Summary of Class

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

- Unifiying theme: high energy processes in high energy objects

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.

Please Fill In Your Evaluations

- Today the Department administrator said
- 'Our high-energy astrophysics classes seem to have low-energy students, especially ASTR 480 (only 27% responses (4 students) !!) '

Todays Press Release

- NASA's Fermi, Swift See 'Shockingly Bright' Burst 05.03.13
- A record-setting blast of gamma rays from a dying star in a distant galaxy has wowed astronomers around the world. ... GRB 130427A, produced the highest-energy light ever detected from such an event.
- "We have waited a long time for a gamma-ray burst this shockingly, eye-wateringly bright," said Julie McEnery, project scientist for the Fermi Gamma-ray Space Telescope at NASA's Goddard Space Flight Center in Greenbelt, Md. "The GRB lasted so long that a record number of telescopes on the ground were able to catch it while space-based observations were still ongoing."
- Optical counterpart was 12th mage
- Story on CNN http://www.cnn.com/2013/05/06/opinion/urry-gamma-ray-burst/index.html?hpt=hp_t4

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

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

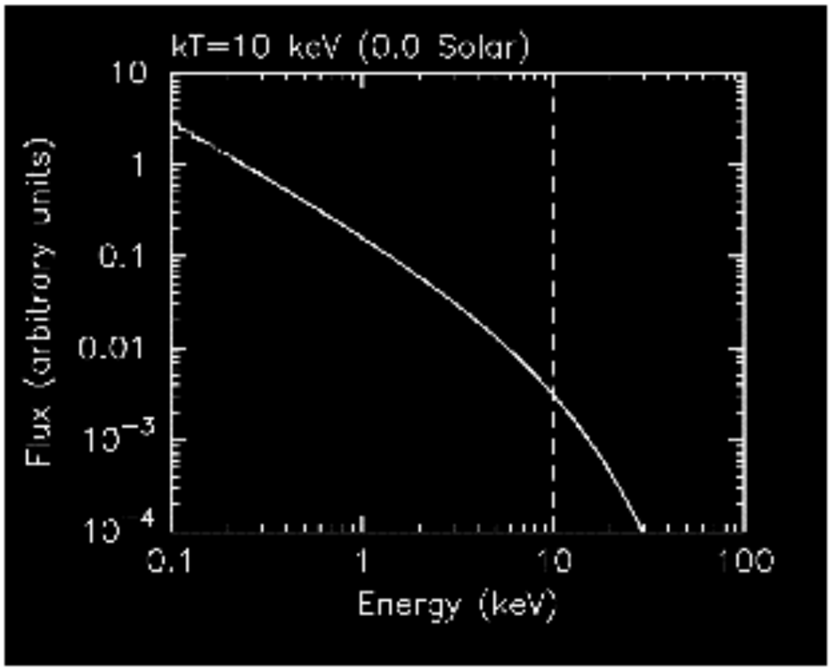
Photons are absorbed by atomic transitions

- 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

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



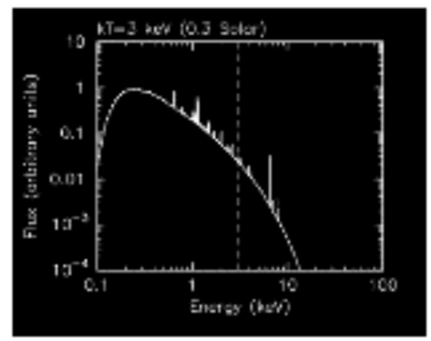
A = normalization, G = Gaunt factor,

Z = charge of positive ions

n_e and n_i electron and ion densities

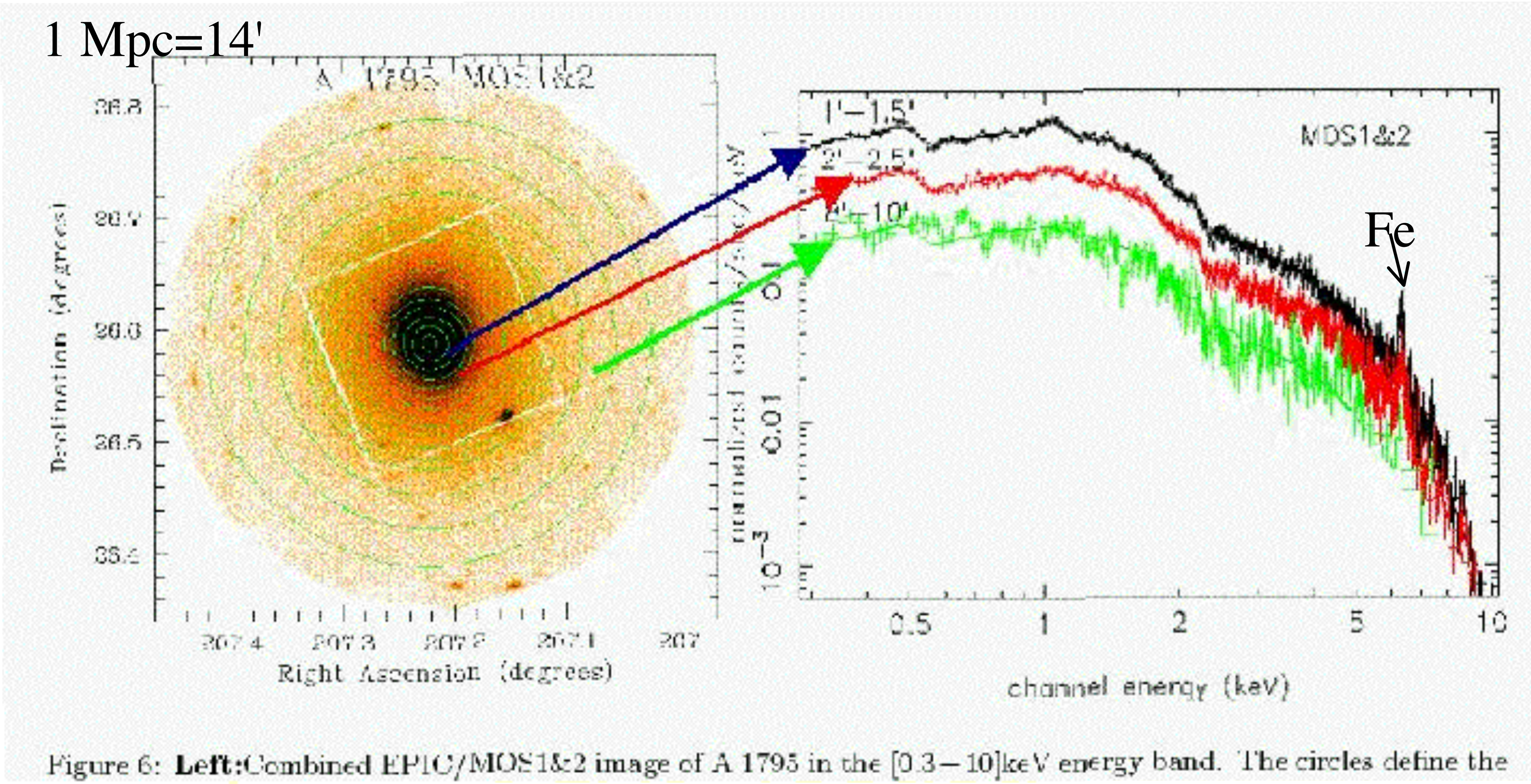
for $E << kT$ the spectrum is approximately a power law

for $h\nu >> kT$ there is an exponential cutoff



[In reality accompanied by recombination line emission]

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

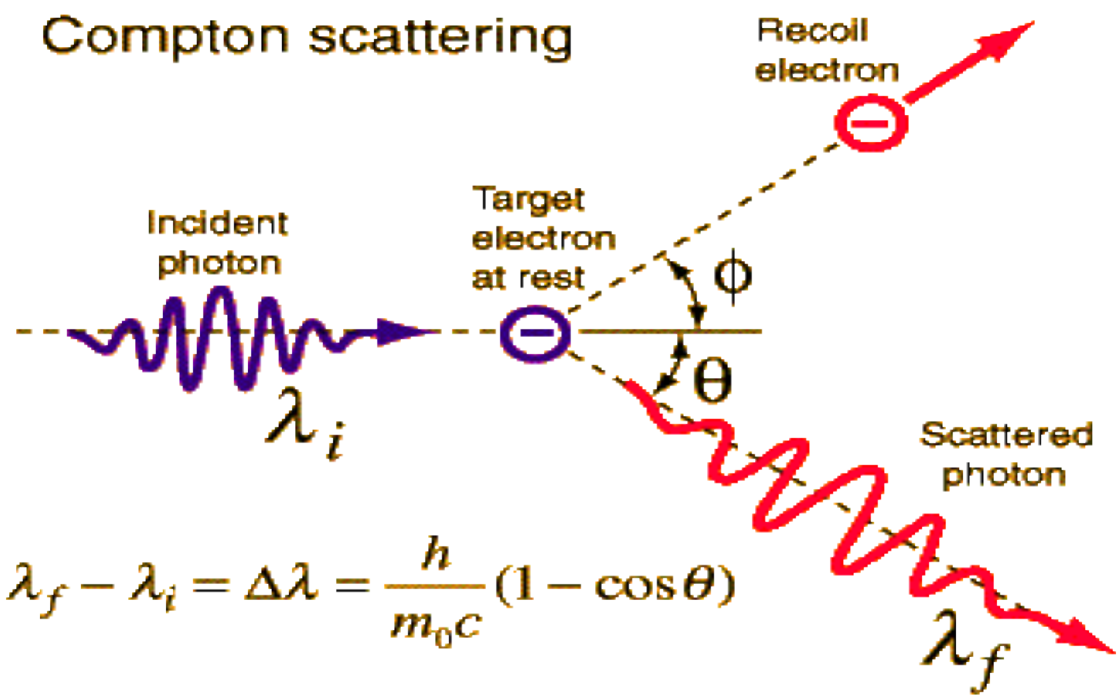


X-ray spectra of a Cluster

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

Compton Wavelength=h/mc=0.00243 nm for an electron

Whether the photon gives energy to the electron or vice versa



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

PHOTOELECTRIC ABSORPTION

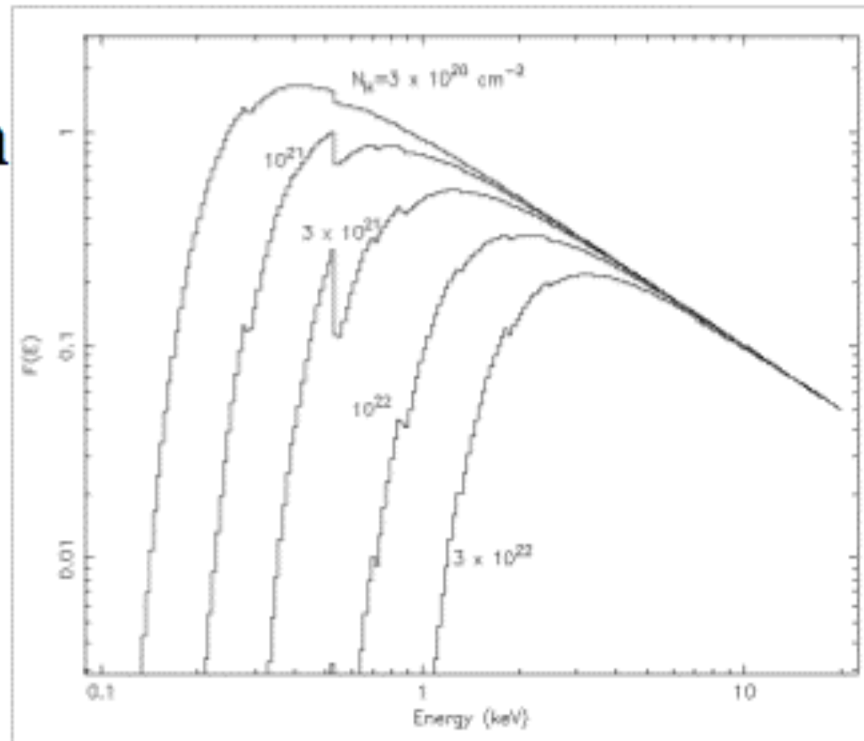
$N_H =$ Equivalent hydrogen column density (cm^{-2})

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

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

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

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

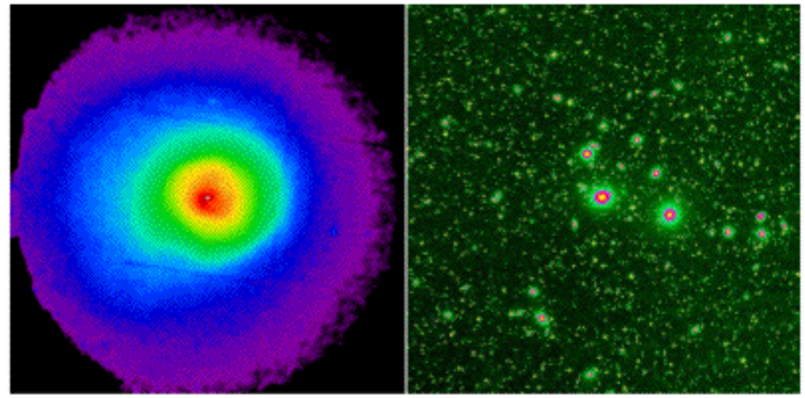


Profile dominated by bound-free edges of abundant elements

Clusters of Galaxies

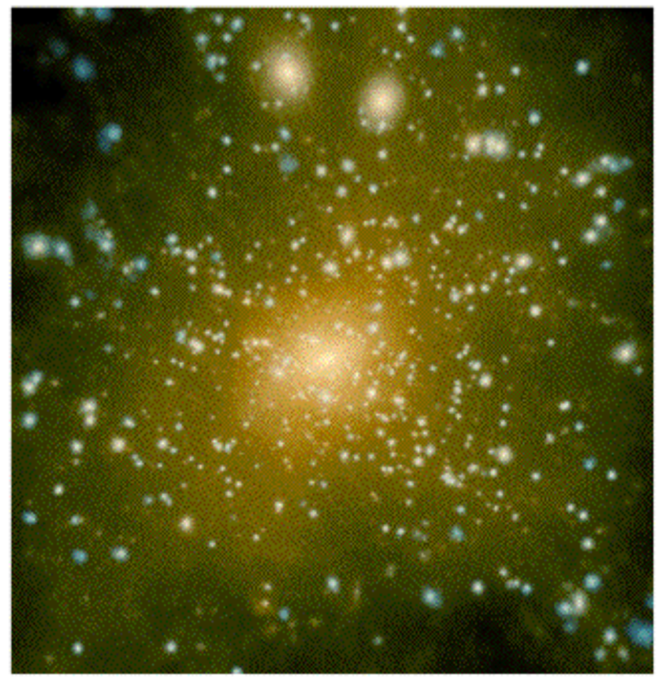
- Clusters of galaxies are the largest gravitationally bound systems in tl Universe.
- At optical wavelengths they are ov densities of galaxies with respect t average density: 100-1000's of galaxies moving in a common gravitational potential well (a sma assembly is defined a galaxy grou
- The typical masses ~ 10^{13}- $10^{15}M_s$ (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
- Fair samples of the universe- laboratory to measure dark matter
- The gravitational potential is dominated by dark matter

on all scales
- Most of the baryons are in the hot gas (80%)

