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 (6.6×10^{-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
$L_{Edd}=4\pi M_x G m_p c/\sigma_T = 1.3\times10^{38} M_{sun}$ 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 ~$GM/R=1.7\times10^{16}$ (R/10km) $^{-1}$ J/kg**~1/2mc^2**

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

Two Modes of Accretion- Longair 14.5.2

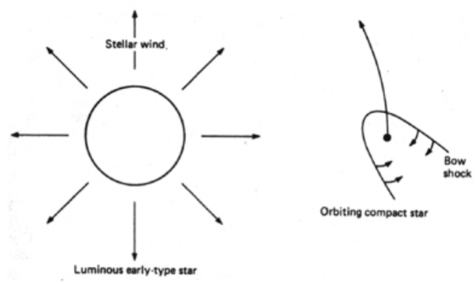


Figure 9: Accretion from a stellar wind.[23]

Accretion from a stellar wind

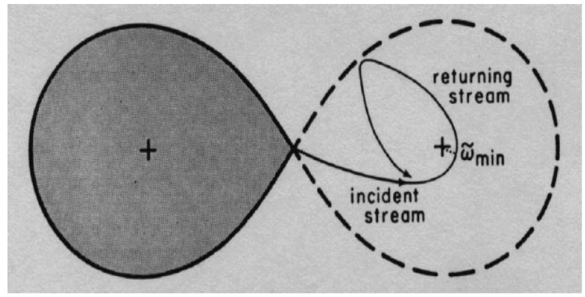


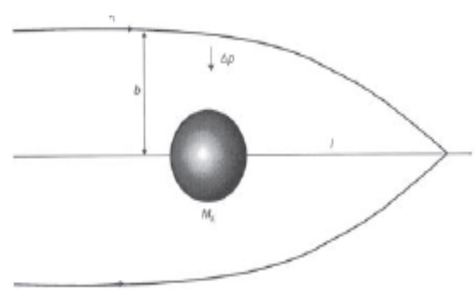
Figure 6: Roche lobe geometry, showing the incident mass stream through the inner Lagrangian point and the intersection of the returning stream with the newly arriving material. The low mass companion on the left hand side completely fills its Roche lobe, while the position of the compact object is denoted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

Accretion from Roche Lobe Overflow

Cominsky (2002)

Accretion From a wind – Following Longair

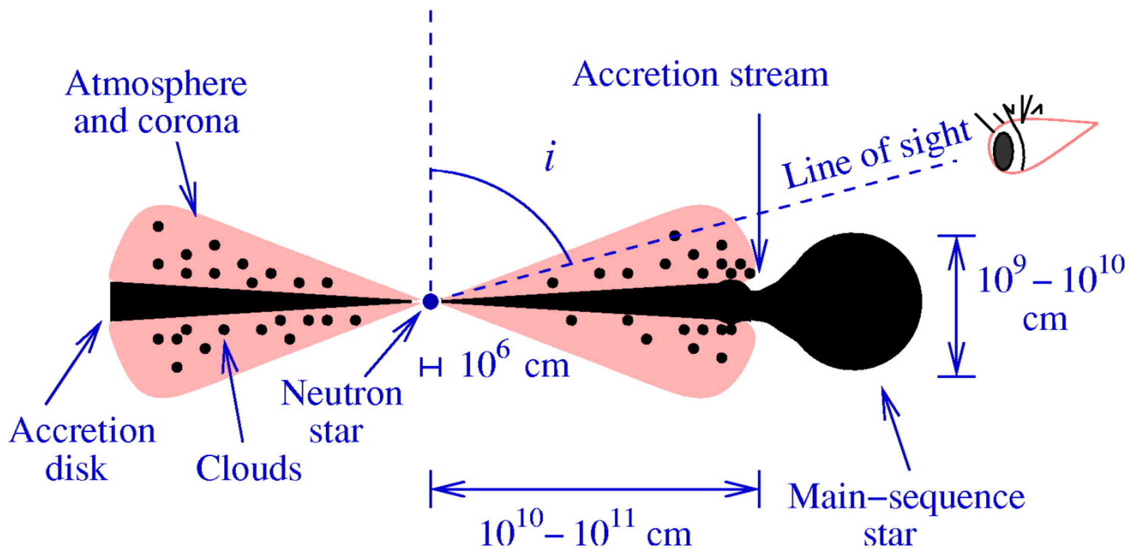
- $L_X \approx [\ \eta \dot{m}_P / 4]\ (2GM_X/R_P)^2 \mathbf{v_w}^{-4}$
- $\dot{m}_P$ the mass loss rate from the donor star
- accretion rate is ~$(\dot{m}_P/4)(R_c/R_p)^2$
- R_p is the distance of the compact object from the donor star
- R_c is the critical (capture radius)
- **Wind velocity v_w>> orbital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



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

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



Jimenez-Garate et al. 2002

Basics of Accretion

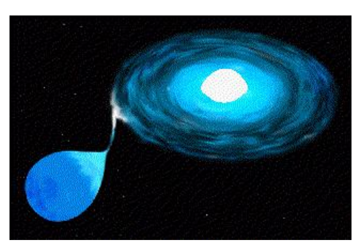
- Because of angular momentum considerations an accretion disk, **almost** always forms
- Matter is thought to form a physically thin (but optically thick* disk) which has Keplerian rotation
- Matter falls into by losing angular mometum via viscosity

the angular velocity is Ω_k=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 $\mathcal{M}$, is

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

assuming the annulus radiates its energy as a blackbody

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

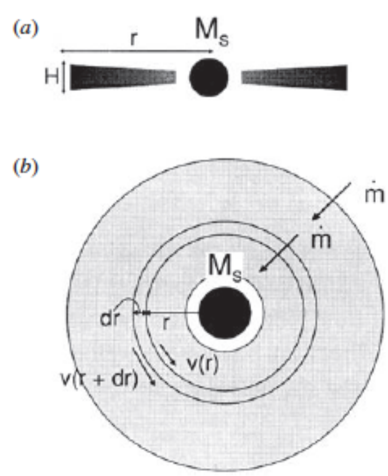
L=M$\mathcal{M}$ dr/r^2 we have

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



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

momentum for it to actually accrete…

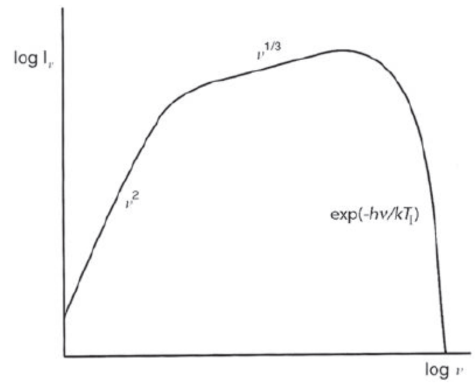
Releases gravitational potential energy in the process!

