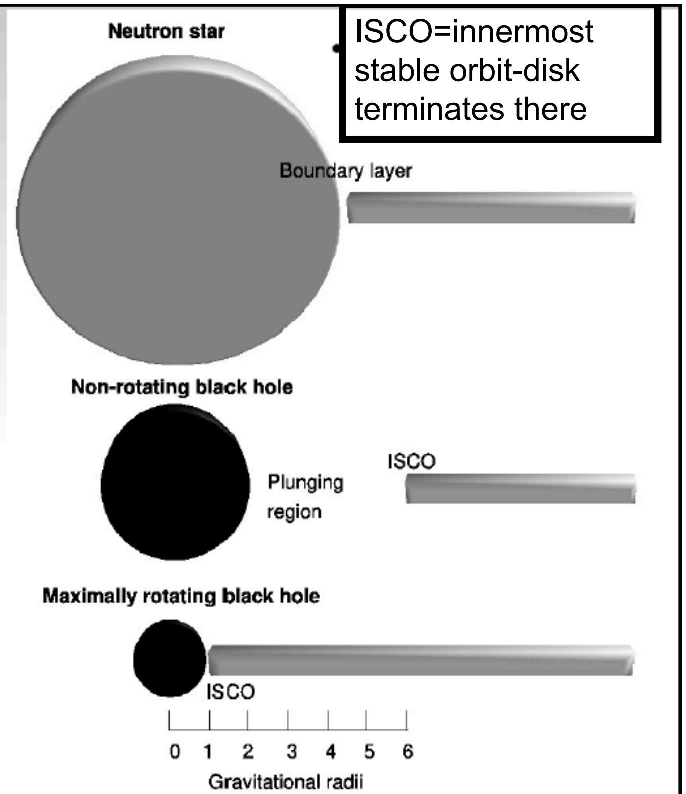
Neutron stars are only about a factor 2—3 larger than their event horizons

<u>What about spin ?</u>

A non-rotating (“Schwarzschild”) black hole has its event horizon at 2 R_G and its ISCO at 6 R_G

A maximally rotating (“Maximal Kerr”) black hole has both its event horizon and ISCO at R_G

→ Spinning black holes are more compact → potentially more radiatively efficient



R. Fender 2007

Some Scales (Rees 1984)

A central mass M has a gravitational radius

$$r_g = \frac{GM}{c^2} = 1.5 \times 10^{13} M_8 \text{ cm}, \qquad 1.$$

where M_8 is the mass in units of $10^8 M_\odot$. The characteristic minimum time scale for variability is

$$r_g/c \simeq 500 M_8 \text{ s}. \qquad 2.$$

A characteristic luminosity is the "Eddington limit," at which radiation pressure on free electrons balances gravity:

$$L_E = \frac{4\pi G M m_p c}{\sigma_T} \simeq 1.3 \times 10^{46} M_8 \text{ erg s}^{-1}. \qquad 3.$$

Related to this is another time scale

$$t_E = \frac{\sigma_T c}{4\pi G m_p} \simeq 4 \times 10^8 \text{ yr}. \qquad 4.$$

The time scale to grow a black hole if it Were accreting at the Eddington luminosity

The characteristic black body temperature if the Eddington luminosity is emitted at r_g $T_E \simeq 5 \times 10^5 M_8^{-1/4}$.