Theoretical Tools

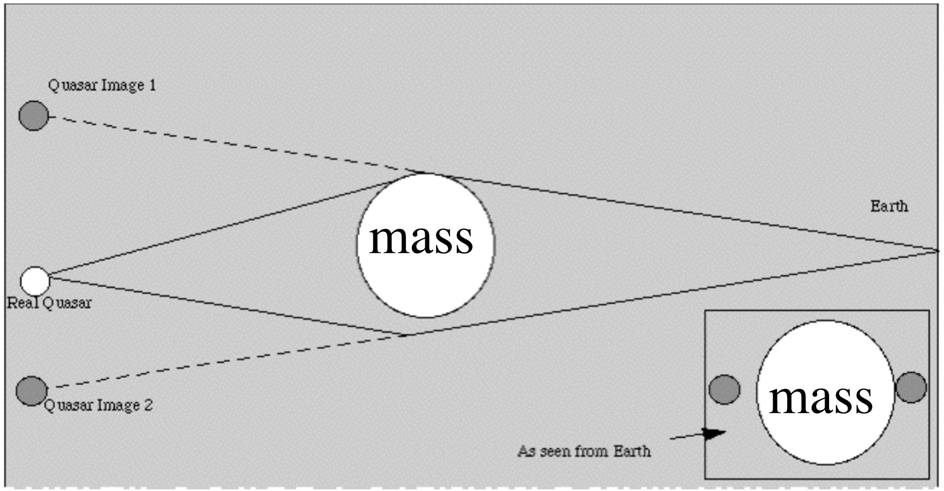
- Physics of hot plasmas
  - Bremmstrahlung
  - Collisional equilibrium
  - Heat transport
  - Etc
- Formation of structure
- Evidence for feedback processes
- How to use lensing to measure gravitational potential (mass)
- Measurement of dark matter, total mass and their distribution via hydrostatic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

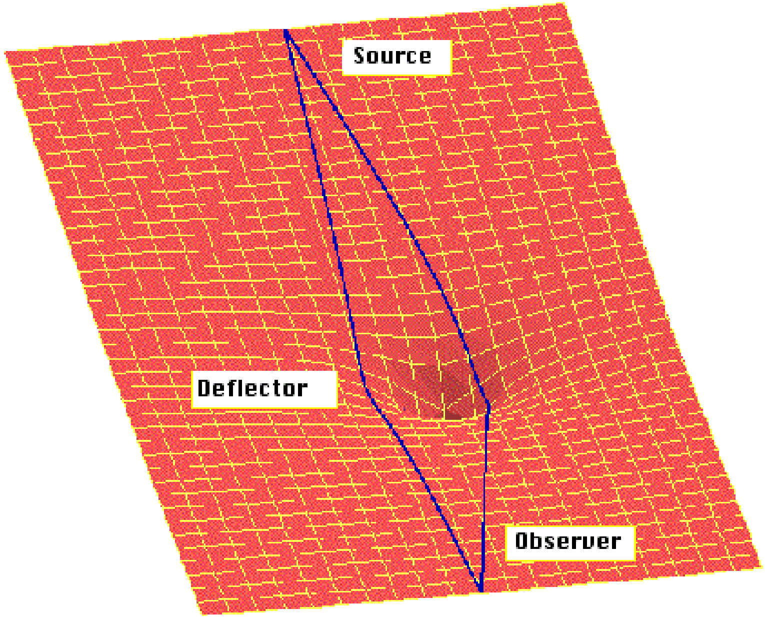
Basics of Gravitational Lensing

- 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

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

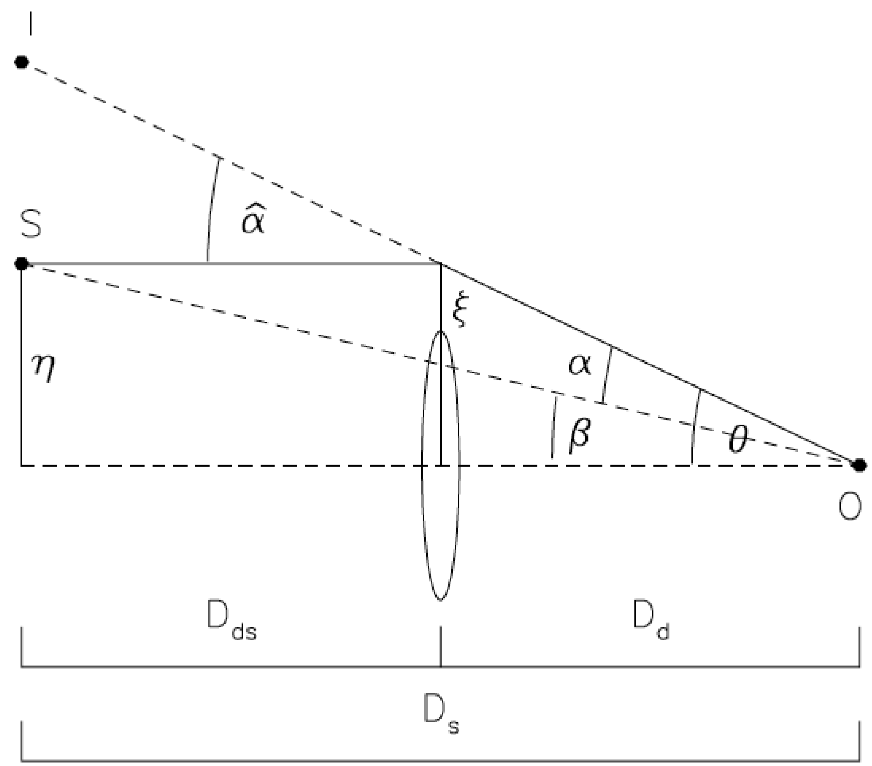
or

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

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

- a projected temperature profile, a 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

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

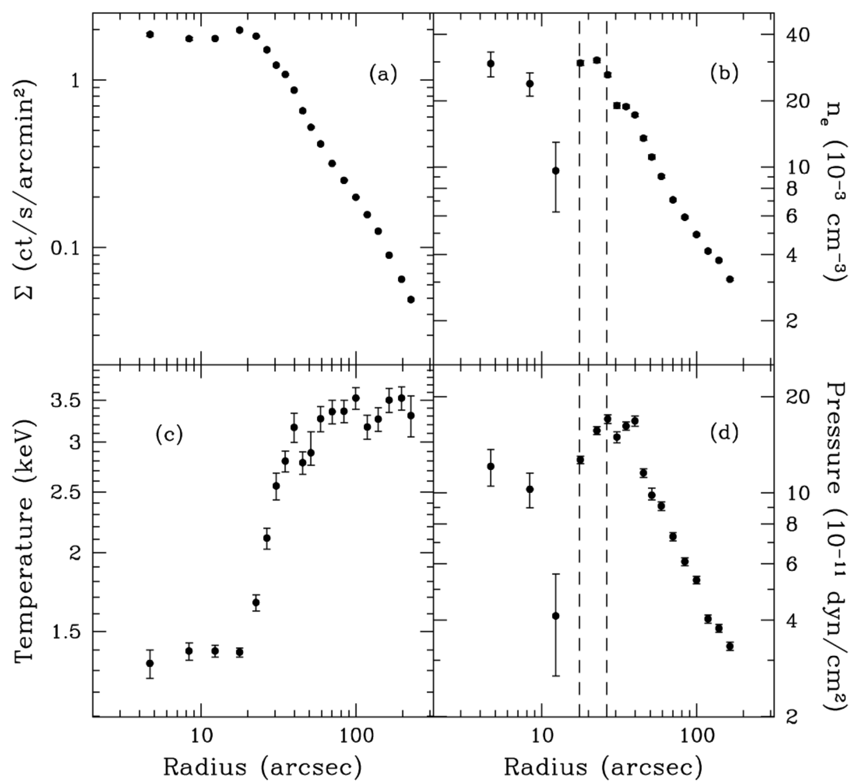
With a little algebra and the definition of pressure - the total cluster mass can be expressed as

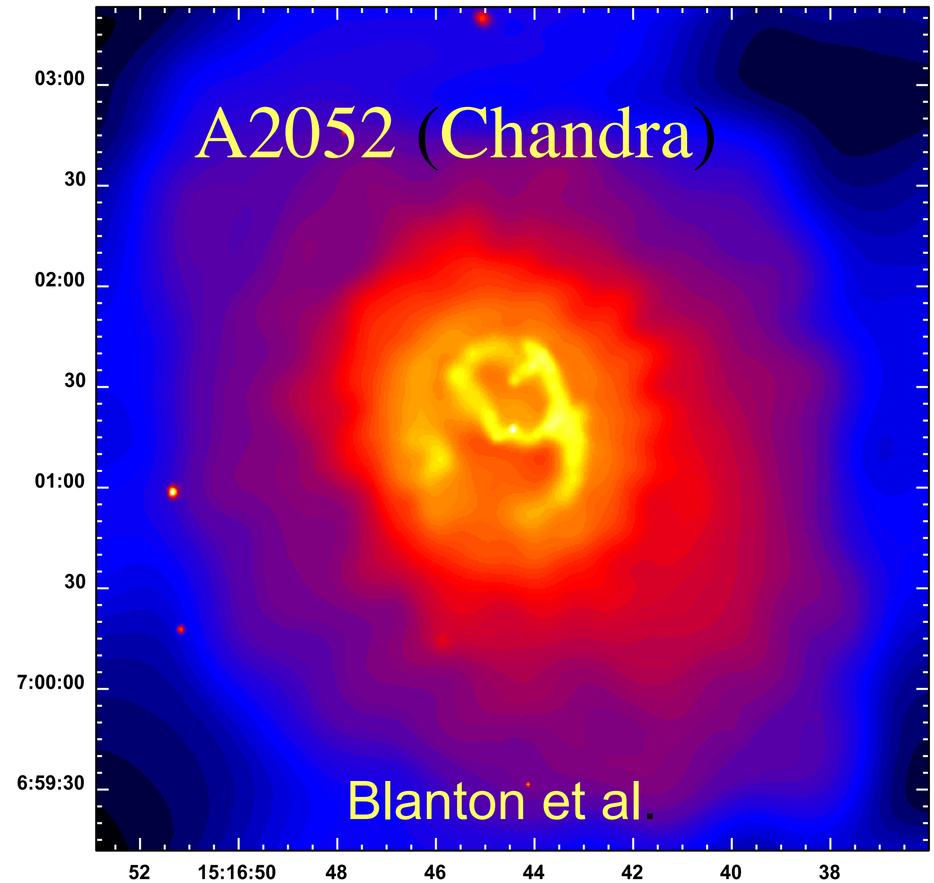
$$\boxed{M(r) = kT_g(r)/\mu G m_p)\mathbf{r}\,(d\ln T/dr + d\ln\rho_g/dr)}$$