Matter goes in, angular momentum goes out!

Total Spectrum

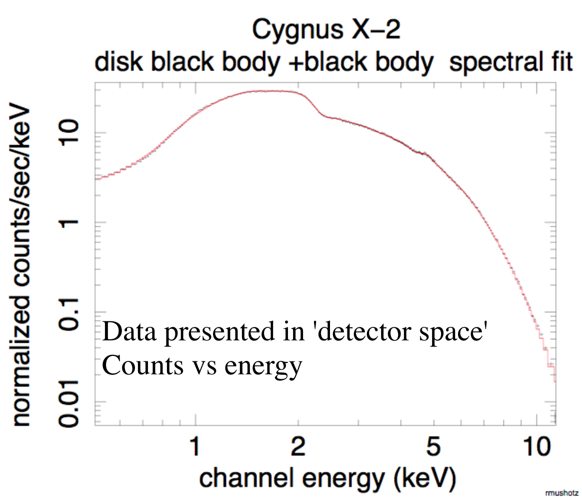
- If each annulus radiates like a black body and the temperature scales as $T \sim r^{-3/4}$ (Longair 14.54)
- The emissivity scales over a wide range of energies as $I(\nu) \sim \nu^{1/3}$
- At lower frequencies the spectrum has a Raleigh-Jeans ν^2 shape and at higher energies has a exponential cutoff 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.

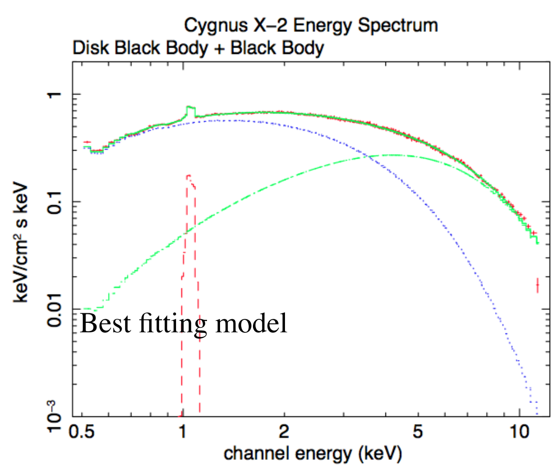
If the disk 'cuts off' at some radius r_{inner} then the temperature profile is
$T(r) = 3GM\dot{m}/8\pi\sigma r^3[1 - (r_{inner}/r)^{1/2}]^{1/4}$
eq in 14.7.1.



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 $I \propto \nu^2$.

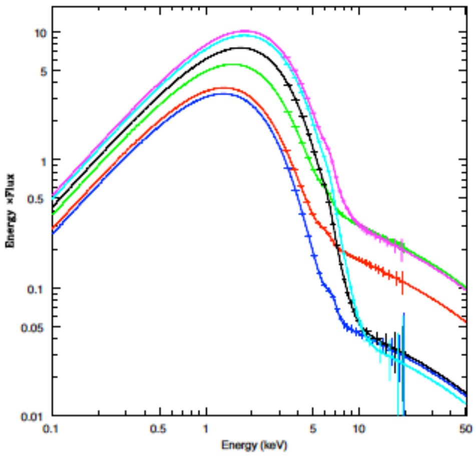
Fit to Real Data

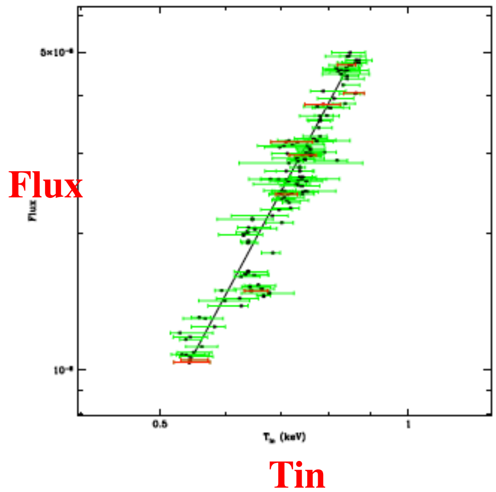




The data is of very high signal to noise
Simple spectral form fits well over a factor of 20 in energy
Emitted energy peaks over broad range from 2-6 kev

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:
- hus 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.

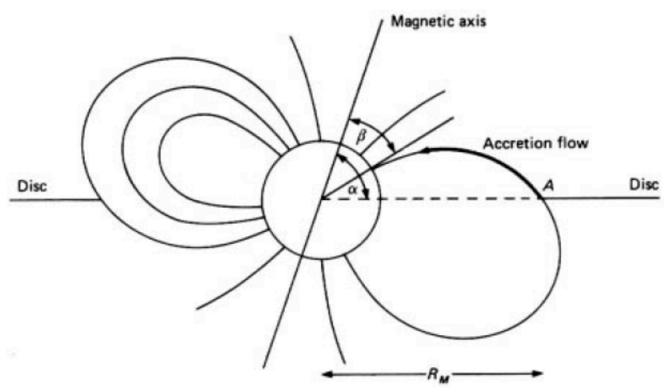


Figure 8: Accretion in a strong ($\sim 10^{12}$ Gauss) magnetic field. Note that the accretion disk is held off the neutron star surface by the centrifugal barrier formed by the rotating magnetosphere.[23]

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

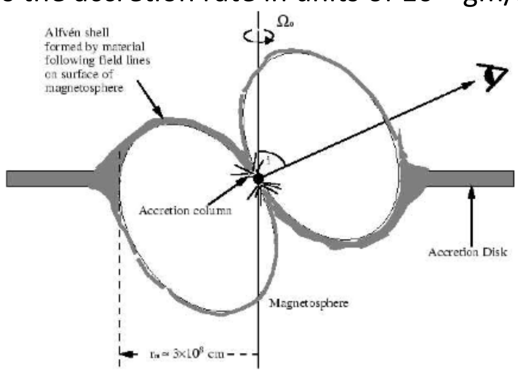
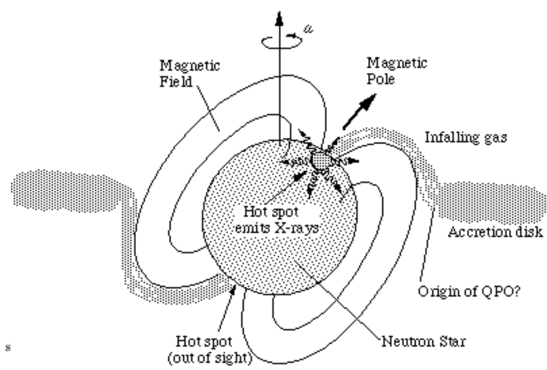


Fig. 1.— Rough sketch of the accretion flow in a disk being picked up by a strong neutron s magnetic field. From http://lheawww.gsfc.nasa.gov/users/audley/diss/img203.gif



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.

