Key questions on AGN

• What is energy source for AGN?

• How does gas manage to get into the BH?

• How much does a BH need to feed to make an AGN?

• How do we know the BHs powering AGN must be massive?
Q: How can a black hole emit lots of energy?

A. It can’t, but some stuff falling TOWARD the black hole gets shot outwards

B. Energy can go into 1 black hole and out another, via a wormhole.

C. It can’t, but stuff falling in can emit lots of energy just before it goes in

D. By the process of Hawking radiation
Q: How can a black hole emit lots of energy?

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D. By the process of Hawking radiation
The energy problem in AGN

$L \approx 10^{12} \ L_{\text{Sun}}$ from $r < 100 \ \text{AU}$

*How does one get so much photon energy from such a small volume?*
Can energy source of AGN be nuclear?
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NO – 2 reasons …
Can energy source of AGN be nuclear?

NO – 2 reasons …

1. *Ultradense star clusters are dynamically unstable*

2. *Low efficiency of nuclear energy*
Energy Efficiency = \[
\frac{\text{Energy output}}{\text{Total mass-energy of input ingredients}}
\]

- Chemical (gas, oil, biofuel) \(\sim 10^{-7}\%\)
- Nuclear (fusion, fission) \(\sim 1\%\)
- Gravity – small fall (hydroelectric) \(\sim 10^{-7}\%\)
- Gravity – big fall (black hole/quasar) \(\leq 30\%\)
- Matter-antimatter annihilation 100%

(but hard to get the stuff!)
Q: Something initially at rest far away falls onto the surface of mass M with radius r. How fast is it moving when it reaches surface, if only force is gravity?
gravitational accretion energy can be very efficient!

A mass falling from $\infty$ to $R$ will have velocity $v = v_{\text{esc}} = \sqrt{\frac{2GM}{R}}$
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KE gained high is $M$ is big, $R$ is small!
e.g., neutron star, $M = 4 \times 10^{33}$ gm $R = 10^6$ cm
$KE_{\text{acc}} = \frac{1}{2}mv_{\text{esc}}^2 = 0.30mc^2$
a mass can produce $\sim 30\%$ of its rest mass energy just by falling!
The difference is that:
on the surface of the earth, \( M \) is small and \( R \) is large.
with BHs, \( M \) is large and \( R \) is small.

So the energy efficiency is much greater with BHs!
Gravitational accretion energy can be very efficient!

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$\text{KE}_{\text{acc}} = \frac{1}{2}mv_{\text{esc}}^2 = 0.30mc^2$

A mass can produce ~30% of its rest mass energy just by falling!

This is simple Newtonian calculation. For neutron stars and black holes, need relativistic calculation:

Maximum for mass falling onto BH is $\text{KE}_{\text{acc}} = 0.42mc^2$
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maximum for mass falling onto BH is $KE_{\text{acc}} = 0.42mc^2$

\textit{this doesn’t mean that the rest mass is converted to energy. the rest mass can be the same. it’s a conversion of gravitational potential energy to kinetic energy.}
how much of KE from gravitational accretion can be converted to photons?

• not all of KE from accretion can be converted into photons which escape region of BH and can be detected .... ...
  ... at most ~25%
  ... but in some cases could be 0% !!

• need to have e.g., particles collide with other particles, accelerate, produce photons, before particles fall into BH
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• $\varepsilon =$ efficiency for generating escaping radiation from inflowing mass $m$

• maximum possible efficiency $\varepsilon \approx (0.42)(0.25) \approx 0.1$
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  efficiency can easily be less than this in some cases!
How much do we need to feed AGN?

since nothing escapes BH, the radiation we detect must be fueled by accretion
What mass feeding rate is needed to sustain constant luminosity of AGN?

\[ E_\gamma = \varepsilon mc^2 \]

\( E_\gamma \) = energy of photons produced in AGN

\( \varepsilon \) = efficiency for extracting escaping photons \( \gamma \) (radiation) from inflowing mass \( m \)

maximum possible efficiency \( \varepsilon \approx (0.42)(0.25) \approx 0.1 \)
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\[ L = \frac{dE_\gamma}{dt} = \varepsilon c^2 \frac{dm}{dt} \]

\( L \) = luminosity of photons produced in AGN

\( \frac{dm}{dt} \) = mass accretion rate
What mass feeding rate is needed to sustain constant luminosity of AGN?