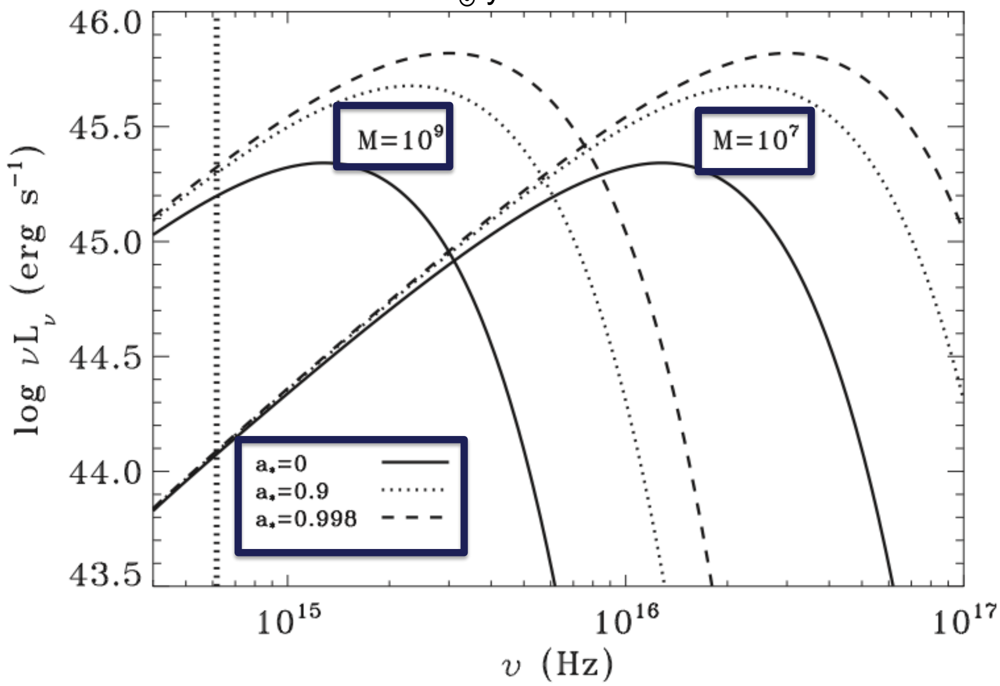
Schwarzschild and Kerr Metric

- Schwarzschild radius R_S=2GM/c^2
- for a <u>Schwarzschild</u> BH the innermost stable radius is 3R_S=6GM/c^2 - there are no **stable** circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- For a Kerr the innermost stable radius is at r_+=GM/c^2 The spinning black hole drags the the inertial frame-
- The smaller critical radius allows more energy to be released by infalling matter
  - For a Kerr BH 0.423 of the energy can be released.

- There is another 'fiducial' radius in the Kerr solution, that radius within which all light cones point in the direction of rotation, the 'static' radius, r_{static}.
- Between r_{static} and r_+ is a region called the 'ergosphere' within which particles must rotate with the black hole and from energy might be extracted (Penrose process).

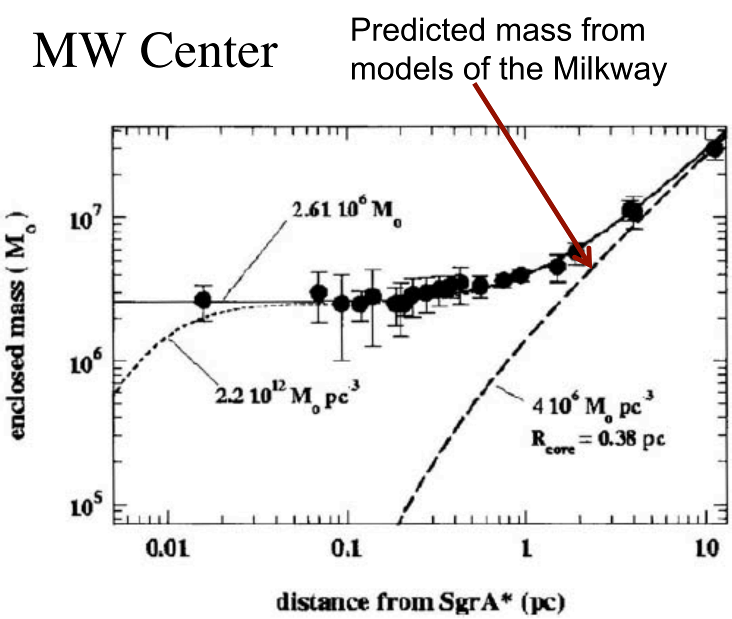
Effect of BH Mass and Spin on Emitted Spectrum

all the curves assume a rate of $1M_{\odot}$/yr



MW Center

- measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is $>10^{12}M_{\odot}/\text{pc}^3$



•As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass $2.6 \times 10^6\ M_{sun}$, and density