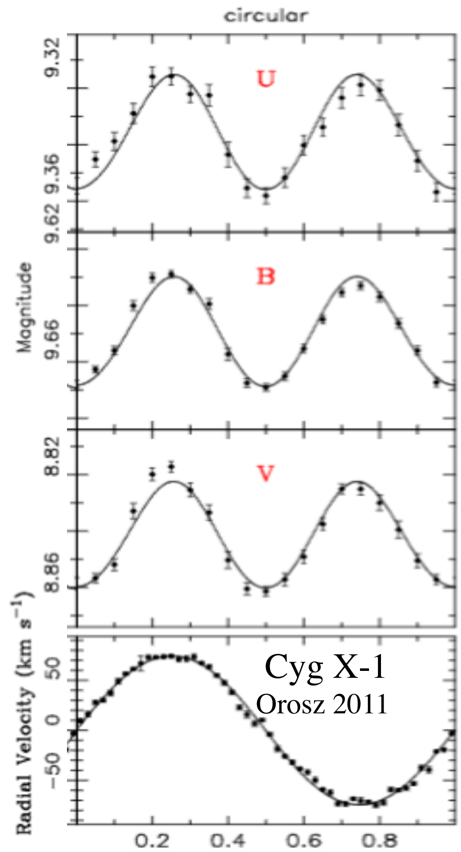
•K_X and P can be obtained very accurately from X-ray pulse timing delay measurementsand K_o is measured from optical spectra of the companion

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…
  - $M_{BH} > f$



So what is the actual size ?

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

So how close are neutron stars to being black holes ?

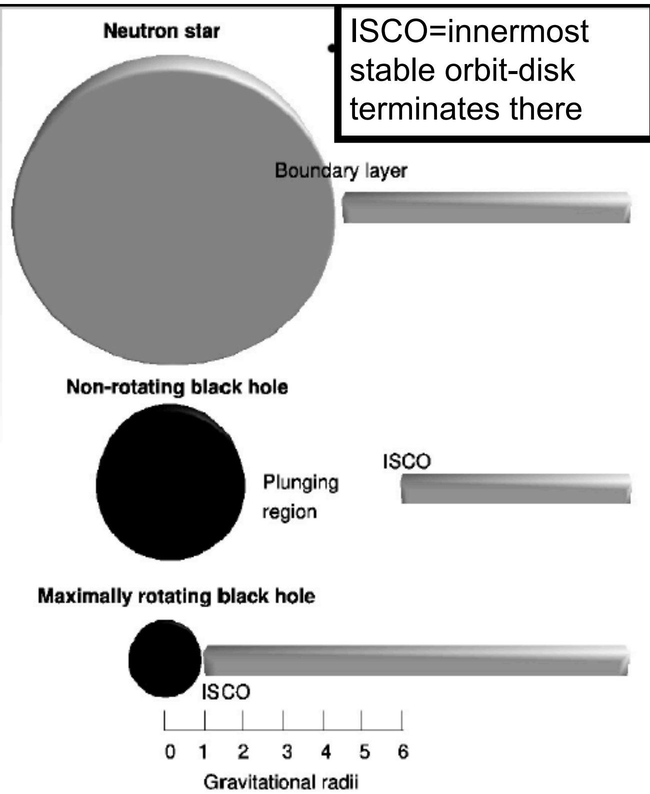
Neutron stars are only about a factor 2—3 larger than their event horizons

What about spin ?

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 $\quad T_E \simeq 5 \times 10^5 M_8^{-1/4}$.