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 in Image and Temperature

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





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

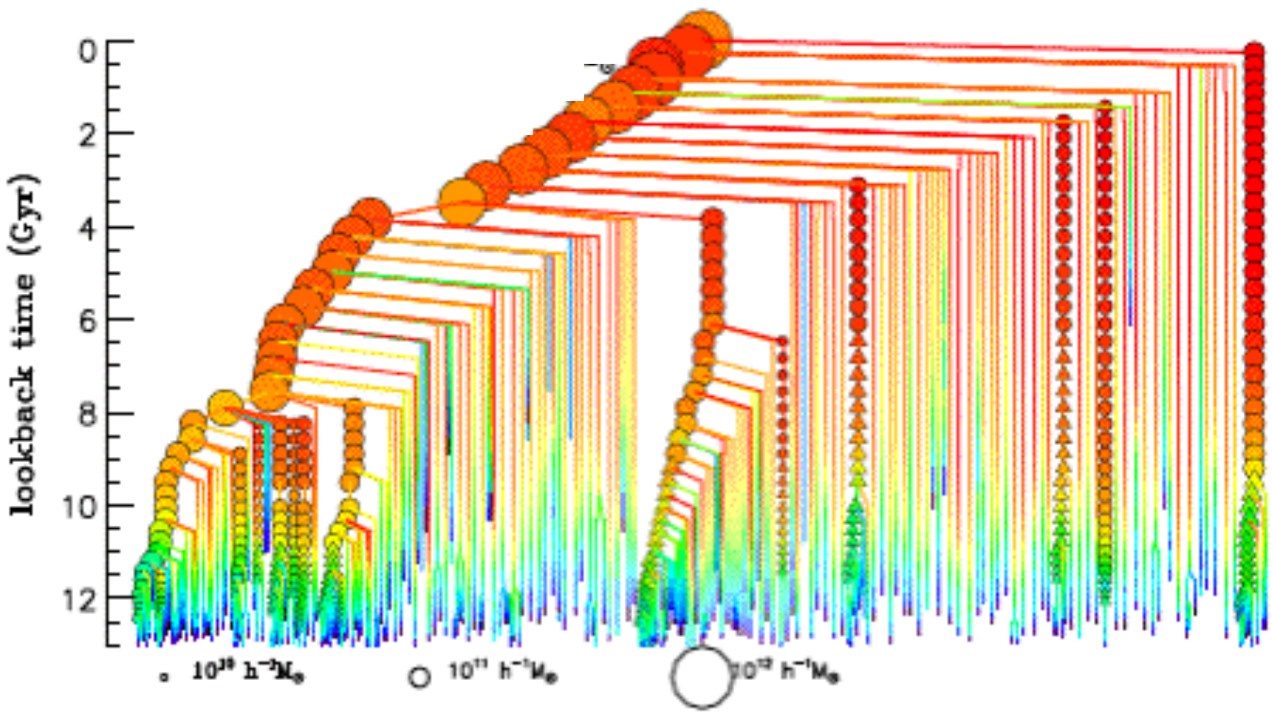


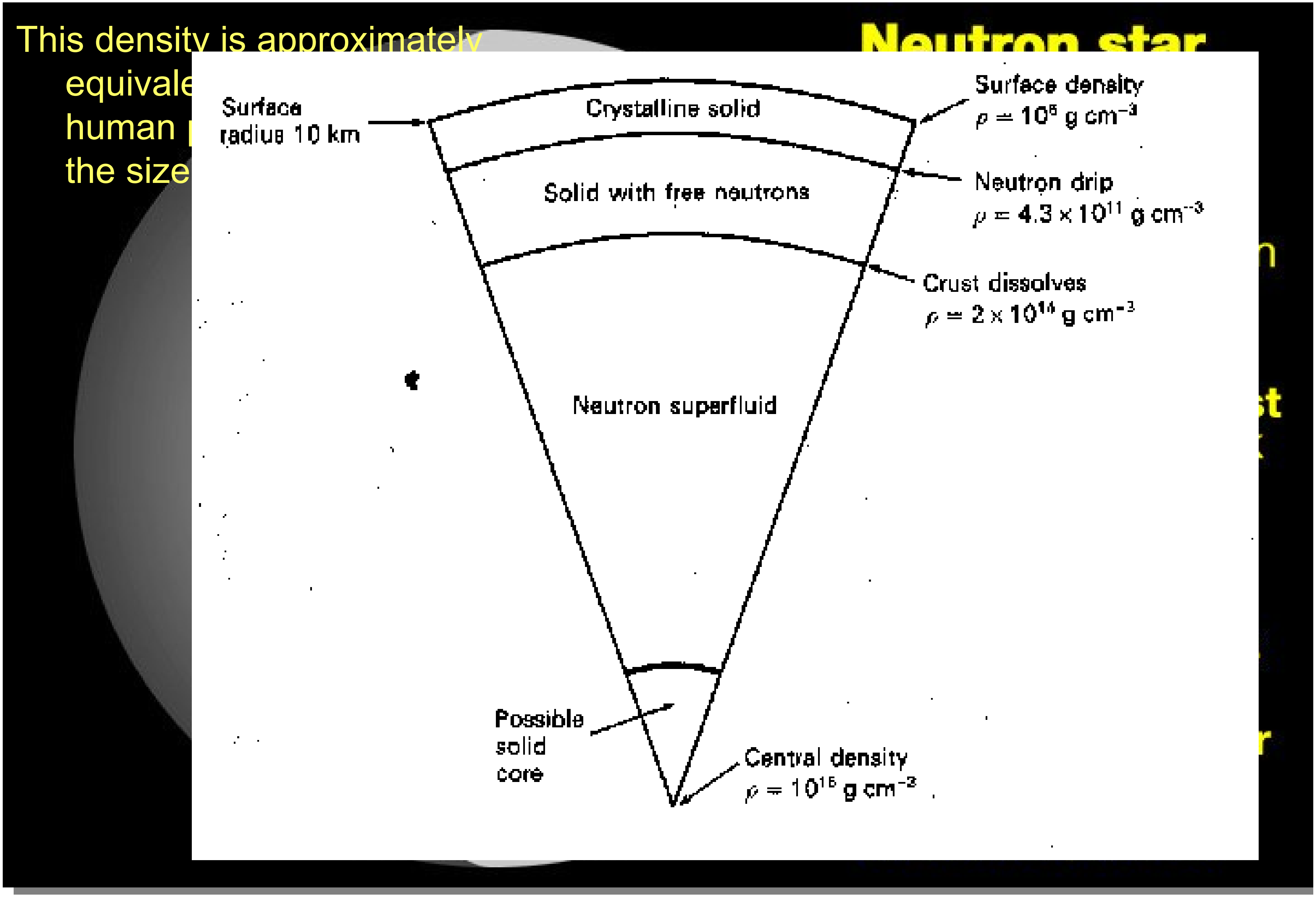
Figure 1. BCG merger tree. Symbols are colour–coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than $10^{10}\ M_\odot\ h^{-1}$ are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. 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; also the period derivatives are small and for radio pulsar periods always increase (slow down)
    - All characteristic timescales scale as $\rho^{-1/2}$ (ρ is density)

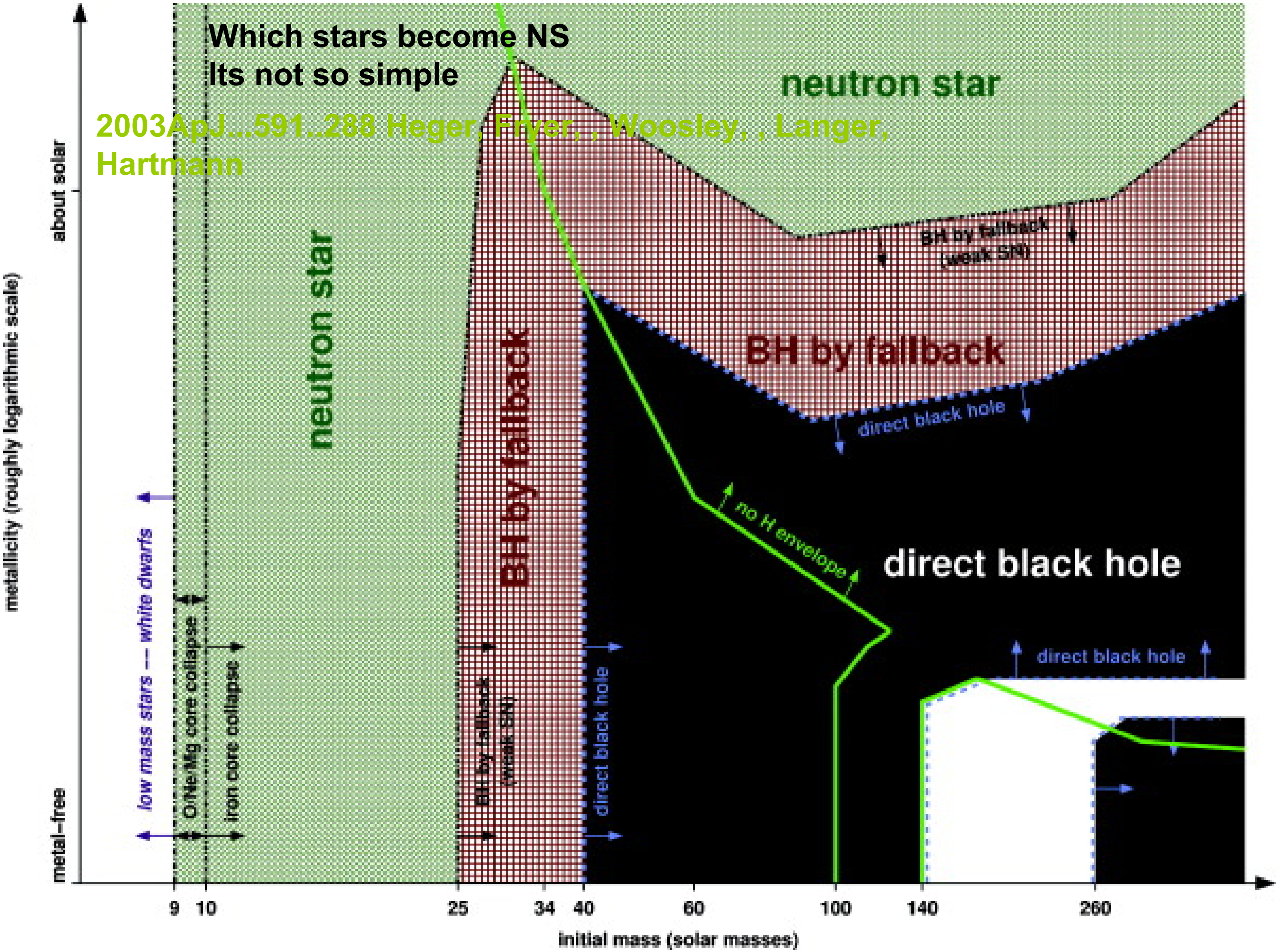
      rotation frequency ω=sqrt(GM/r^3) =sqrt($G\rho$)
    - Shortest periods ~1.5ms- light travel time arguments give a size (ct~ 500km)
- White dwarfs with $\rho \sim 10^7 – 10^8$ gmcm-^{3} maximum rotation periods $P = 2\pi/\Omega \sim 1–10$ s
- To get periods of ~1ms need $\rho \sim 10^{14}$ gmcm-^{3}
- What are the sources of energy?
  - Spin down
  - accretion

Inside Neutron Stars



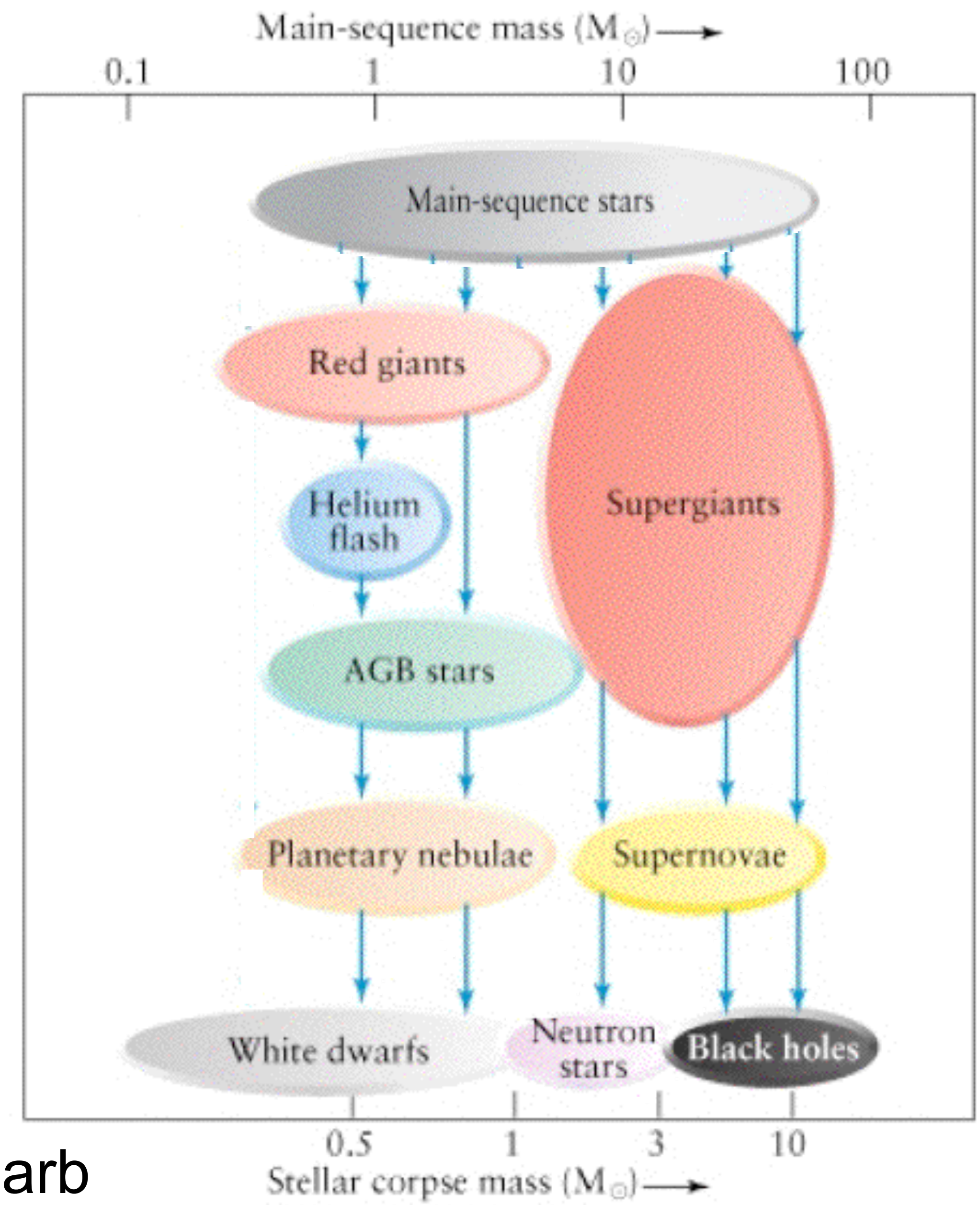
Which stars become NS
Its not so simple

2003ApJ...591..288 Heger, Fryer, , Woosley, , Langer, Hartmann



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

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 ($6.6\mathrm{x}10^{-25}$ 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

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

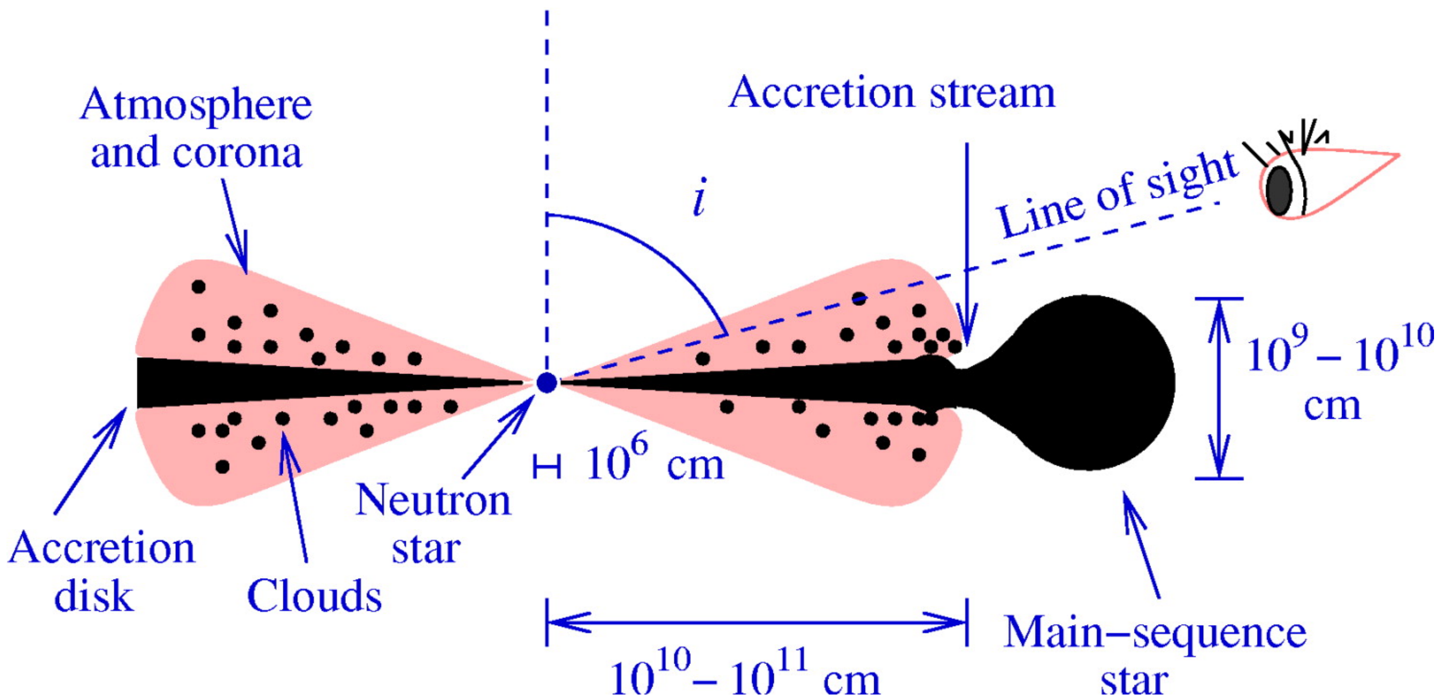
Very efficient process Energy $\sim GM/R = 1.7 \times 10^{16}$ (R/10km) $^{-1}$ J/kg

$\sim 1/2mc^2$

Nuclear burning releases $\sim 7 \times 10^{14}$J/kg

(0.4% of mc^2)

Geometry of heated accretion disk + coronal in LMXB



Jimenez-Garate et al. 2002

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

Gravitational potential energy is

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.