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\[ L = \text{luminosity of photons produced in AGN} \]
\[ \frac{dm}{dt} = \text{mass accretion rate} \]

suppose \( L = 10^{46} \text{ erg s}^{-1} \)
in order to produce this very high luminosity (quasar-like) need a mass accretion rate of:
\[ \frac{dm}{dt} = \frac{L}{\varepsilon c^2} = 1 \text{ M}_{\odot}/\text{yr} \text{ if } \varepsilon \approx 0.1 \]
How much do we need to feed AGN?

Gravitational energy powering AGN

$$E = \varepsilon mc^2 \leq 0.1 mc^2$$

i.e., material falling into a black hole near the nucleus of a galaxy may release up to about 10% of its rest energy in the form of photons.

The release of gravitational energy by a massive black hole (about 100 million solar masses) "eating" one star per year would power a typical quasar.
A big challenge to feeding AGN…

AGN emit huge amounts of radiation, and radiation exerts outward pressure on matter. This pressure tends to drive matter away from central source.
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AGN emit huge amounts of radiation, and radiation exerts outward pressure on matter. This pressure tends to drive matter away from central source.

In order for central source to accrete matter, the inward gravitational force (& therefore the central mass) must be large enough to overcome the outward radiation pressure.
radiation pressure

this shows radiation pressure from reflected light, but also get radiation pressure from absorbed light
What is making the comet’s tail?

- Dust tail formed by radiation pressure
- Gas (ion) tail formed by solar wind
dust tail formed by radiation pressure on dust, not radiation pressure on electrons (thomson scattering)
J Kepler 1610
he said radiation pressure made comet tails

JC Maxwell 1873
his big theory predicted light had momentum therefore pressure

PN Lebedev 1900
experimental demonstration of radiation pressure

EF Nichols 1901
experimental demonstration of radiation pressure
Radiation Pressure

Each photon carries momentum $p = E/c$ so there is a force $F = \Delta p/\Delta t$ exerted by a flux of photons.

Radiation pressure force per unit mass on particle at $r$:

$$F_{\text{rad}} = \kappa \frac{f}{c} = \kappa \frac{L}{(4\pi cr^2)}$$

For isotropic emitters.

Where

$f = L / (4\pi r^2) = \text{flux of radiation}$

$\kappa = \text{mass absorption coefficient (cm}^2 \text{gm}^{-1})$

A measure of how well the matter absorbs the momentum of the photons.
Radiation Pressure Force vs Gravitational Force

gravitational force per unit mass:
\[ F_{\text{grav}} = \frac{GM}{r^2} \]

in order for particle to accrete,
\[ F_{\text{grav}} > F_{\text{rad}} \]
\[ \frac{GM}{r^2} > \frac{\kappa L}{(4\pi cr^2)} \]
\[ L < \frac{4\pi cGM}{\kappa} \]
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what do we use for \( \kappa \) ?
\( \kappa = \text{mass absorption coefficient (cm}^2 \text{ gm}^{-1}) \)

a measure of how well the matter absorbs the momentum of the photons

minimum value of \( \kappa \) is that for pure ionized hydrogen, due to Thomson scattering off free electrons

\[
\kappa = \frac{\sigma_T}{m_p}
\]

\( \sigma_T = 6.65 \times 10^{-25} \text{ cm}^2 \)

Thomson cross section
Thomson scattering

elastic scattering of electromagnetic radiation by a free charged particle
energy of photon and KE of particle unchanged, but direction of momentum changes

JJ Thomson
1856
Thomson Scattering

low-E photon scattered by electron -

\[ h\nu \xrightarrow{\text{electron}} h\nu \]