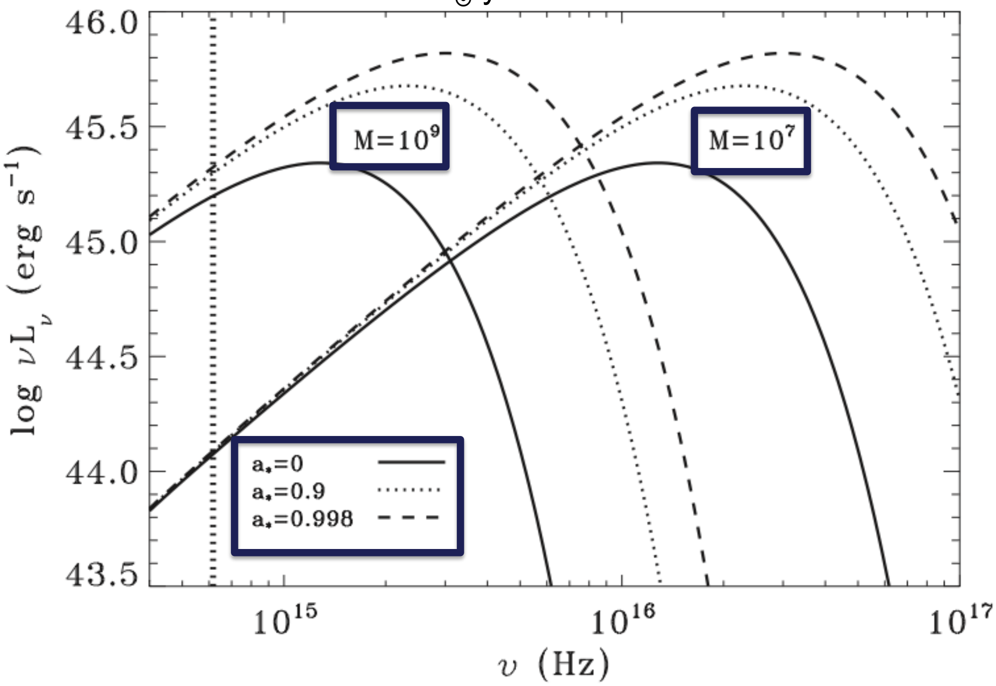
Schwarzschild and Kerr Metric

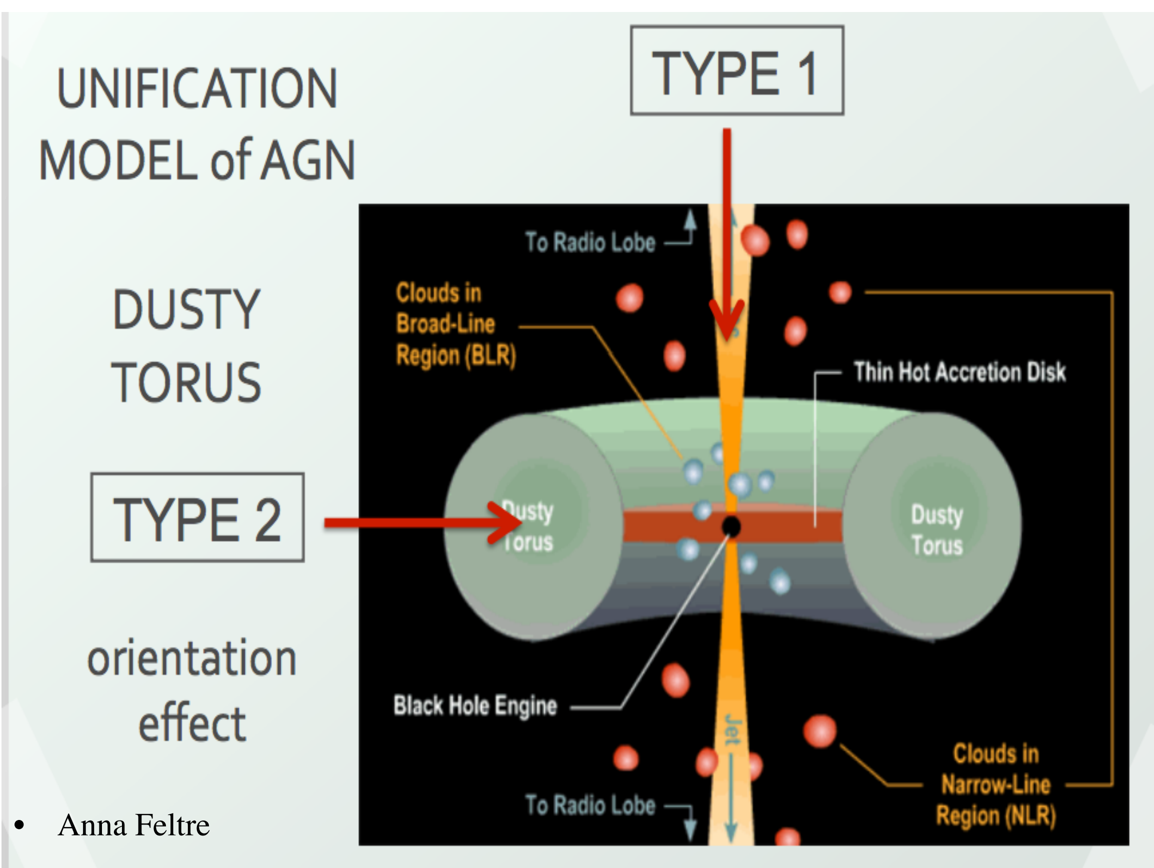
- Schwarzschild radius $R_S=2GM/c^2$
- for a Schwarzschild BH the innermost stable radius is $3R_S=6GM/c^2$ - there are no **stable** circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- For a Kerr the innermost stable radius is at $r_+=GM/c^2$ The 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 $1 M_{\odot}/yr$

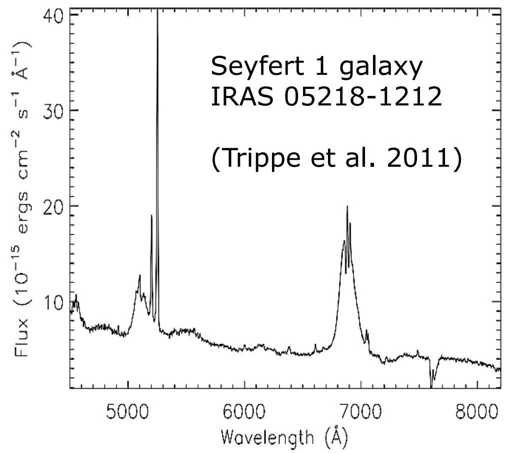




AGN Unification

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/s
- Narrow optical/UV lines
  - Emission lines from both permitted and forbidden transitions
  - FWHM~500km/s
  - Sometimes spatially resolved 0.1-1kpc

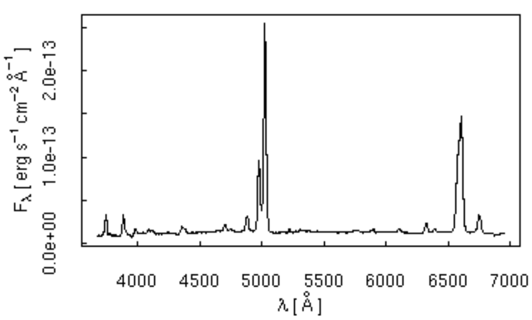


- **Overall spectrum reveals unabsorbed/ unreddened nucleus**

AGN Unification

Narrow line (type-2) objects

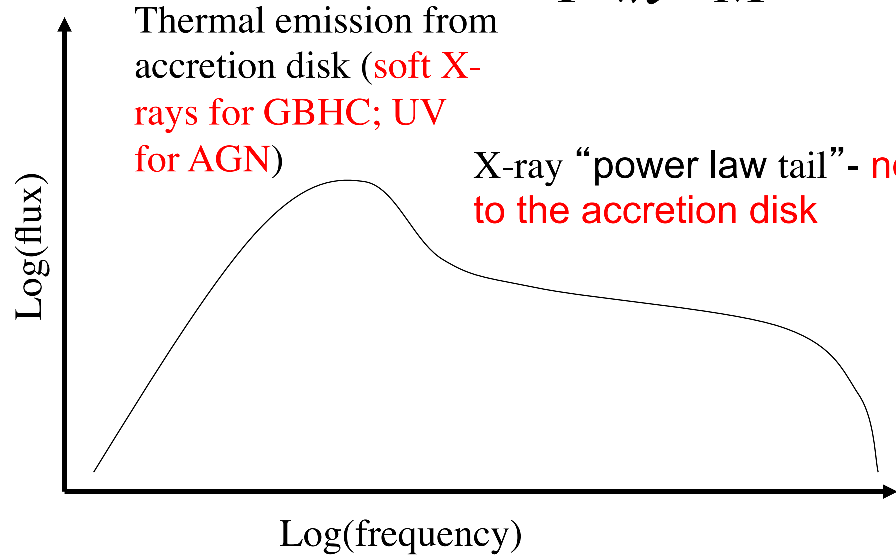
- Reddened Optical/UV continuum
- Emission line spectrum
  - "Full light" spectrum only shows narrow optical/UV lines
  - Broad optical/UV lines seen in polarized light… shows that there is a hidden broad line region **seen in scattered light** (Antonucci & Miller 1985)
- **X-ray spectrum usually reveals highly absorbed nucleus ($NH>10^{22}$cm-2)**