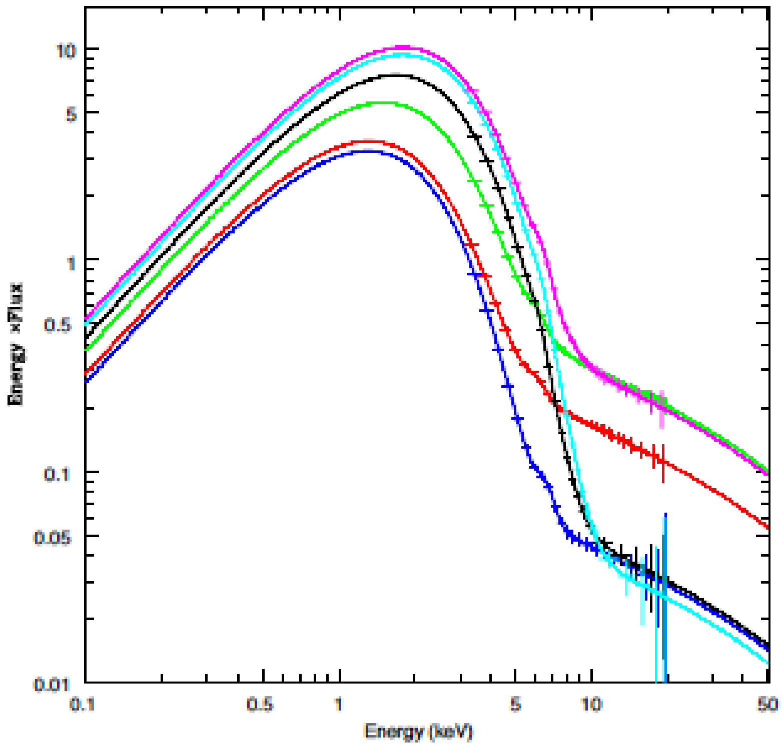
assuming the annulus radiates its energy as a blackbody

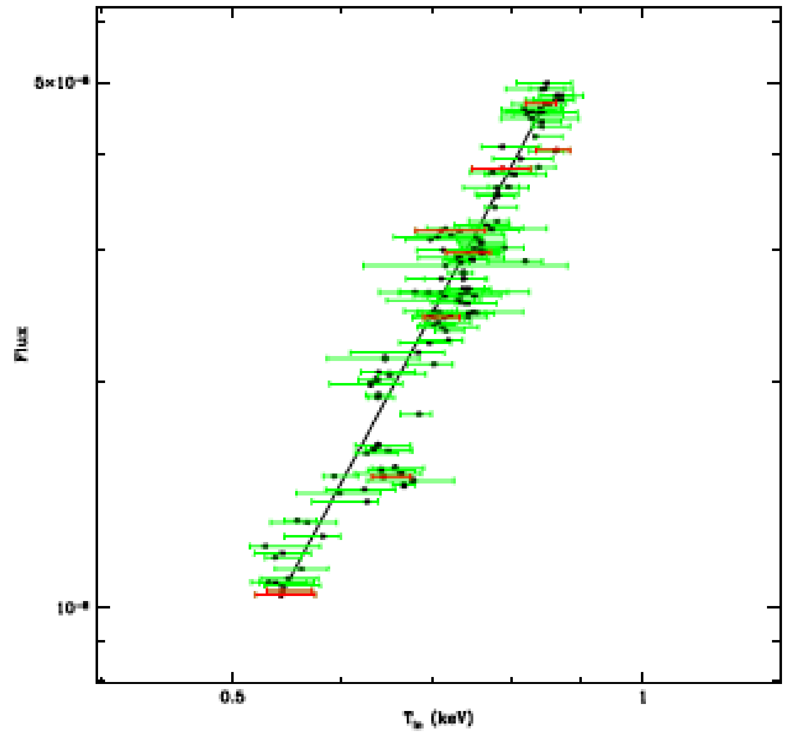
L = σAT^4. The area of the annulus is 2πrdr, and since

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}$

Do They Really Look Like That





- X-ray spectrum of accreting Neutron star at various intensity levels
- 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:
- As a result, almost all of 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 see pulsations in the X-rays.

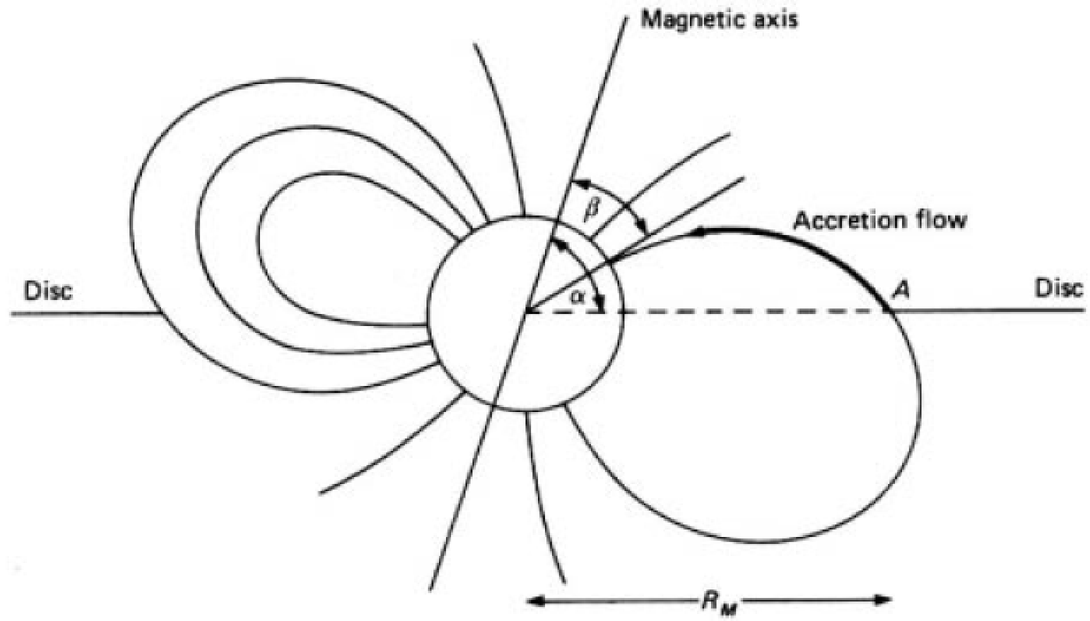


Figure 8: Accretion in a strong ($\sim 10^{12}$ Gauss) magnetic field. Note that the accretion disk is held off the neutron star surface by the centrifugal barrier formed by the rotating magnetosphere.[23]

Cominsky (2002)

- Putting in typical numbers the radius where magnetic and material stresses are equal is 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

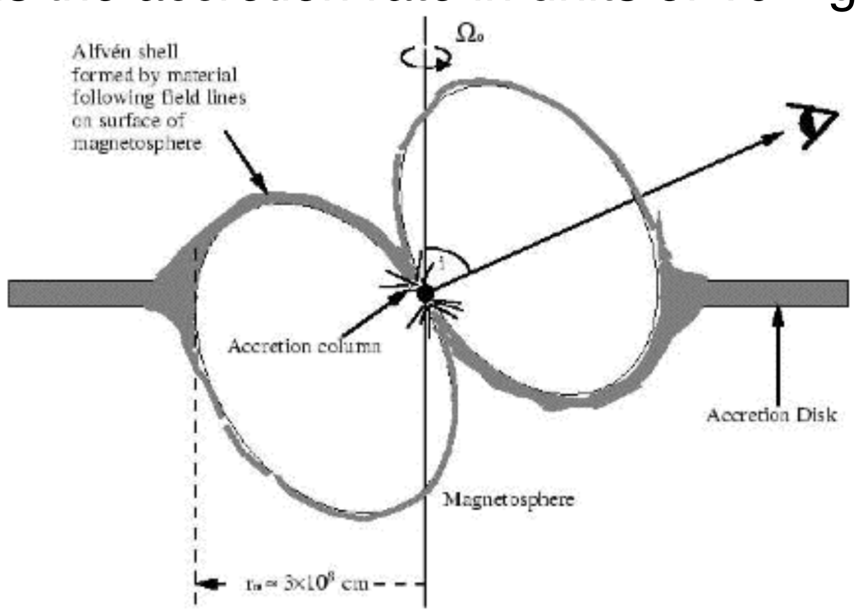
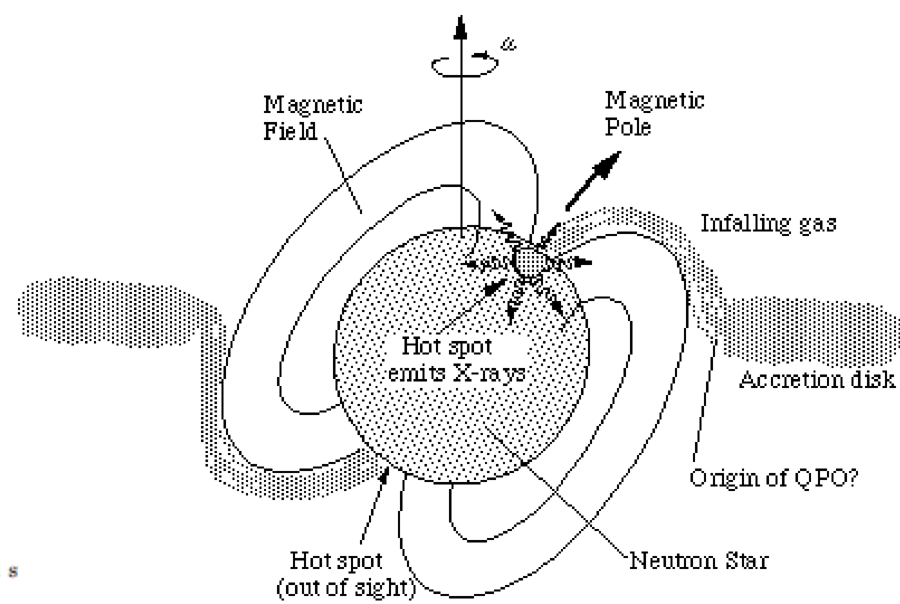


Fig. 1.— Rough sketch of the accretion flow in a disk being picked up by a strong neutron s magnetic field. From http://lheawww.gsfc.nasa.gov/users/audley/diss/img203.gif



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 with K_o is measured from optical spectra for the companion

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

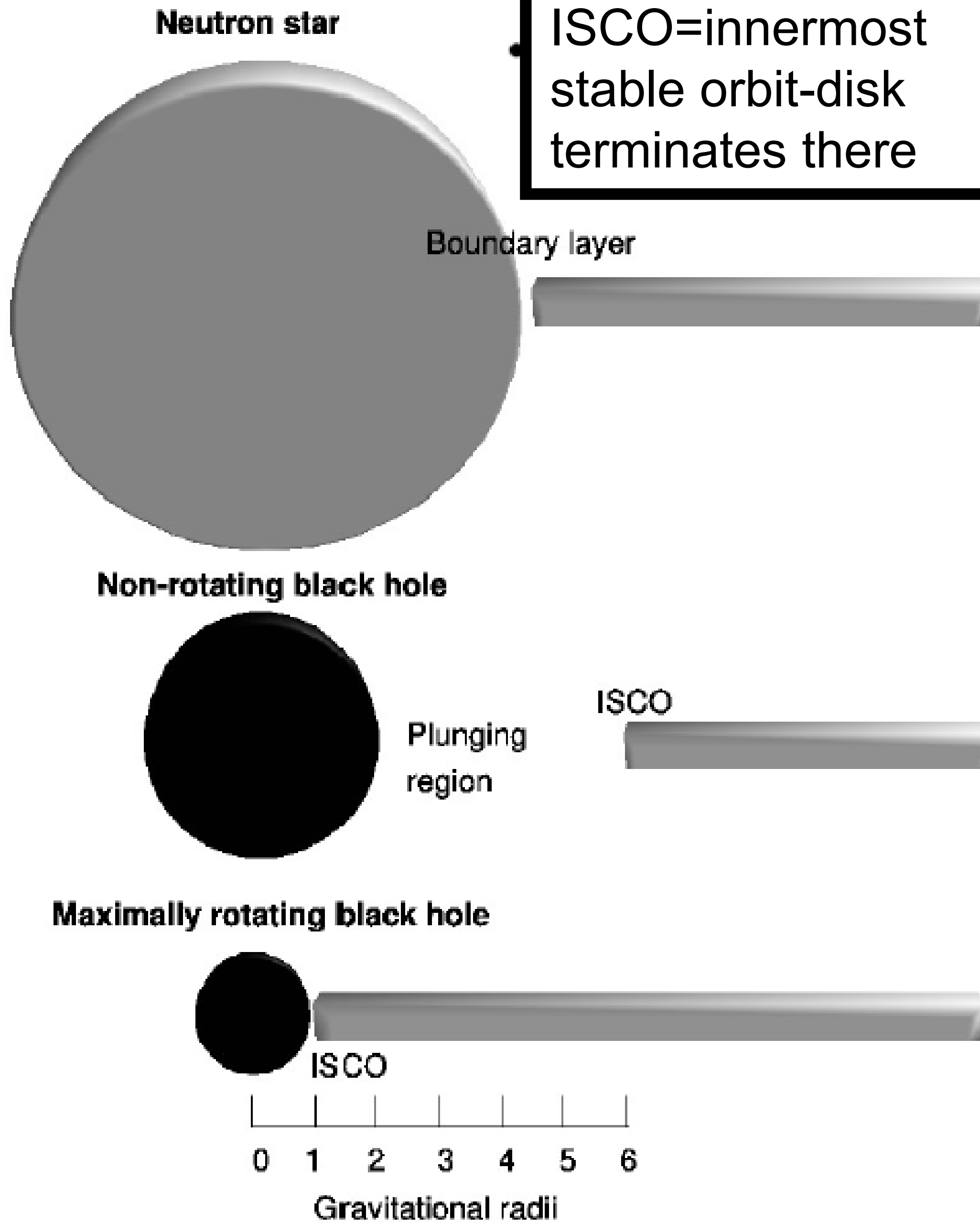
What about spin ?