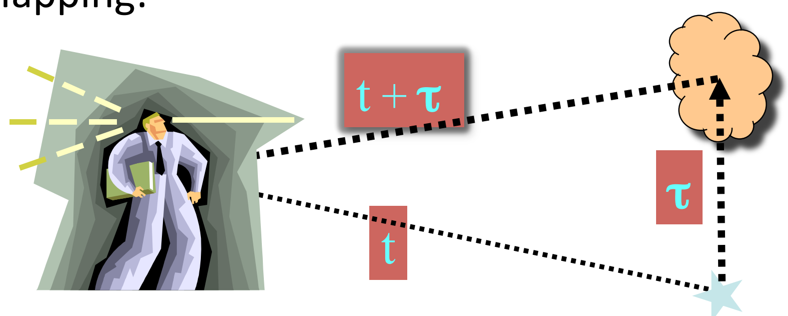
$20M_{sun}pc^{-3}$ or greater can not be stable for more than about 10 million years

Virial Mass Estimates/Reverberation Mapping- Longair 20.5

$M_{BH} = f\ v^2 R_{BLR}/G$

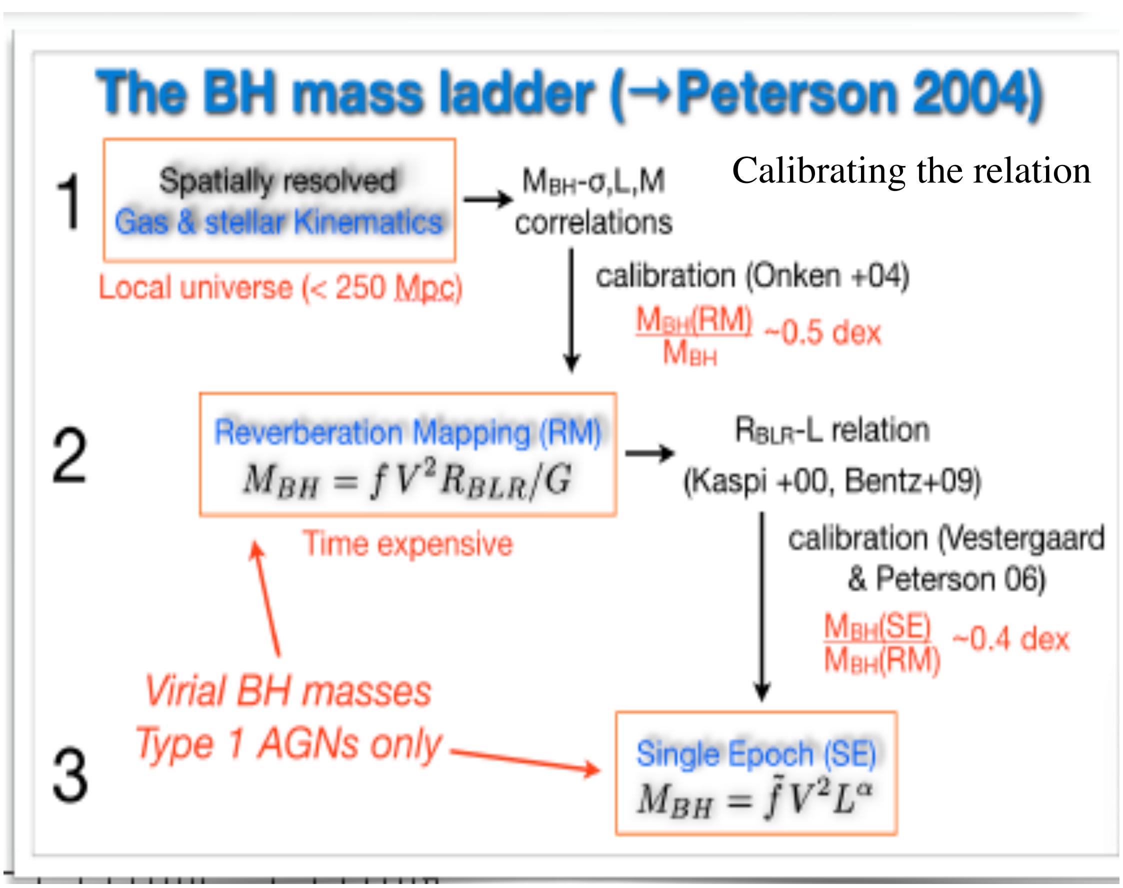
Reverberation Mapping:

- **$R_{BLR} = c\,\tau$**

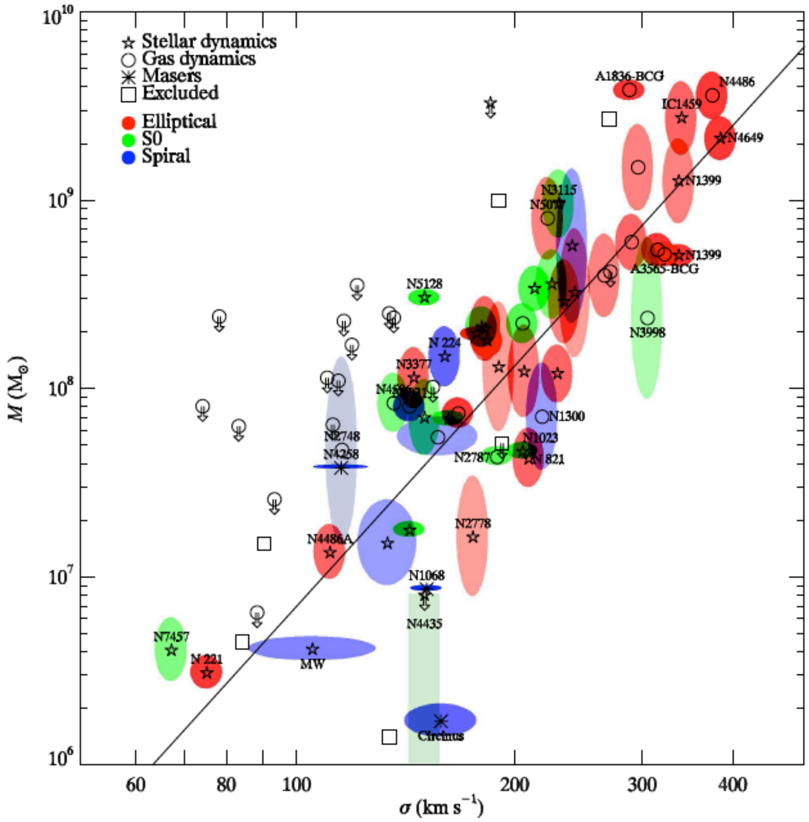


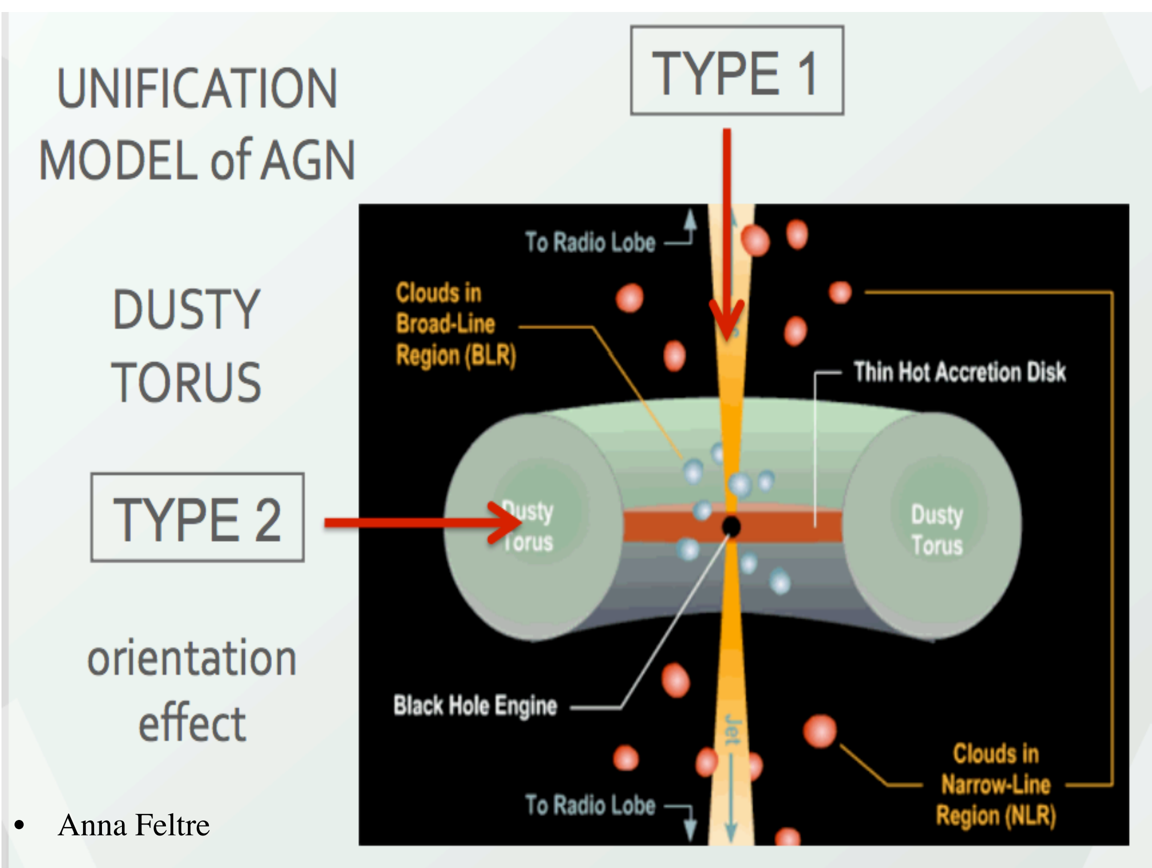
- **v_{BLR}**

  Line width in variable spectrum



- All the Nearby Galaxies with Dynamical Masses for their Central Black Holes
- scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- Galaxies know about their BH and vice versa



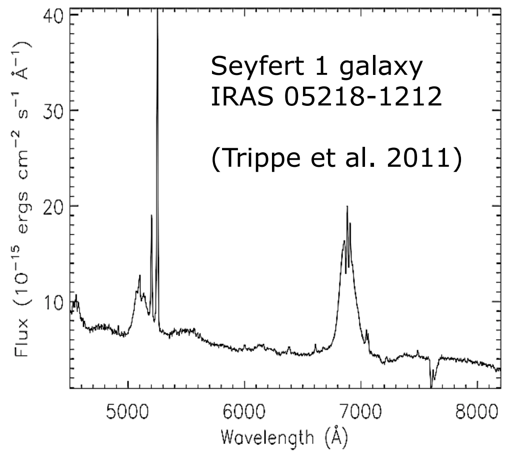


- Anna Feltre

AGN Unification

Broad line (type-1) objects

- Blue optical/UV continuum
- Broad optical/UV lines
  - Emission lines from permitted (not forbidden) transitions
  - Photoionized matter $n>10^9 cm^{-3}$
  - – BLR lines FWHM~2000-20000 km/
- Narrow optical/UV lines
  - Emission lines from both permitted and forbidden transitions
  - FWHM~500km/s
  - Sometimes spatially resolved 0.1-1k