- type II **do not 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

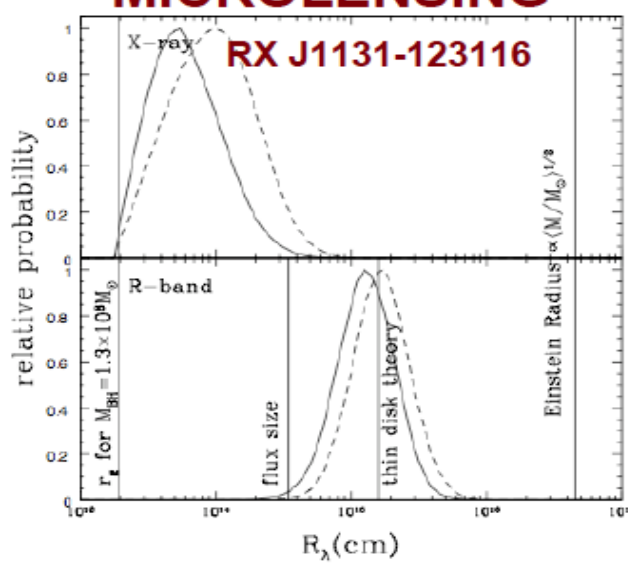
$T \sim \mathcal{M}^{1/4} M^{-1/4}$



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

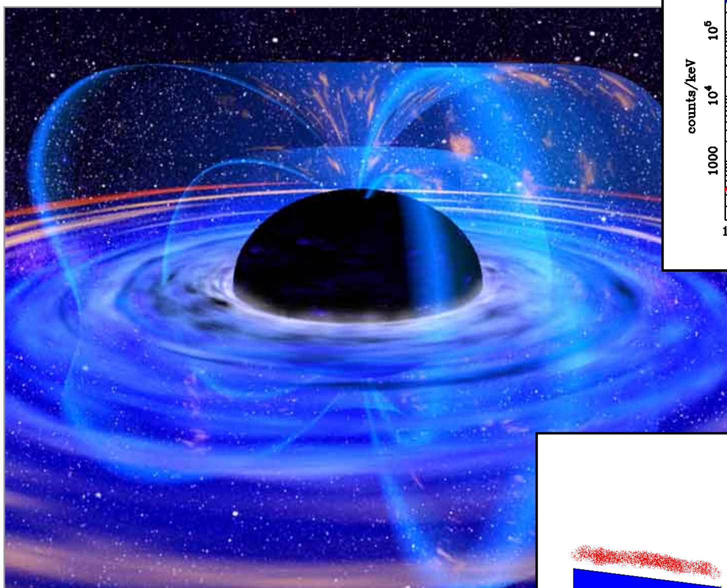
- microlensing observations of a few QSOs have 'resolved' the x-ray and optical sources
- The optical source size and dependence of luminosity on wavelength are consistent with standard disk theory

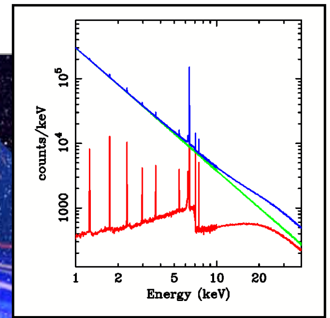
MICROLENSING



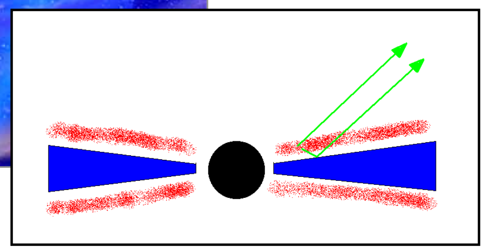
X-rays from 10 R_g (Optical 70 R_g)

Chartas et al. 2009
Dai et al. 2009





Reynolds (1996)

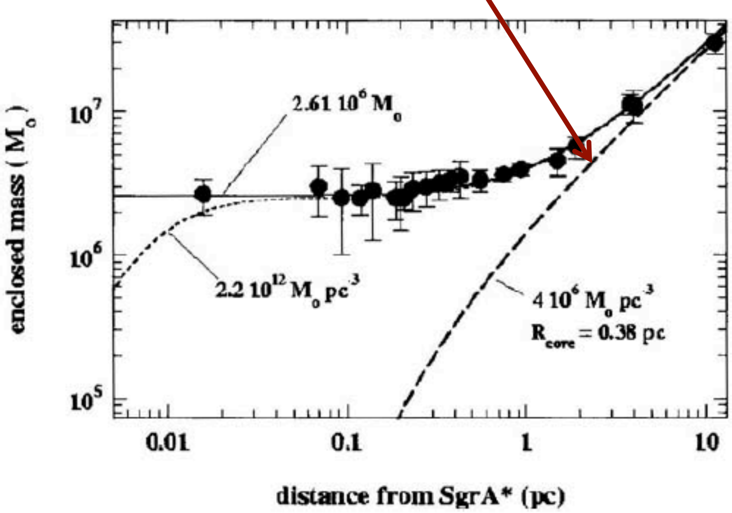


- X-ray "reflection" imprints well-defined features in the spectrum

MW Center

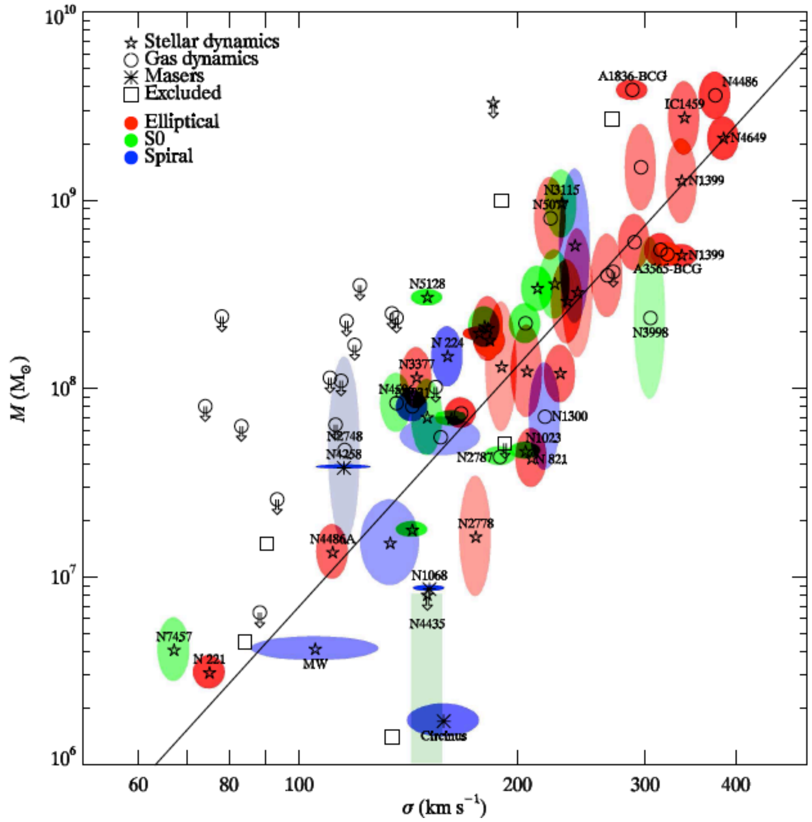
- measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is $>10^{12} M_{\odot}/pc^3$