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

ISCO=innermost stable orbit-disk terminates there



R. Fender 2007

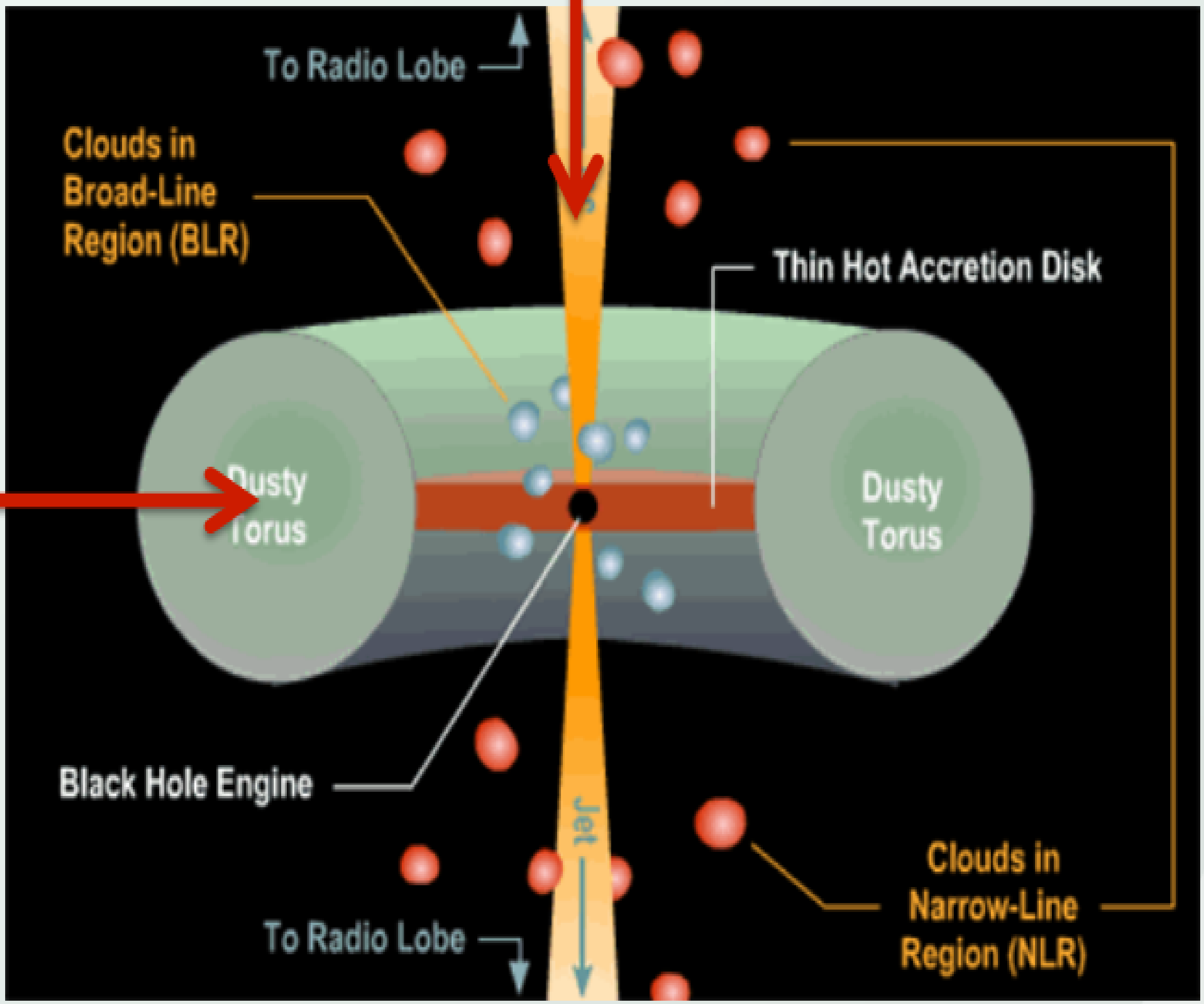
UNIFICATION MODEL of AGN

TYPE 1

DUSTY TORUS

TYPE 2

orientation effect

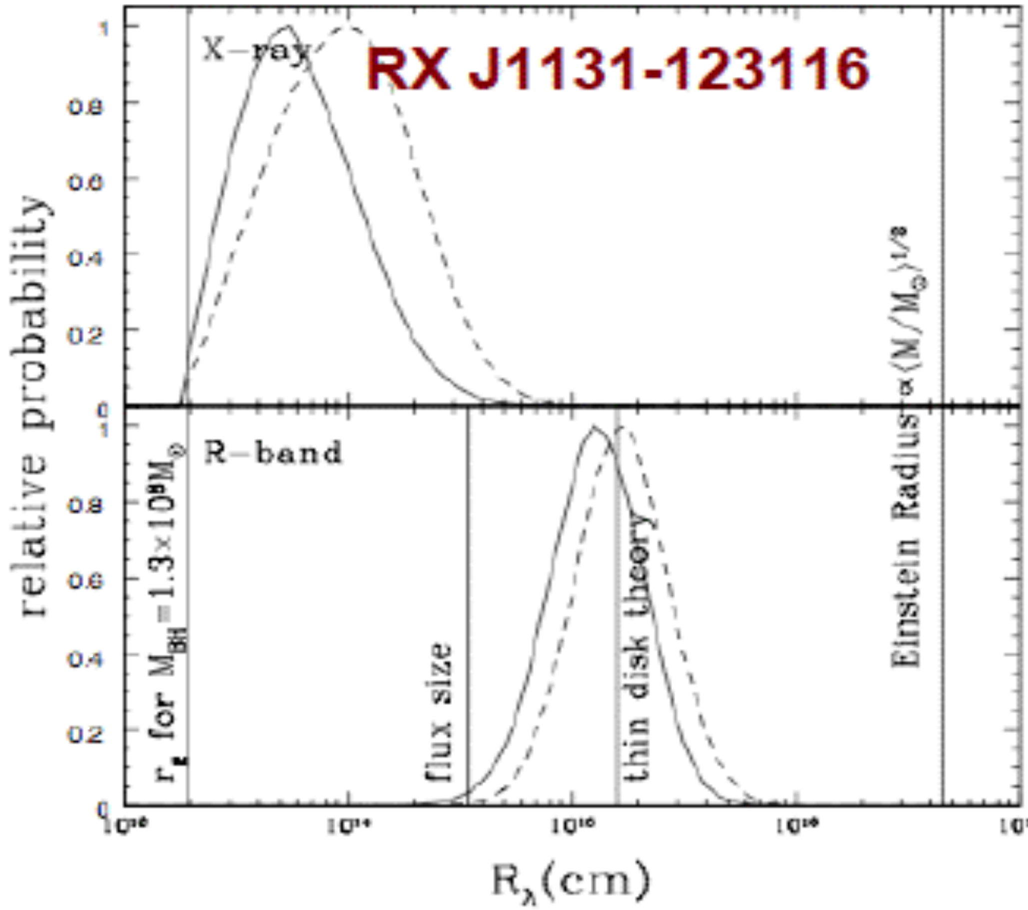


- Anna Feltre

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

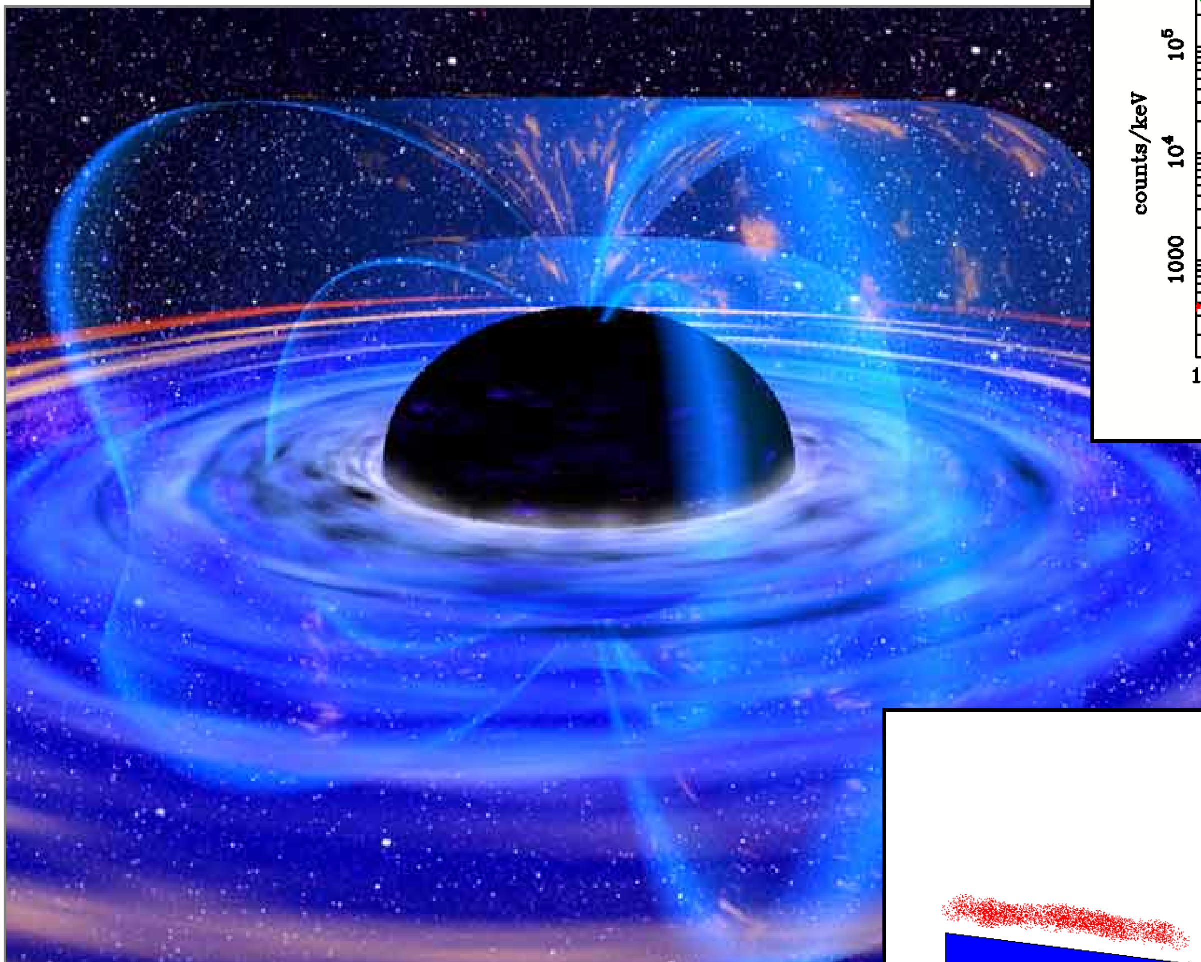
- microlensing observations of a few QSOs have 'resolved' the x-ray and optical sources
- The optical source size and dependence of luminosity on wavelength are consistent with standard disk theory

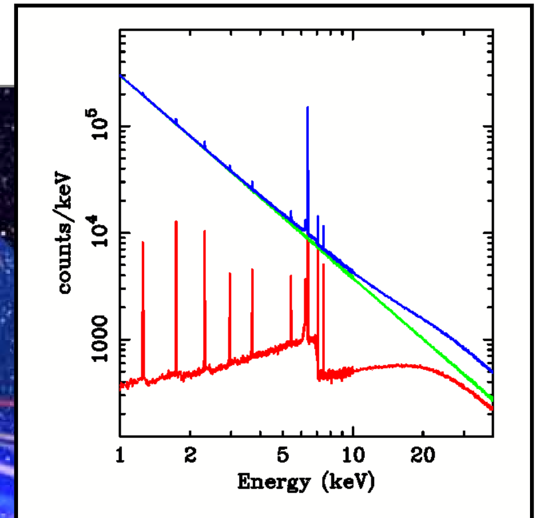
MICROLENSING



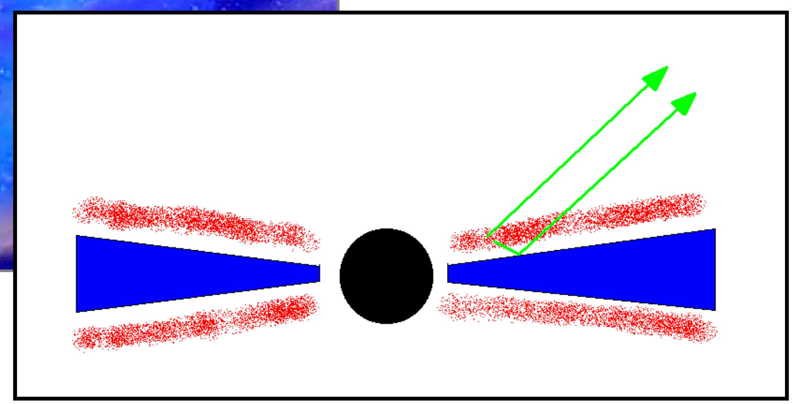
X-rays from 10 R_g (Optical 70 R_g)

Chartas et al. 2009
Dai et al. 2009





Reynolds (1996)



