Group

AL	**Hunt**	Paige	**Quinn**	Jamie	**Devkota**	Bishwash
AR	**Prater**	Zane	**Fernandez**	Elizabeth	**Schott**	Connor
BL	**Smith**	Jaihan	**Fernandez**	Corey	**Thompson**	Natalie
BR	**Tlustos**	Travis	**White**	Erin	**Wood**	Noelle
CL	**DeMeyer**	Lauren	**Oconnor**	McKenna	**Burdette**	Lily
CR	**Gunalan**	Vishnu	**Shrimplin**	Skylar	**Morris**	Riley
DL	**Golovin**	Anita	**Pappageorge**	Lauren	**Mongillo**	Hailie
DR	**Lee**	Tony	**Gregory**	Brinley	**Beezley**	Claire
EL	**Tomczyk**	Aaron	**Ehardt**	Bella	**Adkins**	Leo
ER	**Desmond**	Sarah	**Aleman**	David	**Davis**	Jackson
FL	**Holtgrewe**	Emily	**McGeough**	Natasha	**Stringer**	Jason
FR	**Shell**	Brookelynn	**Green**	Kailey	**Ausler**	Kiara
GL	**Keeney**	Alex	**Takeuchi**	Fuka	**Brown**	Tatianah
GR	**Byrum**	Faith	**Evans**	Hannah	**Ziff**	Caitlin
HL	**Jones**	Justice	**Rosentreter**	Riley	**Tucker**	Kali
HR	**Swartz**	Alicia	**Barr**	Abigail	**Ashlin**	Bradley

AL	**Knight**	Cassidy	**Bourcier**	Savannah	**Pike**	Alena
AR	**Stirewalt**	Robert	**Ellis**	Alexander	**Roberts**	Jay
BL	**Stinnett**	Nic	**Hunter**	Kris		
BR	**Still**	Martin	**Price**	Elijah		
CL	**Kolath**	Caroline	**Petinaris**	Joanna		
CR	**Davis**	Samantha	**Brown**	Quincy		
DL	**Stiers**	Alexis	**Bayer**	Caeden		
DR	**Hunt**	Taylor	**Chabino**	Conner		
EL	**Yoss**	Aaron	**Czeschin**	Kyle		
ER	**Lambeth**	Gabe	**Cherukumilli**	Shan		
FL	**Ayers**	Carley	**McBurney**	Sullivan		
FR	**Bowe**	Ava	**Adams**	Autumn		
GL	**McPike**	Aiden	**Bradshaw**	Jenny		
GR	**Todd**	Ana	**Maune**	Cole		
HL	**Saucedo**	Brithny	**Sauceda**	Emma		
HR	**Coomes**	Austin	**Govero**	Brady		

Test 2 on April 3 in class..