Predicted mass from models of the Milkway



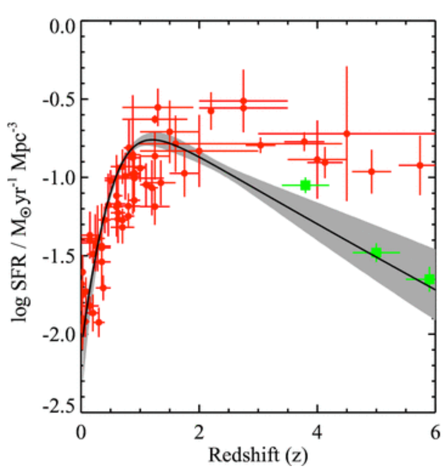
•As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass $2.6 \times 10^6 M_{sun}$, and density $20 M_{sun} pc^{-3}$ or greater can not be stable for more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

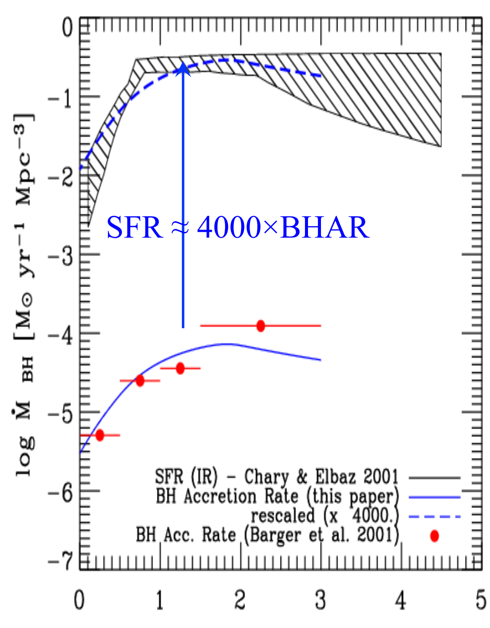
- All the Nearby Galaxies with Dynamical Masses for their Central Black Holes
- scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- Galaxies know about their BH and vice versa



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

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

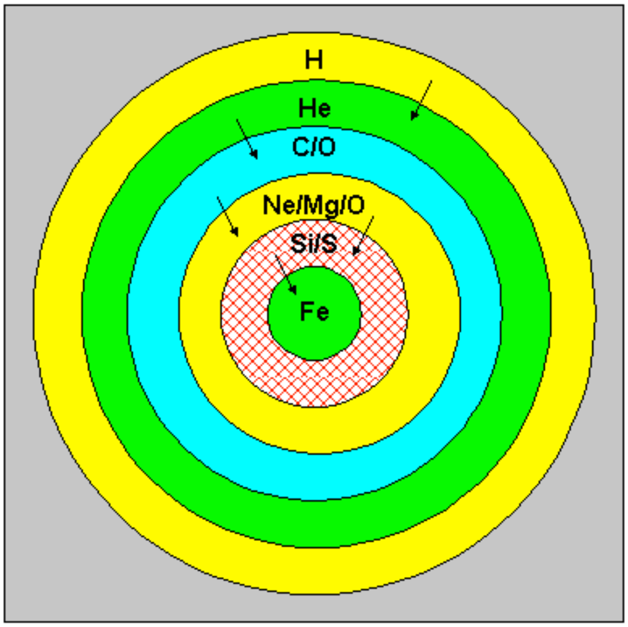
- Supernova come in two types (I and II)
  - Type Ia is the explosion of a white dwarf pushed over the Chandrasekar limit- details are not understood
    - However they are used as a 'standard candle' for cosmology
  - Type Ib and II is the explosion of a massive star after it has used up its nuclear 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