- X-ray “reflection” imprints well-defined features in the spectrum

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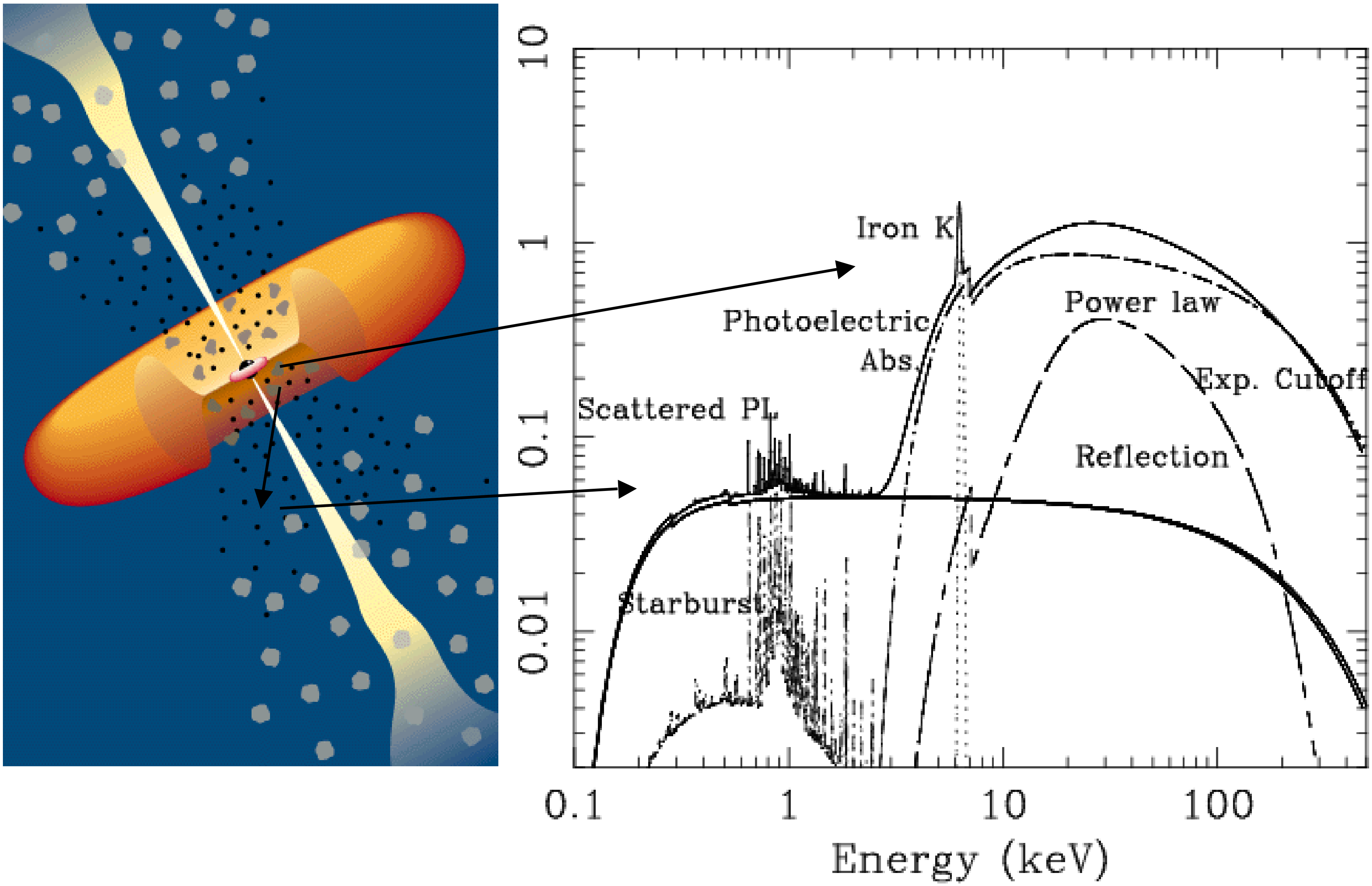
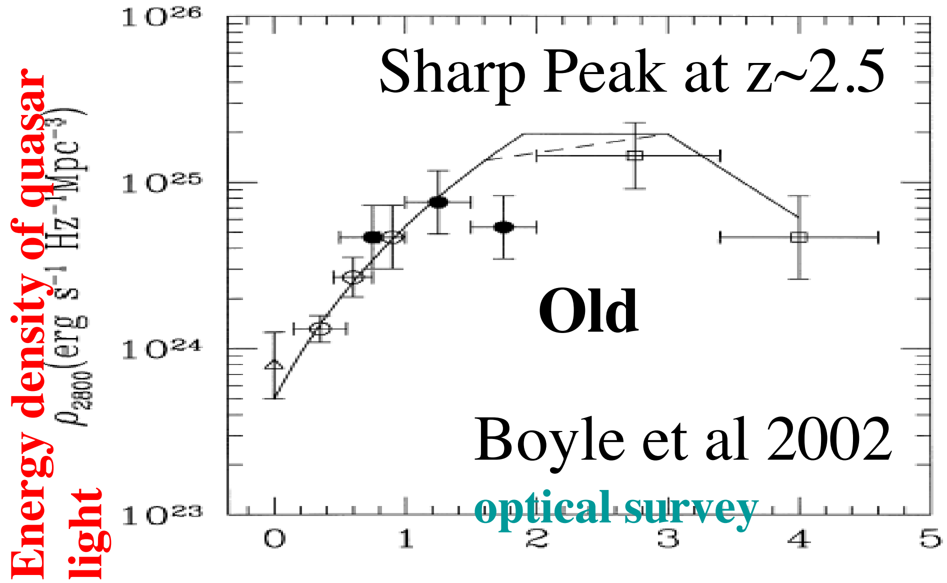
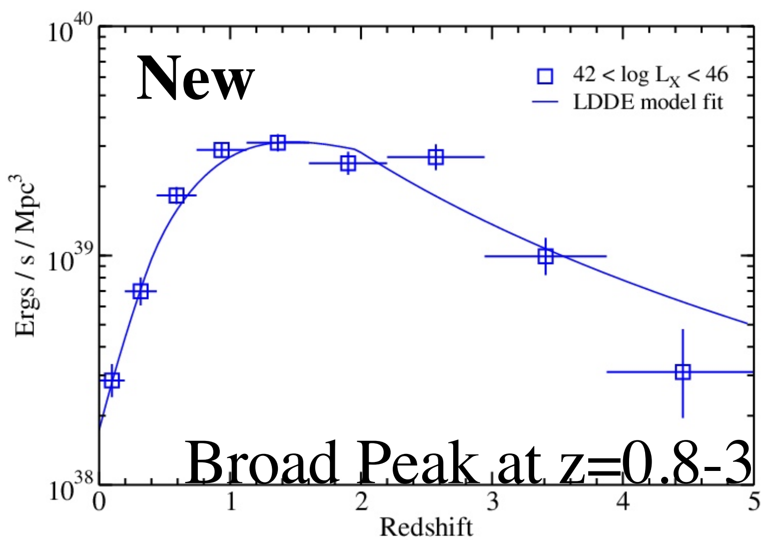


Iron K
Photoelectric
Abs.
Power law
Exp. Cutoff
Scattered PL
Reflection
Starburst
10
1
0.1
0.01
0.1
1
10
100
Energy (keV)

AGN populations evolve- more numerous and luminous out to z~1

- Discovery that most of the AGN in the universe are obscured
- Strong indications that AGN have had a major influence on the formation and evolution of structure



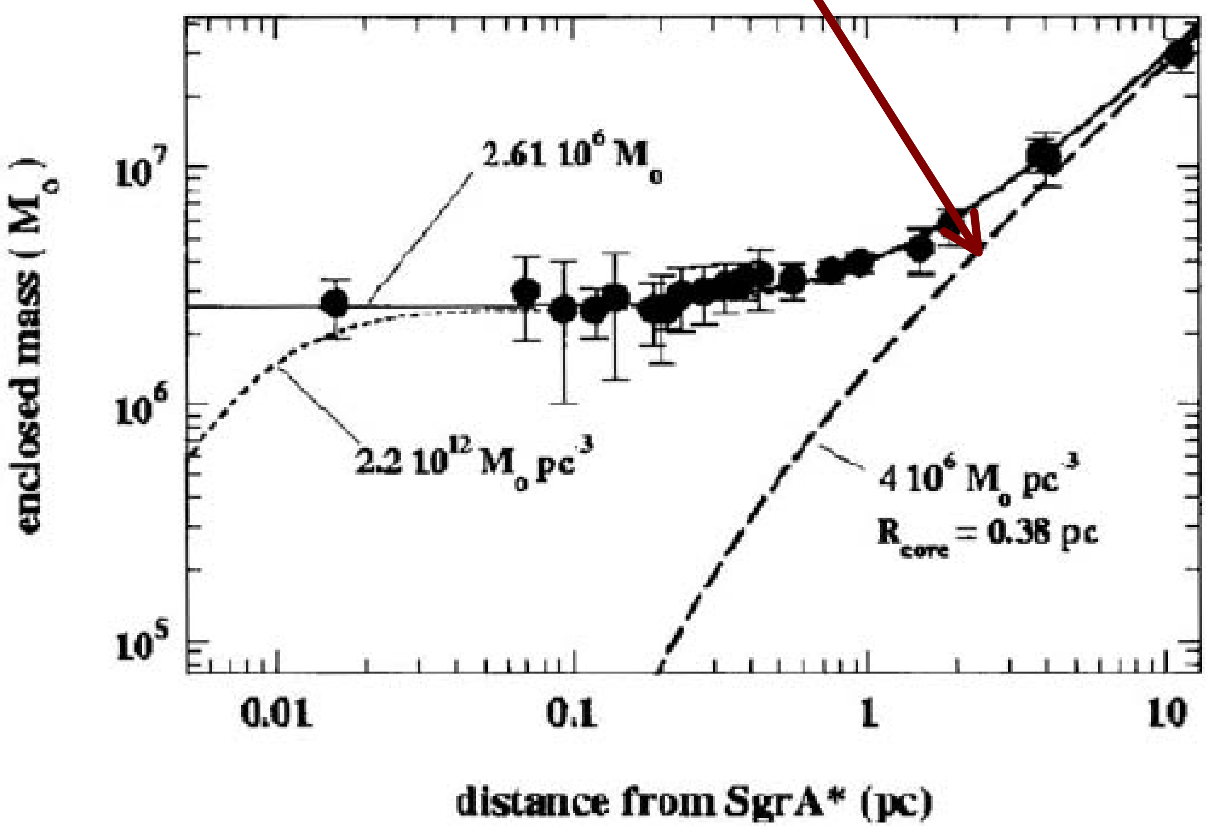


Yencho et al 2009- xray survey

MW Center

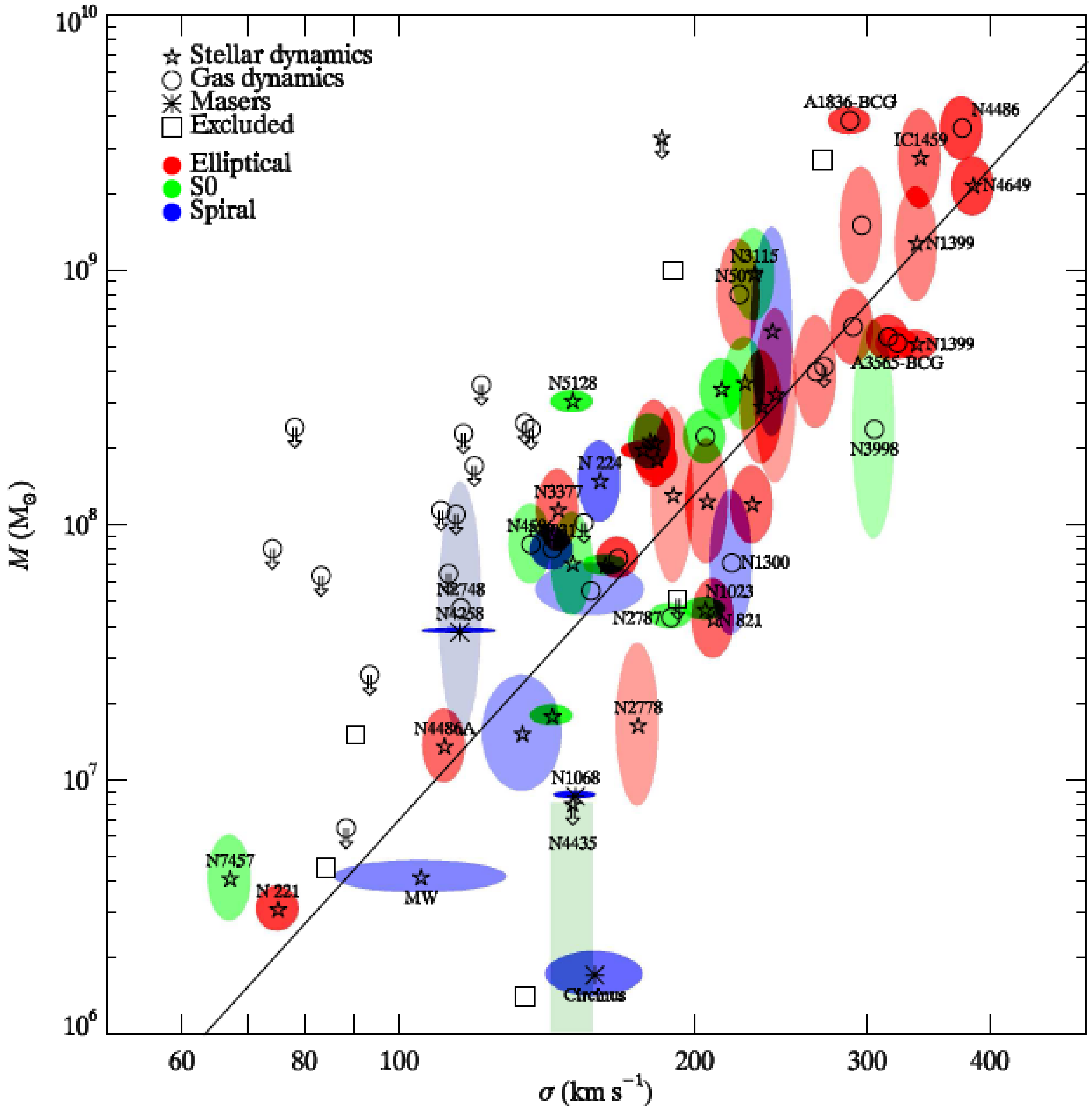
- Two teams led by R. Genzel and A. Ghez have measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is $>10^{12} M_{\odot}/pc^3$

Predicted mass from models of the Milkway



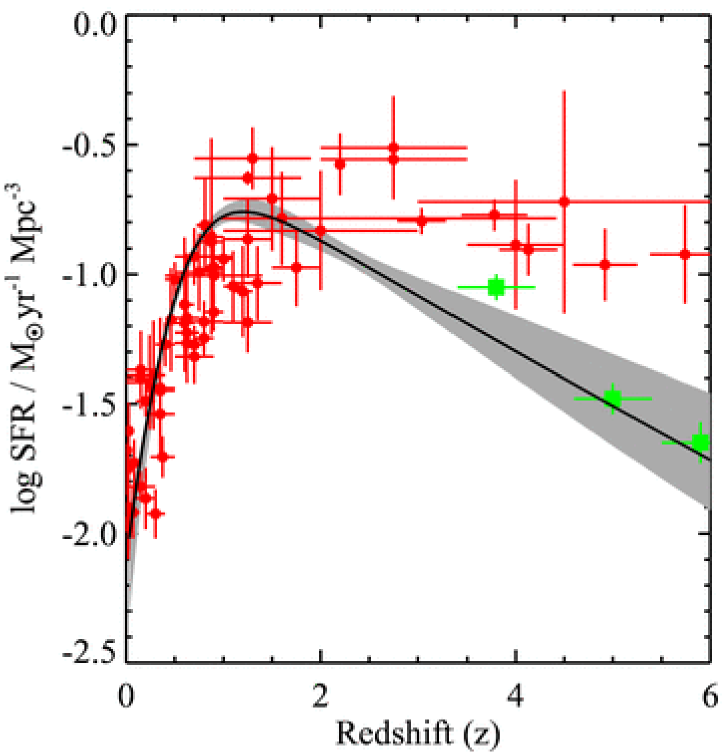
•As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass $2.6 \times 10^6 M_{sun}$, and density $20 M_{sun} pc^{-3}$ or greater can not be stable for more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

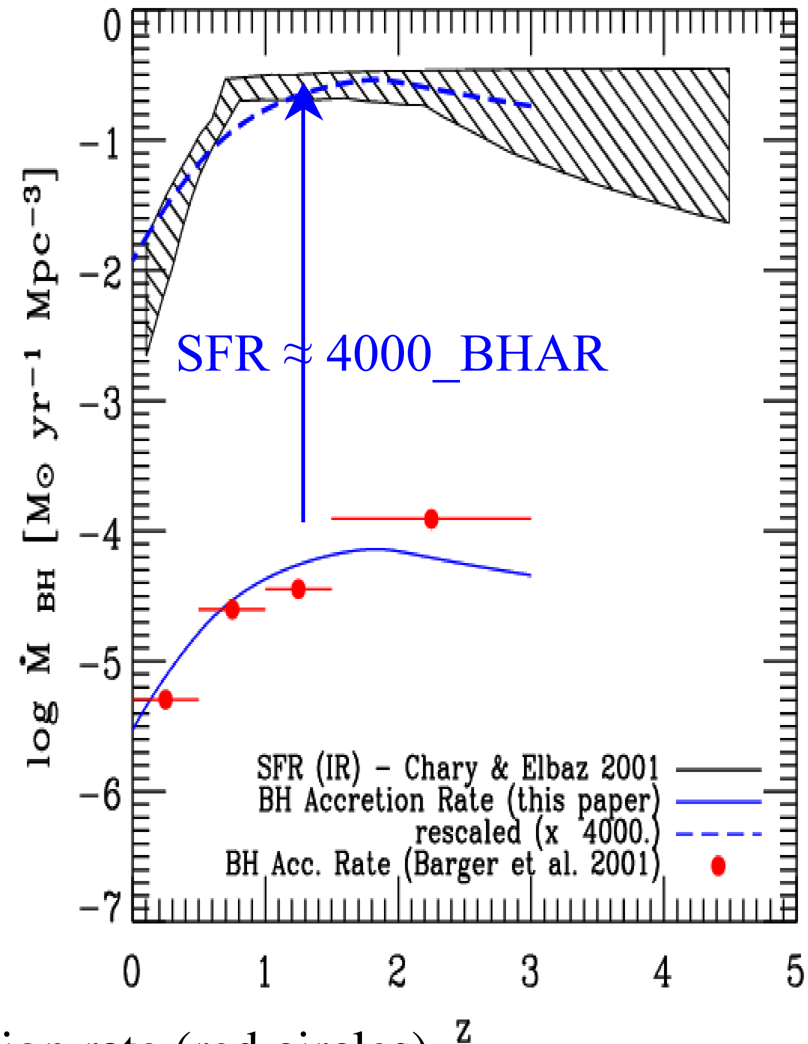
- All the Nearby Galaxies with Dynamical Masses for their Central Black Holes (Gultekin 2009)
- There seems to be a scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- Galaxies know about their BH and vice versa