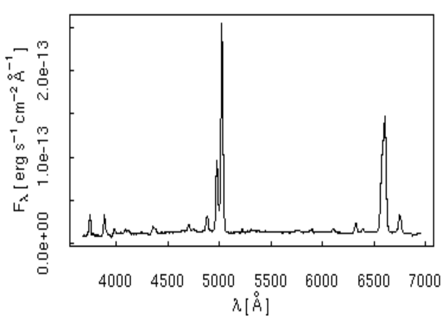


- **Overall spectrum reveals unabsorbed/ unreddened nucleus**

AGN Unification

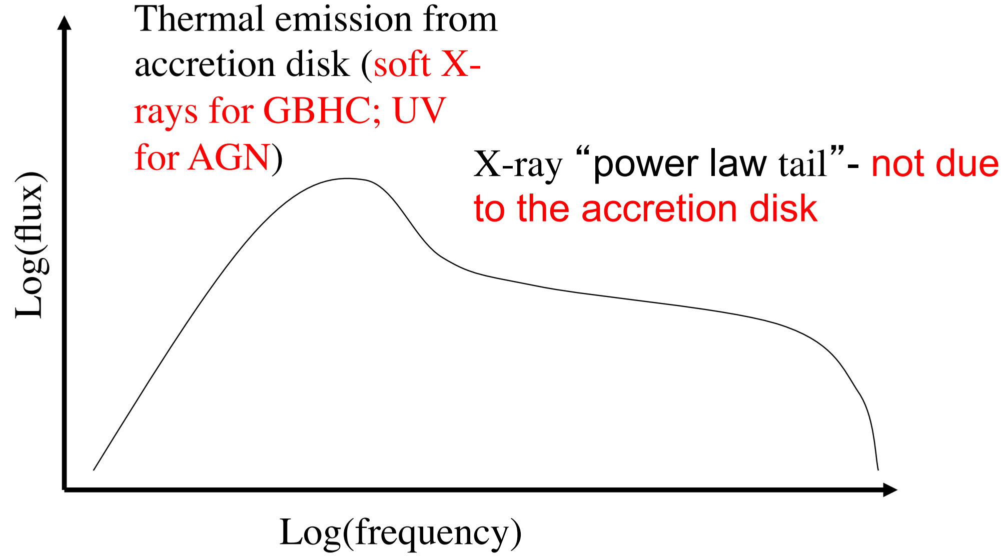
Narrow line (type-2) objects

- Reddened Optical/UV continuum
- Emission line spectrum
  - "Full light" spectrum only shows narrow optical/UV lines
  - Broad optical/UV lines seen in polarized light… shows that there is a hidden broad line region **seen in scattered light** (Antonucci & Miller 1985)



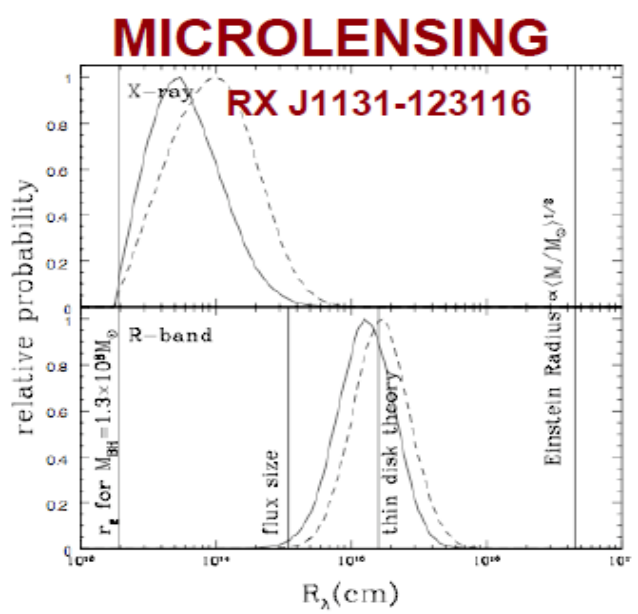
- **X-ray spectrum usually reveals highly absorbed nucleus (NH>10^{22}cm-2)**
- type II **<u>do not</u> have broad lines and have a weak or absent 'non-stellar' continuum**
- **Depending on the type of survey and luminosity range ~50% of all AGN are of type II**

What Do Broad Band Spectra of Black Holes Look Like



How do we know that there really is a disk??

- microlensing observations of a few QSOs have 'resolved' the x-ray and optical sources
- The optical source size and dependence of luminosity on wavelength are consistent with standard disk theory