Thomson cross-section is given by -

\[ \sigma = \frac{8}{3} \pi r_e^2, \text{ where } r_e = 2.82 \times 10^{-15} \text{ m} \]

\[ \Rightarrow \sigma_e = 6.65 \times 10^{-29} \text{ m}^2 \]
minimum value of $\kappa$ is that for pure ionized hydrogen, due to Thomson scattering off free electrons

$$\kappa = \frac{\sigma_T}{m_p} \quad \sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$$

Thomson cross section
The minimum value of $\kappa$ is that for pure ionized hydrogen, due to Thomson scattering off free electrons:

$$\kappa = \frac{\sigma_T}{m_p}$$

$\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$

Thomson cross section

Q: Why is the mass of the proton in the denominator, if it’s the electrons that scatter the photons?
minimum value of $\kappa$ is that for pure ionized hydrogen, due to Thomson scattering off free electrons

$$\kappa = \frac{\sigma_T}{m_p}$$

$$\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$$

Thomson cross section

although electrons scatter the radiation far more than protons, the protons are carried along with the e’s by the strong electrostatic attraction between them, so we consider the total mass of protons and electrons ($m_p + m_e \approx m_p$)
in order to accrete must have $F_{\text{grav}} > F_{\text{rad}}$
therefore $L < L_E$, where

$$L_E = \frac{4\pi G M m_p c}{\sigma_T}$$

\textit{Eddington luminosity} = maximum possible luminosity for spherical accretion

$$L_E = 1.25 \times 10^{38} \left[ \frac{M}{M_{\text{sun}}} \right] \text{ erg s}^{-1} \approx 30,000 \left[ \frac{M}{M_{\text{sun}}} \right] L_{\text{sun}}$$
maximum possible luminosity for spherical accretion = \textit{Eddington luminosity}

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the sun has \( L_{\text{sun}} = \frac{1}{30,000} L_E \) radiation pressure does not prevent atoms from accreting onto Sun!
maximum possible luminosity for spherical accretion = *Eddington luminosity*

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\[ L_E = 1.25 \times 10^{38} \left( \frac{M}{M_{\text{sun}}} \right) \text{ erg s}^{-1} \approx 30,000 \left( \frac{M}{M_{\text{sun}}} \right) L_{\text{sun}} \]

the sun has \( L_{\text{sun}} = (1/30,000) \) \( L_E \)

the most massive stars with \( M=100 \, M_{\text{sun}} \) have \( L \approx 10^6 \, L_{\text{sun}} \approx L_E \)

radiation pressure does not prevent atoms from accreting onto Sun!

radiation pressure limits continued accretion and further growth of the largest stars!
how we know luminous AGN must have *massive* BHs

in order to feed AGN with $L=10^{46}$ erg/s, must have $L<L_E$

$\Rightarrow M > 10^8 \left( \frac{L}{1.25 \times 10^{46} \text{ erg/s}} \right) M_{\text{sun}}$

this is strictly for spherical systems; could exceed Eddington limit by ~factor of few if not spherically symmetric

e.g. radiation goes out preferentially in some directions, matter comes in preferentially in other directions

if $L>L_E$ luminosity is super-Eddington

if $L<L_E$ luminosity is sub-Eddington (common..! can have matter flowing into BH without producing much radiation!)
Why do accretion disks form?
Why do accretion disks form?

Why don’t SMBHs get any bigger than $M_{\text{BH}} \sim 10^{-3} M_{\text{gal}}$?
Bigger black holes in bigger galaxies (or bigger bulges of galaxies)

Black hole mass $\sim 10^{-3}$ galaxy bulge mass
Why do accretion disks form?

Why don’t SMBHs get any bigger than $M_{BH} \sim 10^{-3} M_{\text{gal}}$?