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

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

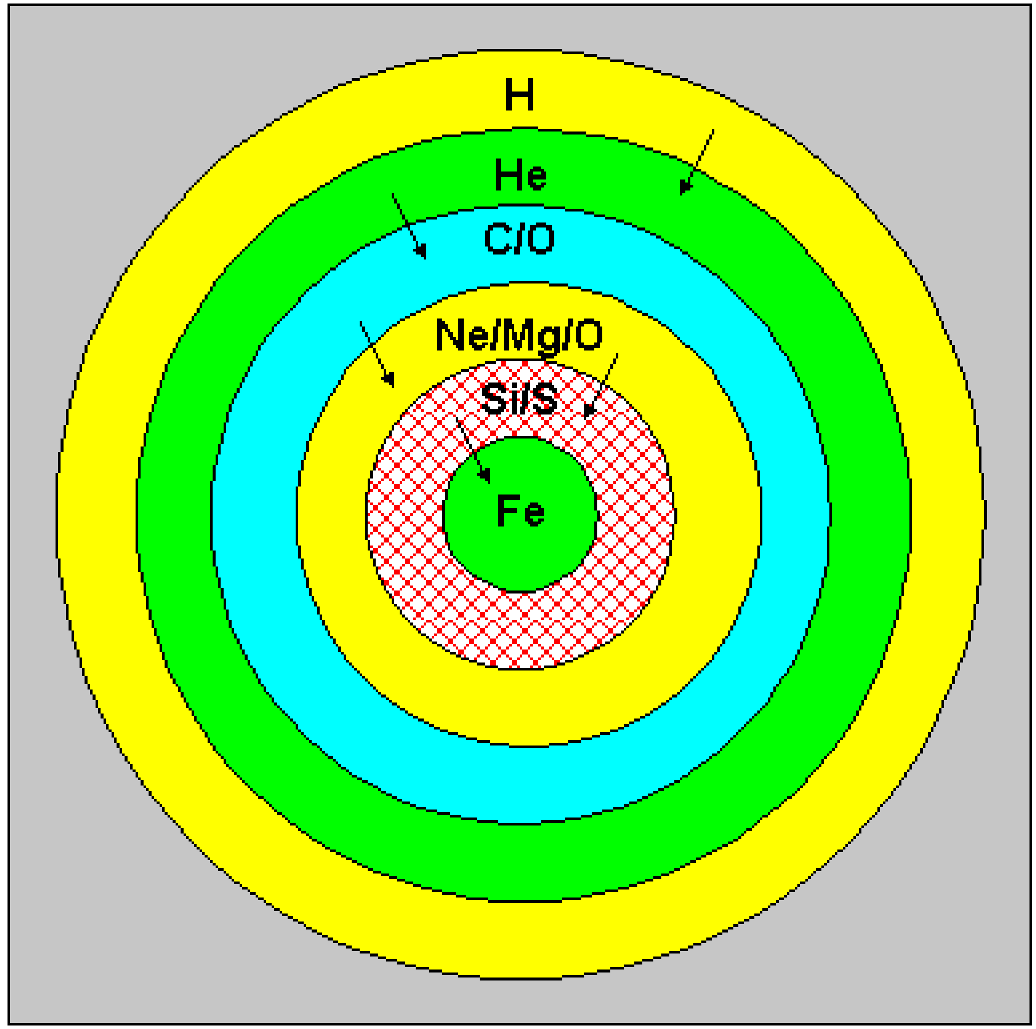
Supernova Explosions

- 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

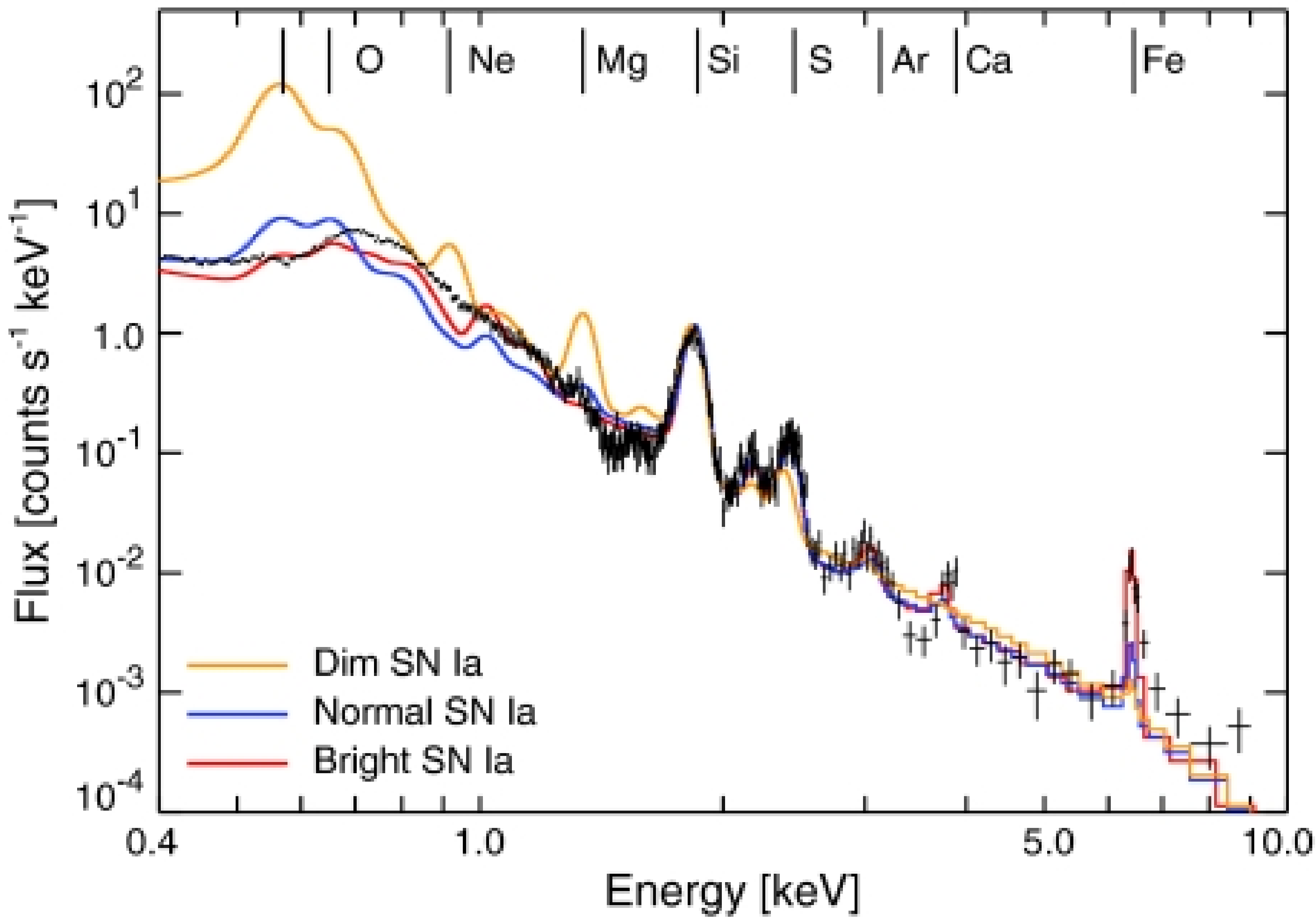


Initially in core-collapse supernovae (type II) the energy comes from the gravitational energy freed in the collapse- later times from radioactive decay

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

C. Badenes

Proc Natl Acad Sci U S A. 2010 107(16): 7141–7146.



Remnant Evolution

Free Expansion

Ejecta expand without deceleration r~t (see movie Rudnick et al., 1996, BAAS, 188.7403.) - 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

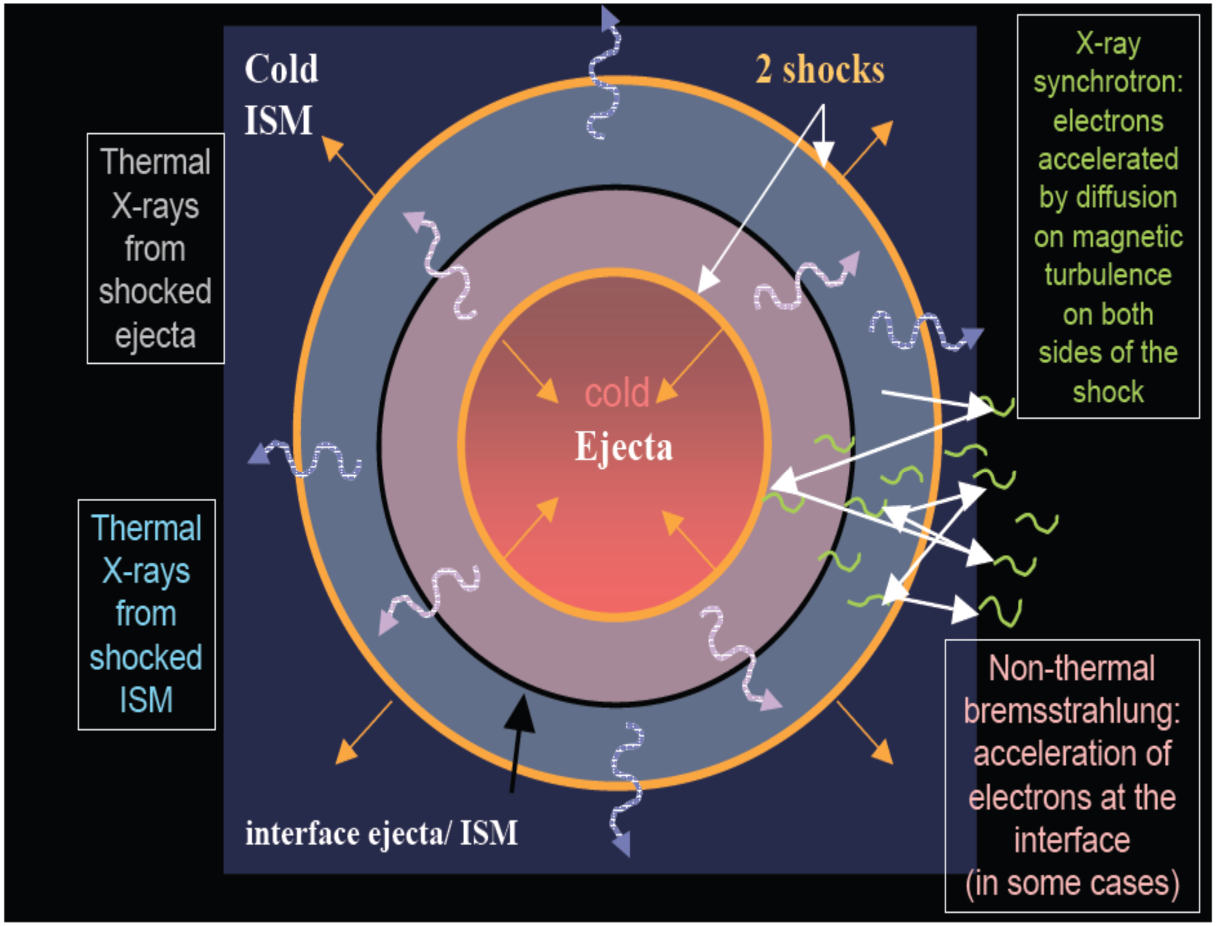
Dissipation of remnant energy into ISM

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

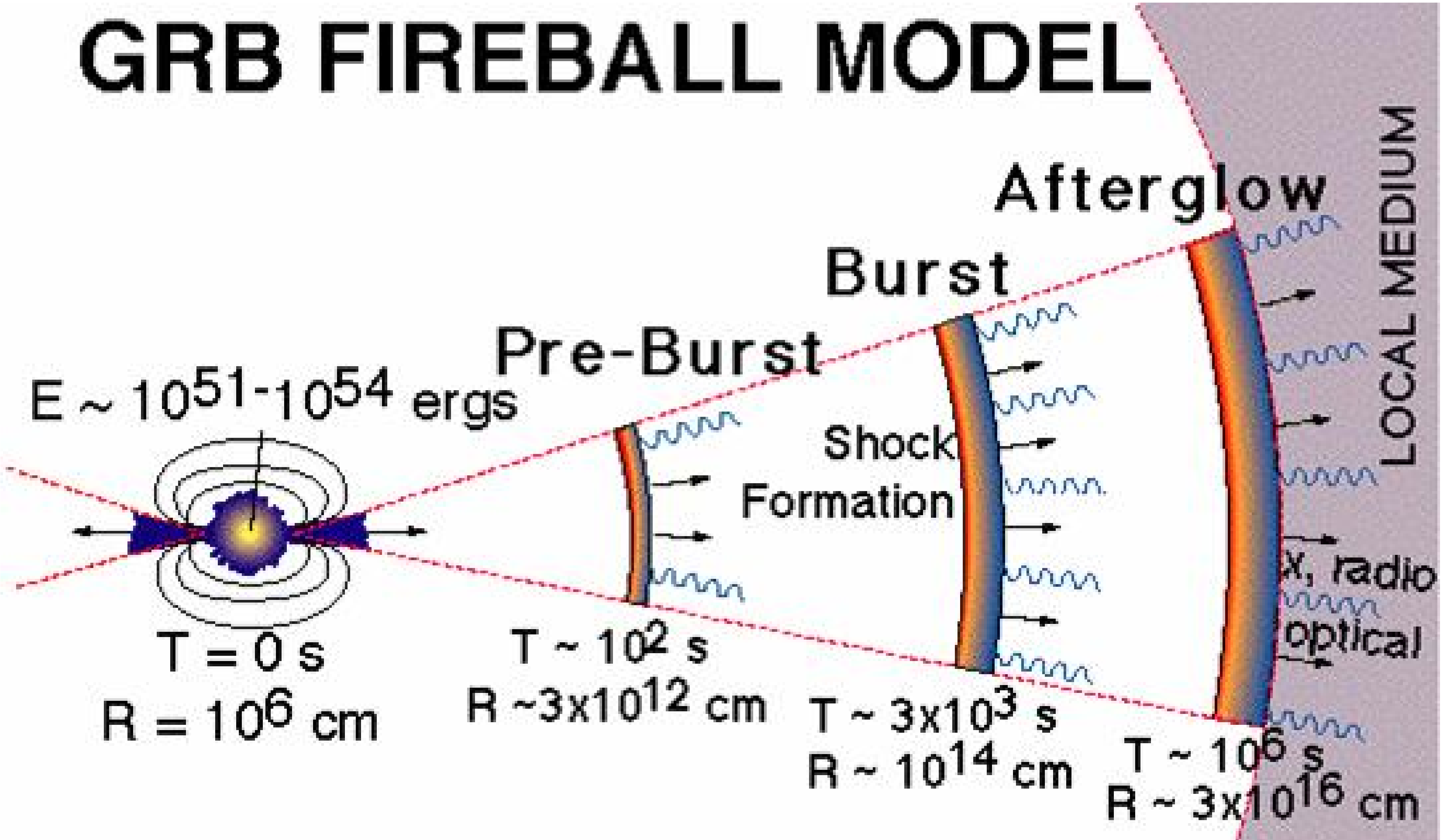
Nice analogy- ping pong ball bouncing between descending paddle and table