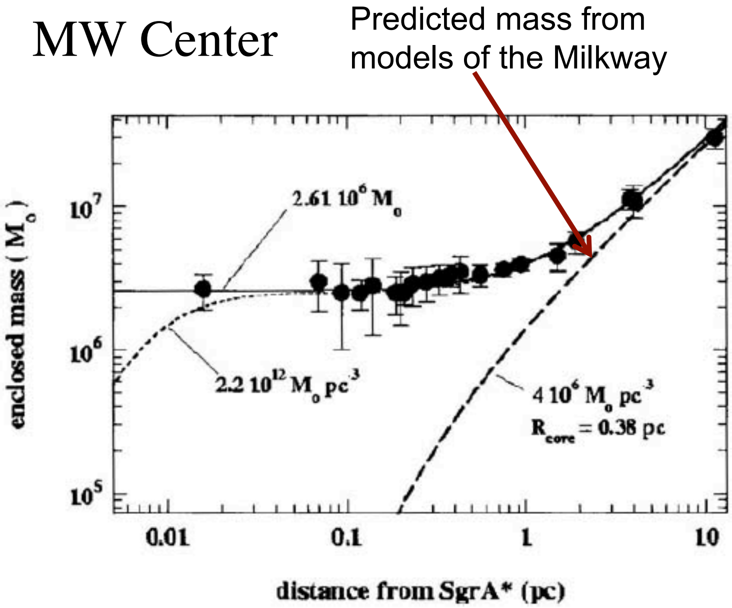


X-rays from 10 R_g (Optical 70 R_g)

Chartas et al. 2009
Dai et al. 2009

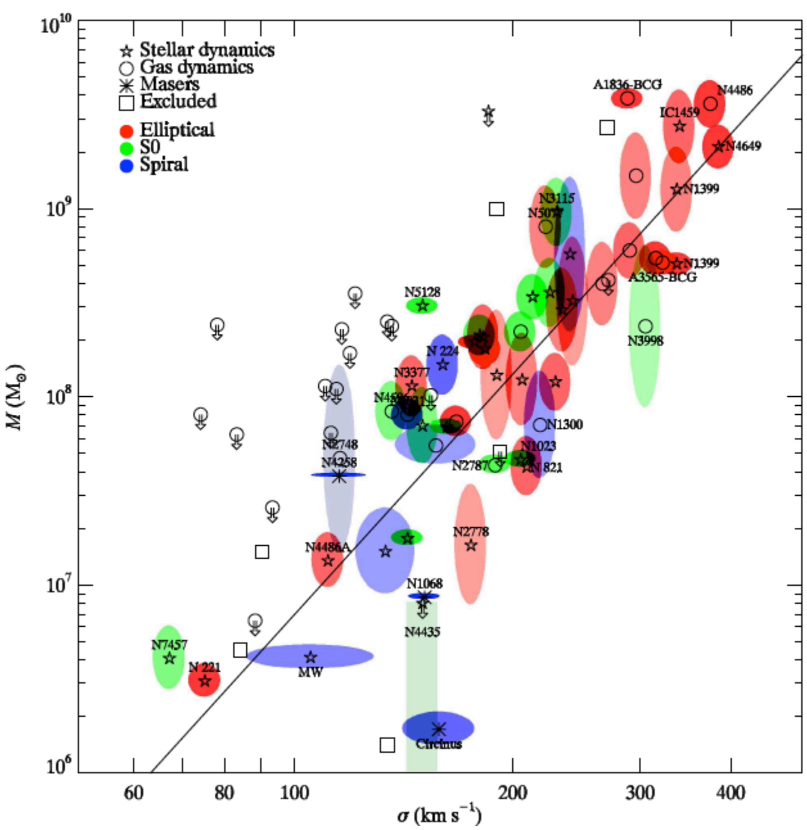
MW Center

- measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is $>10^{12} M_\odot/pc^3$



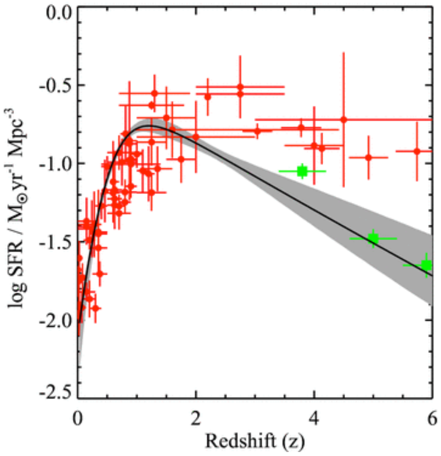
•As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass $2.6 \times 10^6 M_{sun}$, and density $20 M_{sun} pc^{-3}$ or greater can not be stable for more than about 10 million years