*angular momentum*… it is hard for gas to lose enough angular momentum to make it down to the Schwarzschild radius
Suppose you have gas in circular orbit at a radius of 1 kpc. How much angular momentum does the gas need to lose to reach the Schwarzschild radius?
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**specific angular momentum of gas**

\[ h = \left| \mathbf{r} \times \mathbf{p} \right| / m = \left| \mathbf{r} \times \mathbf{v} \right| = rv \text{ for circular orbit} \]
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Gas at \( r = 1 \text{kpc} \) and \( v_{\text{rot}} = 300 \text{ km/s} \)

\[ h = (1 \text{kpc}) (300 \text{ km/s}) = 10^{29} \text{ cm}^2 \text{ s}^{-1} \]
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**specific angular momentum of gas**

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\mathbf{h} = \left| \mathbf{r} \times \mathbf{p} \right| / m = \left| \mathbf{r} \times \mathbf{v} \right| = rv 
\]

for circular orbit

gas at \( r = 1 \text{kpc} \) and \( v_{\text{rot}} = 300 \text{ km/s} \)
\[
\mathbf{h} = (1 \text{kpc}) (300 \text{ km/s}) = 10^{29} \text{ cm}^2 \text{ s}^{-1}
\]

*maximum* \( h \) for gas flowing into BH
\[
\mathbf{h} = R_s c = \left( \frac{2GM}{c^2} \right) / c = \frac{2GM}{c} \\
= 5 \times 10^{23} \text{ cm}^2 \text{ s}^{-1} \text{ (for } M=10^8 \text{ M}_{\odot})
\]
Suppose you have gas in circular orbit at a radius of 1 kpc. How much angular momentum does the gas need to lose to reach the Schwarzschild radius?

so gas needs to lose factor of $>10^5$ in angular momentum!

this is difficult!

only small fraction of galaxy gas can manage to lose enough angular momentum to even reach the accretion disk. gas that manages to reach central region still has significant angular momentum, so forms a rotating disk of gas. gas in this disk continues to lose angular momentum (by processes within the disk) and therefore ends up accreting onto the BH.
Why aren’t the nuclei of most nearby large galaxies “active”? 

A. They don’t have nuclear black holes

B. Their nuclear black holes have small masses

C. They are not accreting much matter at present

D. Our view of these nuclei is obscured, but they really are active
since nothing escapes BH, the radiation we detect must be fueled by accretion

stars can produce energy long after they have formed. but SMBHs can’t – they can only produce energy when they are growing. this is why stars still shine in the universe but SMBHs don’t shine much any more!
We think all galaxies have central BHs, but most galaxies are not AGN since most are not being fed now.

If there is little/no gas in accretion disk, it means:

- There is nothing around the black hole to produce light to detect (not an AGN)
- Black hole is not fed & not growing

The best way to feed nuclear BH is to have a galaxy interaction, which drives gas toward the center.

This happened more often in early universe, which is why quasars (luminous AGN) are rare today.
Galaxy interactions cause central black holes to be fed, making active galactic nuclei (AGN)
Quasars are SMBHs being fed in massive, merging galaxies. *Quasars (the most luminous AGN) are very rare today.* Quasars were $>1000x$ more common at $z=3-4$, $t_{\text{ABB}} = 1.5-3$ Byr. The black holes are still in these galaxies – why don’t we see photons from them?
Star formation activity in universe is low today
Star formation activity was >20x higher at $z=3-4$, $t_{ABB} = 1.5-3$ Byr
Star formation is enhanced when galaxies form, in part through mergers
AGN and star formation activity both peak at $z=3-4$, $t_{\text{ABB}} = 1.5-3$ Byr

Both are fueled by galaxy mergers, which are key part of galaxy formation process

So $z=3-4$, $t_{\text{ABB}} = 1.5-3$ Byr is the era of peak galaxy formation, star formation and supermassive black hole growth
Final exam

• Mon Dec 17, 7pm in WTS A46 (normal classroom!)
• Will cover class material & readings & HWs:
  – starting Lecture 9, Sept 26
  – starting SG 3.0
  – HW 5-10
  – I will put problems similar to HW10 on the exam
• Exam will feature a mix of problems and written answers
• Advice: review PPTs & classnotes & HWs. Re-read textbook, focusing on things we covered in class.
• know ‘basic’ simple equations, I will provide others
• bring calculator