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 3×10^{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)

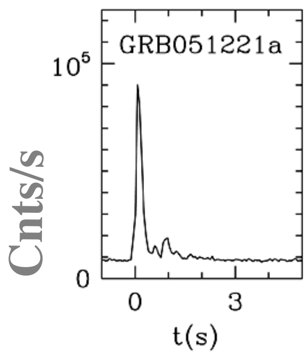
- discovered by U.S. spy satellites (1967; secret till 1973)
- have remained one of the biggest mysteries in astronomy until 1998 (isotropic sky distribution; location: solar system, Galactic halo, distant Universe?)
- discovery of afterglows in 1998 (X-ray, optical, etc.) with redshifted absorption lines has resolved the puzzle of the location of GRBs $\rightarrow$ 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 $2 \times 10^{47}\,$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) $\rightarrow$ fireball model
- relativistic energy $\sim 10^{46} - 10^{47}\,\mathrm{J}\,\epsilon^{-1}\,\mathrm{f}_{\Omega}$ (ϵ: efficiency, f_{Ω}: beaming factor; typical energy $10^{45}\,$J?)
- event rate/Galaxy: $\sim 10^{-7}\,\mathrm{yr}^{-1}\,(3 \times 10^{45}\,\mathrm{J}/\epsilon\,\mathrm{E})$

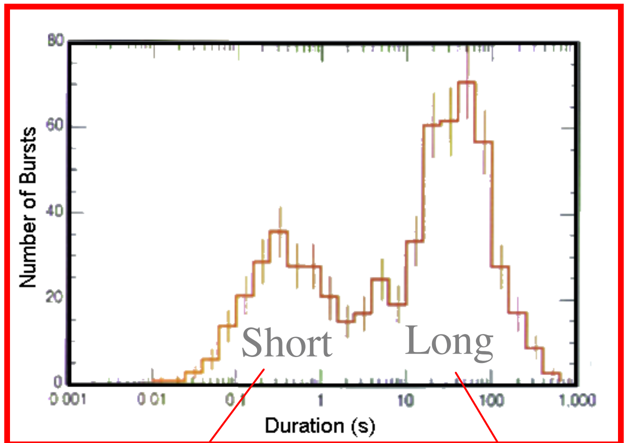


γ-ray bursts can be produced if part of a relativistic bulk flow is converted back into high-energy photons through particle acceleration in a relativistic shock between the outflow and the surrounding medium

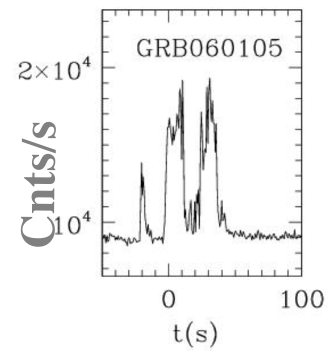
Short vs Long GRBs

Short GRB

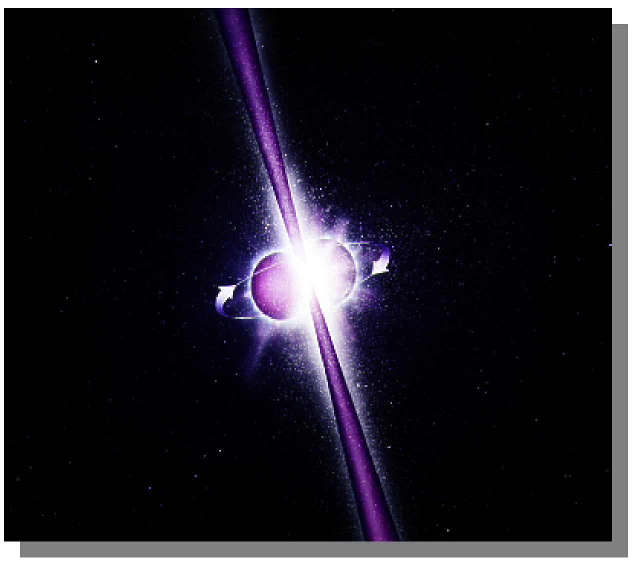


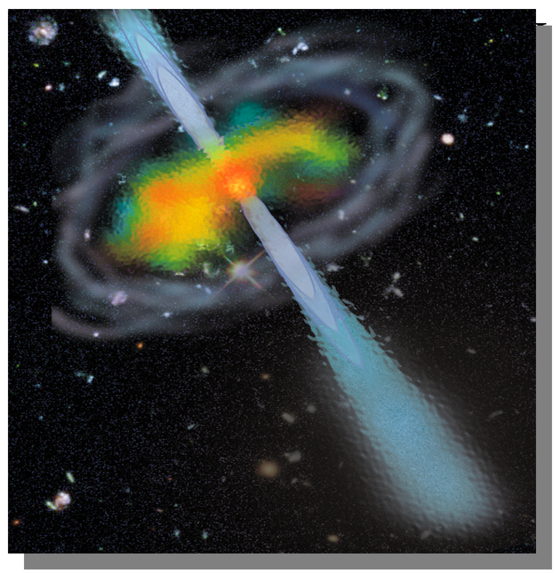


Long GRB



Short GRBs in non-SF elliptical galaxies

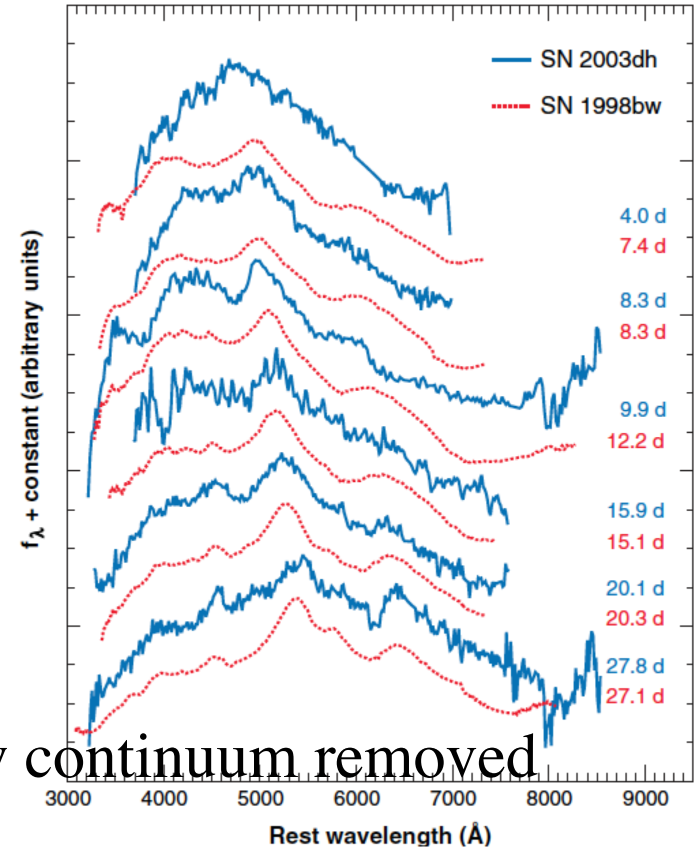




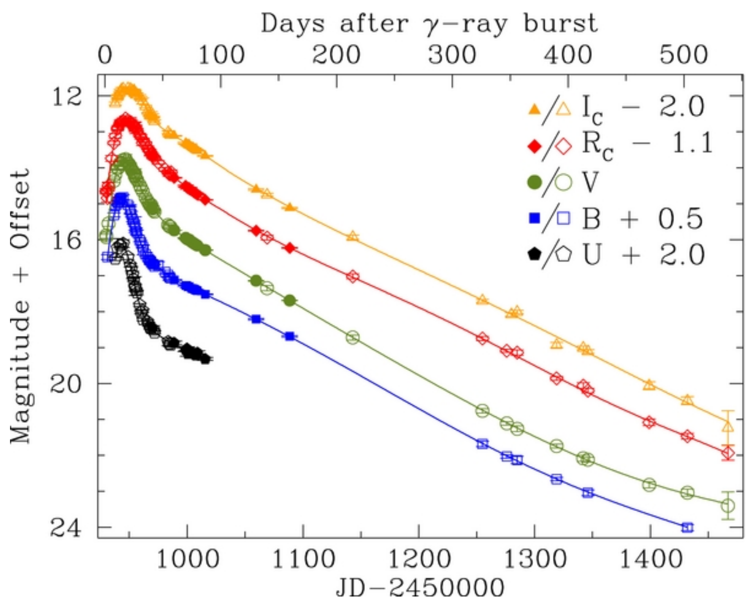
Long GRBs in SF galaxies

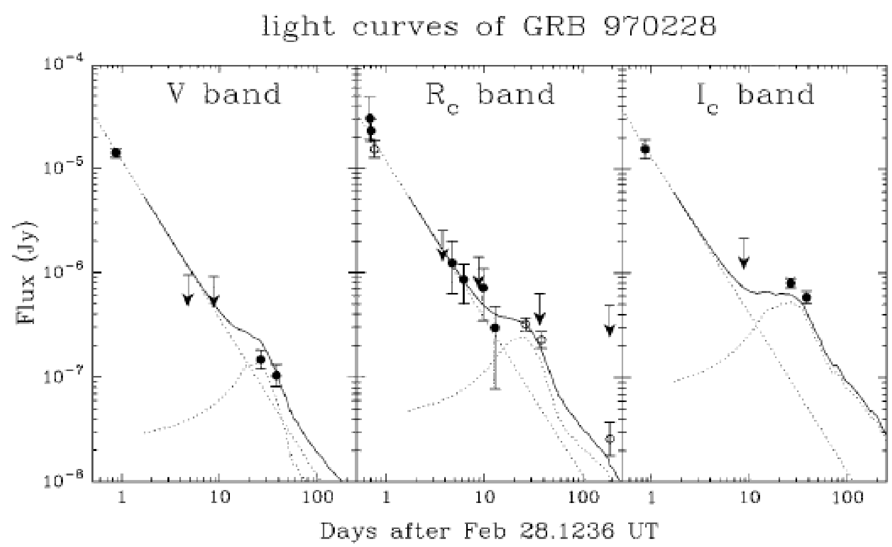
Long Burst Nature of Progenitor

- 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)
- Right now theoretical, but no observational support
- Based on their observed properties
- SGRBs are cosmological in origin ($z > 0{:}1$)
- have a beaming-corrected energy scale of $\sim 10^{49}$–10^{50} erg
- lack associated supernovae
- occur in a mix of star-forming and elliptical galaxies
- have a broad spatial distribution around their

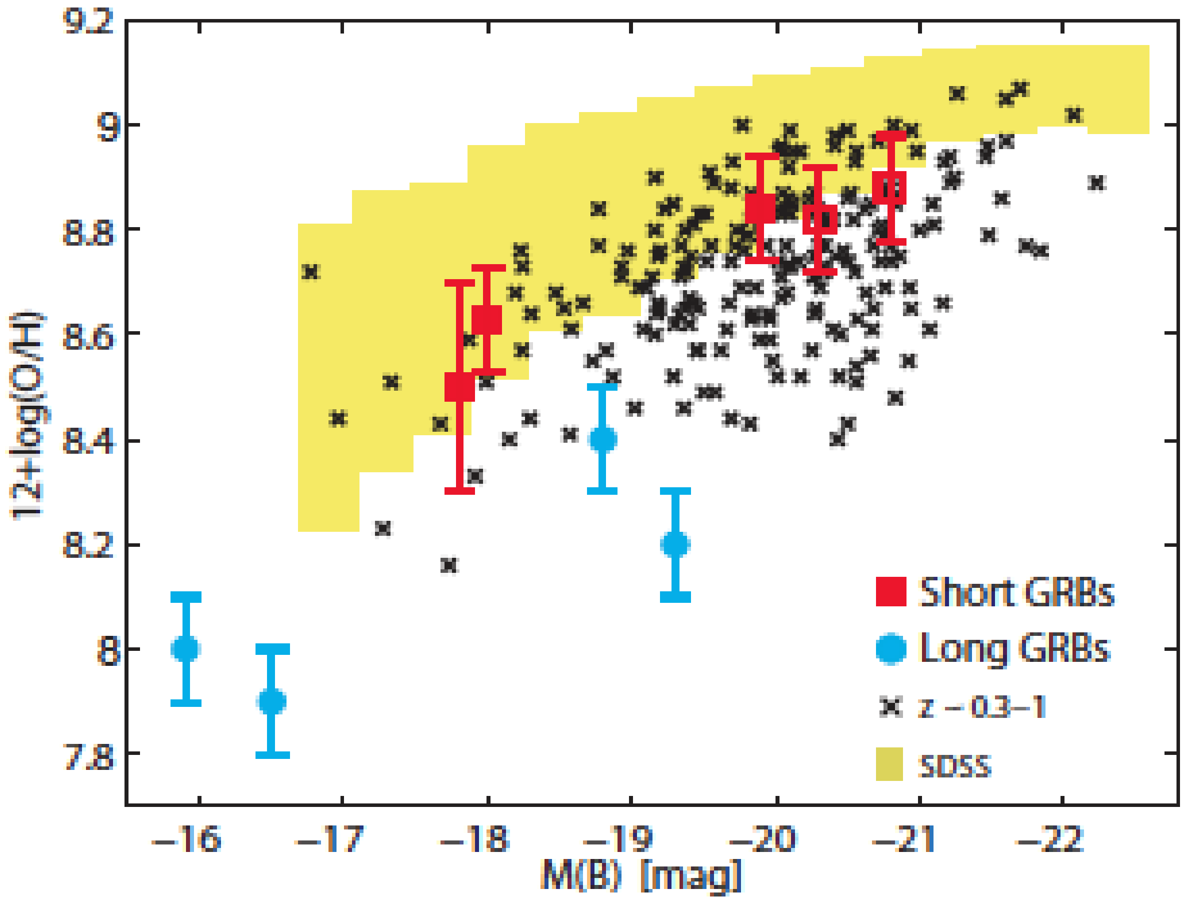
hosts, with some events offset by tens of kpc

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