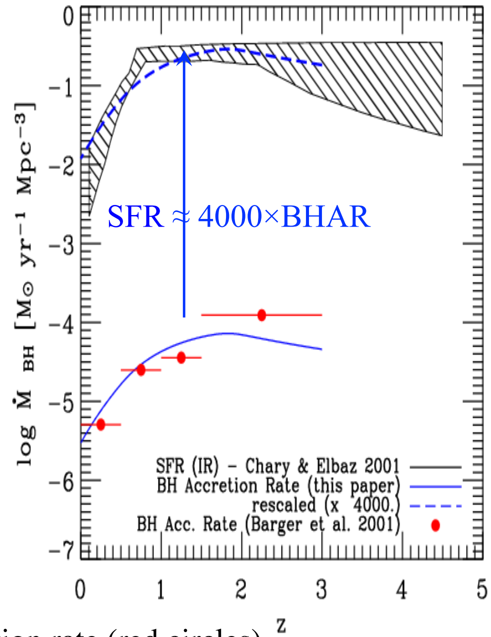
- All the Nearby Galaxies with Dynamical Masses for their Central Black Holes
- scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- Galaxies know about their BH and vice versa



Comparison of Growth of BH and Star Formation Rate

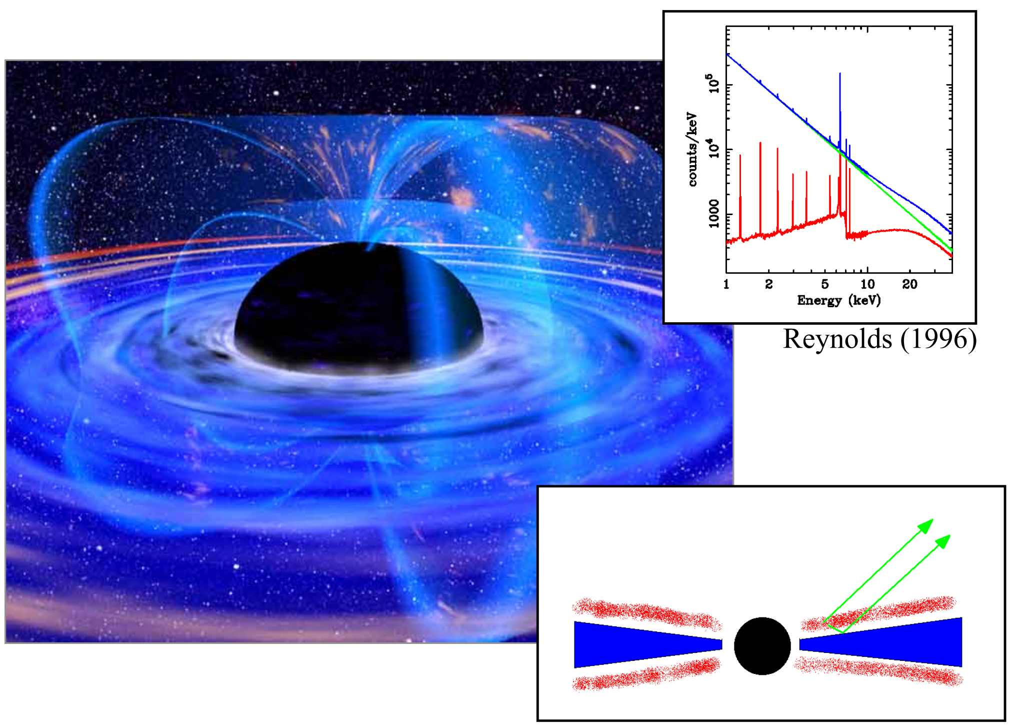
- half of the accreted supermassive black hole mass density has formed by z~ 1
- rough similarity of evolution of supermassive black holes and star formation





Star formation rate (red circles)

AGN evolution rate (grey band) scaled up by 5000 Aird et al 2010



Reynolds (1996)

- X-ray "reflection" imprints well-defined features in the spectrum

AGN

- Material from the last 2 AGN lectures is not in this review.... will be on exam however !