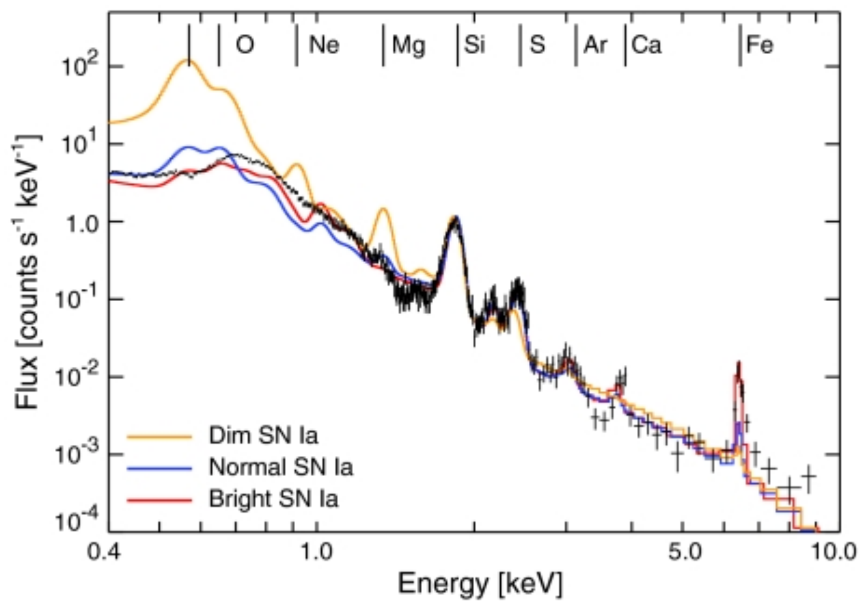
Supernova Explosions



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

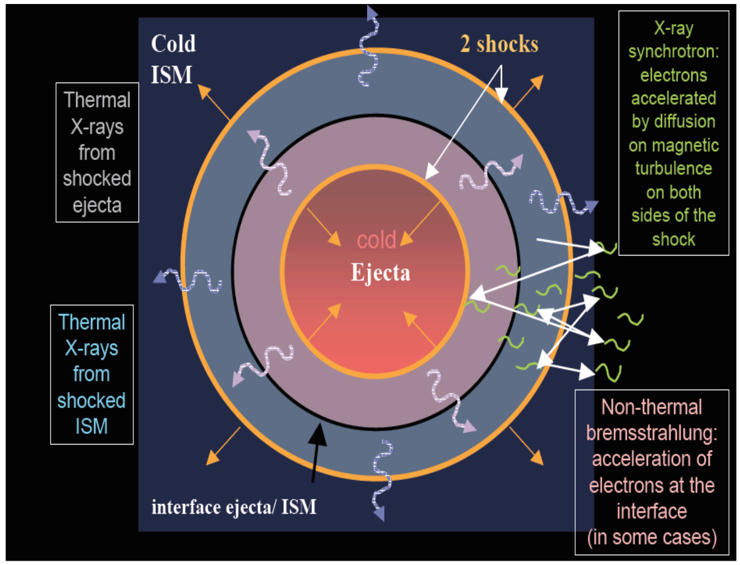
Dissipation of remnant energy into ISM

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

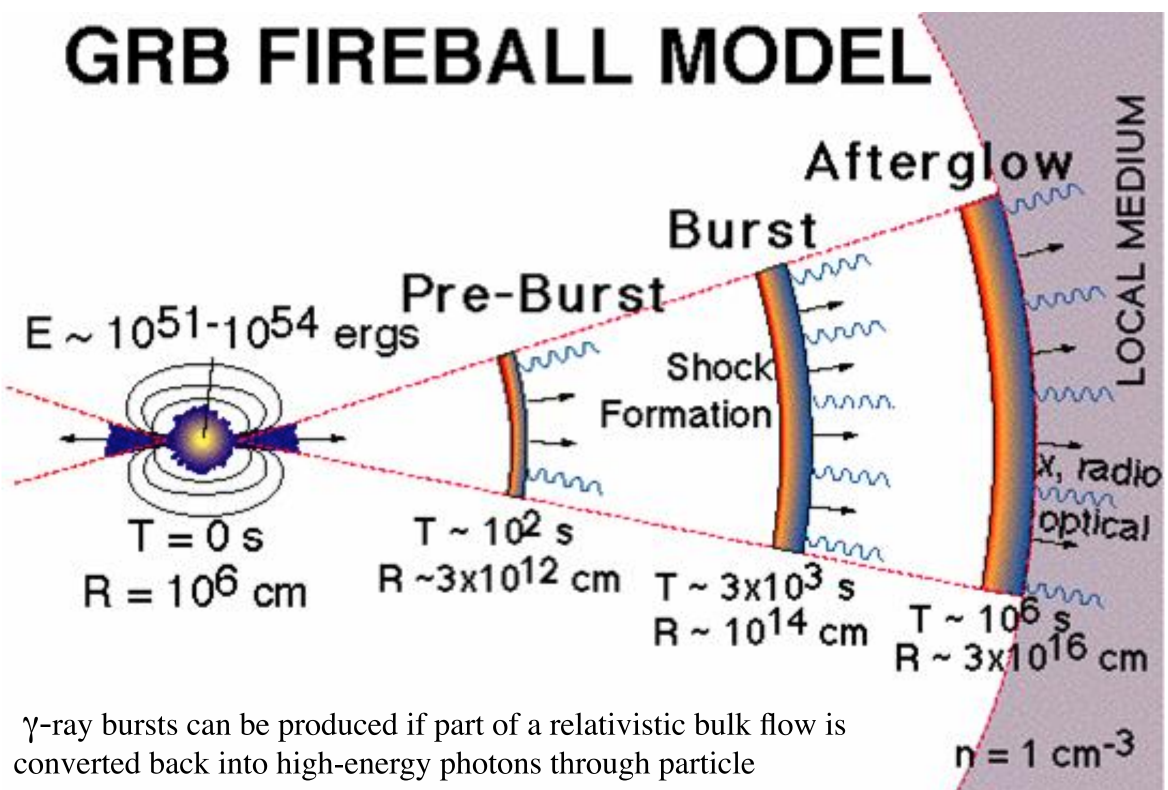
Nice analogy- ping pong ball bouncing between descending paddle and table

Gamma-Ray Bursts

- Are bright flashed of γ-rays- for short period of time (<100 sec)
- fluxes of ~0.1-100 photon/cm^2/sec/keV emitted primarily in the 20-500 keV band.
  - Distribution is isotropic on the sky
- Because of these properties it took ~30 years from their discovery (1967) to their identification
  - **They are at very large distances (z up to 8 (!)) with apparent luminosities of 3x10^{54} erg/sec**
  - Rate is ~10^{-7}/yr/galaxy
- What are they??- short timescales imply compact object ; what could the energy reservoir be- Mc^2 implies M~10^{33} gms~ M_{sun} if total conversion of mass into energy How does all this energy end up as γ-rays ?
  - Location of long γRBs is in and near star forming regions in smallish galaxies- associated with star formation
  - A few γRBs have been associated with a type Ic supernova

Gamma-Ray Bursts (GRBs)

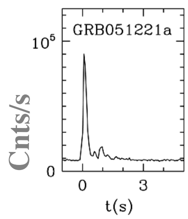
- **discovered by U.S. spy satellites (1967; secret till 1973)**
- **have remained one of the biggest mysteries in astronomy until 1998 (isotropic sky distribution; location: solar system, Galactic halo, distant Universe?)**
- **discovery of afterglows in 1998 (X-ray, optical, etc.) with redshifted absorption lines has resolved the puzzle of the location of GRBs → GRBs are the some of the most energetic events in the Universe**
- **duration: 10^{-3} to 10^{3} s (large variety of burst shapes)**
- **bimodal distribution of durations: 0.3 s (short-hard), 20 s (long-soft) (different classes/viewing angles?)**
- **GRBs are no standard candles! (isotropic) energies range from 5×10^{44} to 2×10^{47} J**
- **highly relativistic outflows (fireballs): ($\gamma \gtrsim 100$), possibly highly collimated/beamed**
- **GRBs are produced far from the source ($10^{11} - 10^{12}$ m): interaction of outflow with surrounding medium (external or internal shocks) → fireball model**
- **relativistic energy $\sim 10^{46} - 10^{47}\,\mathrm{J}\,\epsilon^{-1} f_\Omega$ (ϵ: efficiency, f_Ω: beaming factor; typical energy 10^{45} J?)**
- **event rate/Galaxy: $\sim 10^{-7}\,\mathrm{yr}^{-1}\,(3 \times 10^{45}\,\mathrm{J}/\epsilon\,E)$**

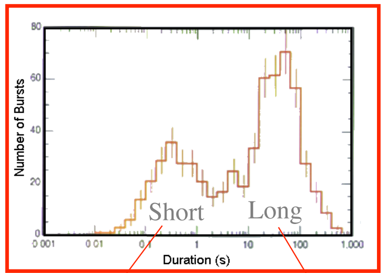


γ-ray bursts can be produced if part of a relativistic bulk flow is converted back into high-energy photons through particle acceleration in a relativistic shock between the outflow and the surrounding medium

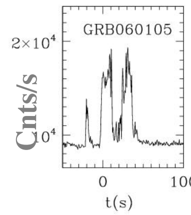
Short vs Long GRBs

Short GRB

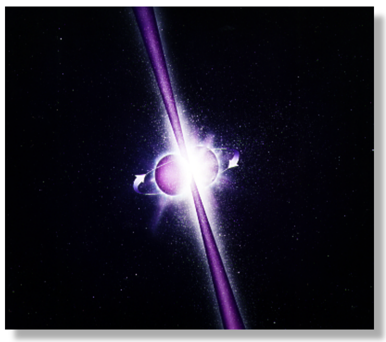


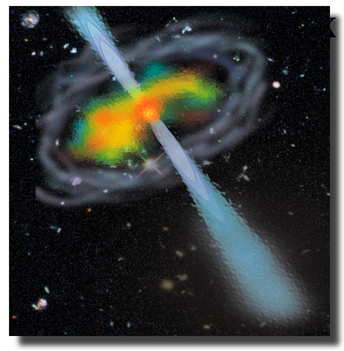


Long GRB



Short GRBs in non-SF elliptical galaxies

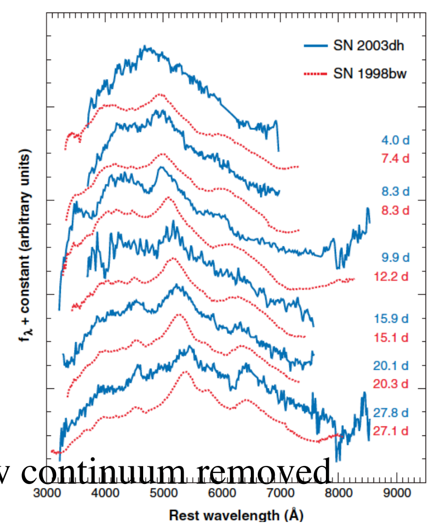




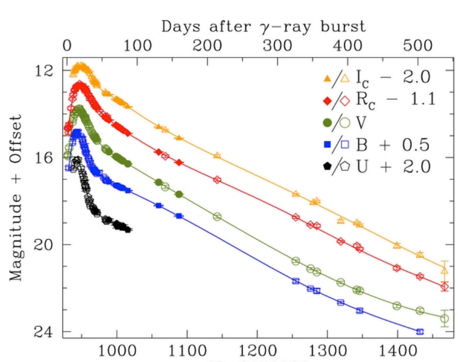
Long GRBs in SF galaxies

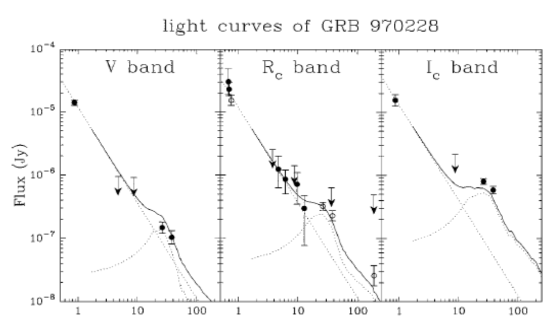
Long Burst Nature of Progenitor

- It is believed that the progenitor is a massive star based on the association of some (<10%) bursts with a peculiar type of SN (SNIbc, characterized by an absence of hydrogen, helium and silicon absorption lines (ARA& a44: 507 S.E. Woosley and J.S. Bloom)
- most z<1 hosts are dwarf galaxies with intense star formation, and the GRB locations track the brightest star formation regions in the hosts



Power law continuum removed





Short Bursts- Progenitor

- One of the ideas is that short bursts are the result of the merger of 2 neutron stars (B. Paczynski 1991)
- Based on their observed properties
- SGRBs are cosmological in origin (z > 0:1)
- have a beaming-corrected energy scale of ~10^{49}–10^{50} erg
- lack associated supernovae
- occur in a mix of star-forming and elliptical galaxies
- have a broad spatial distribution around their

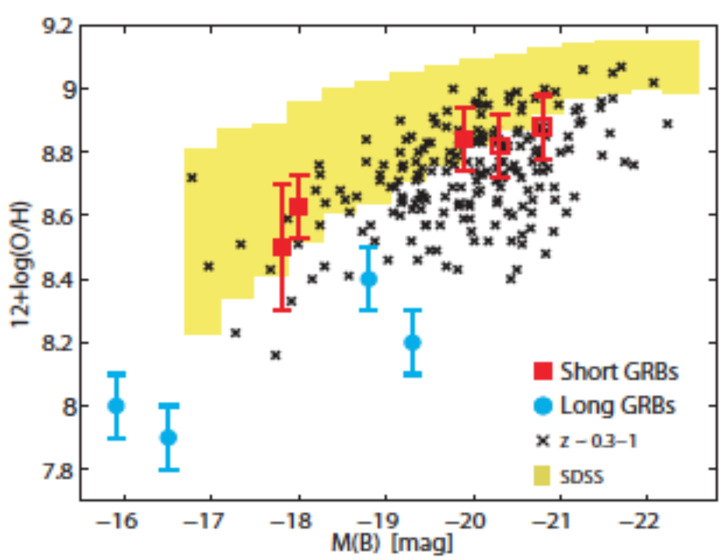
hosts, with some events offset by tens of kpc

and are located in low-density parsec-scale environments

The confluence of these characteristics provides support to the popular model of compact object (CO) mergers (Stone et al 2013)

Where GRBS occur- clues to their origin

- Long GRBs occur preferentially in low mass and low metallicity galaxies at z<1
- Tend to occur in regions of high star formation rate (see next page)- consistent with origin in high mass stars



yellow band is distribution of luminosity and metallicity of 'random' galaxies at low z from SDSS