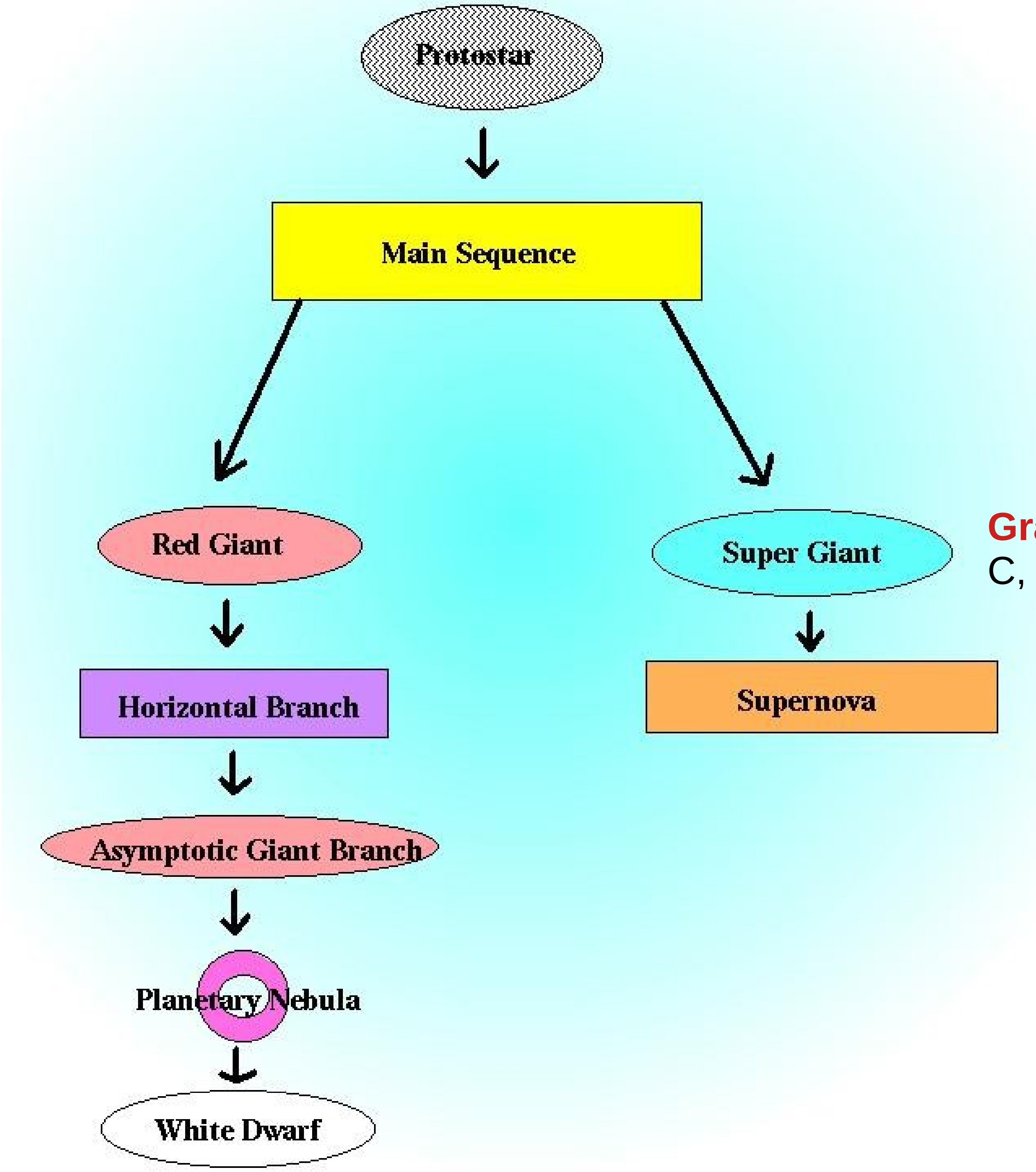
Sample Tests and study guide on the course web page now.

Group project 1 is due on April 1.

Important points:

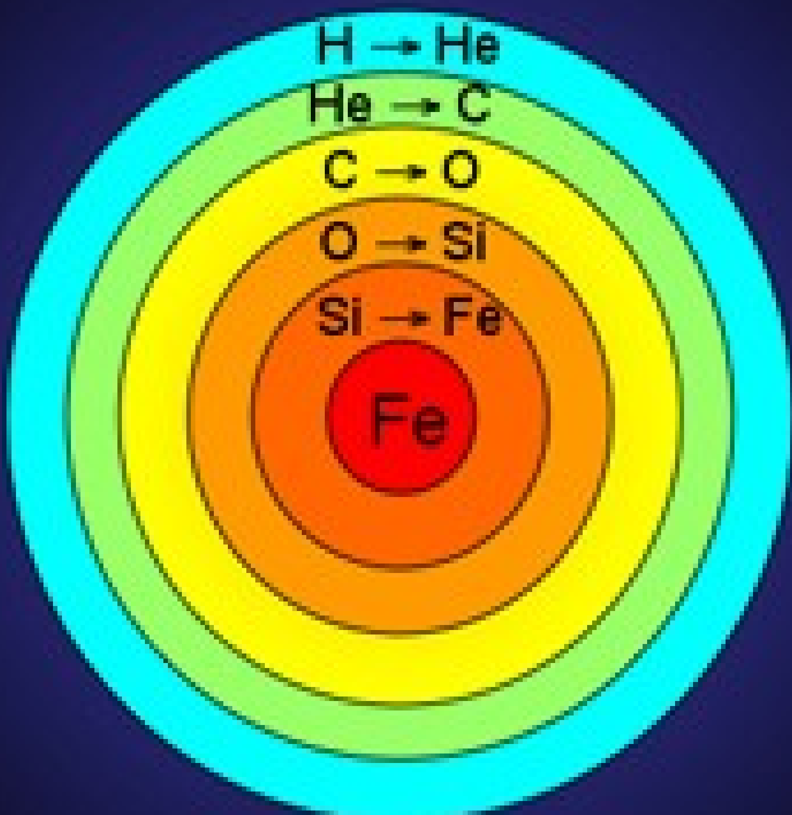
Most stars (98%) end up as white dwarfs.

stars can make elements beyond H & He



Gravity + fusion (He, C, N, O, Si)

Supergiant Fusion Timescales



For a 25 solar mass star:

Stage	Duration
H → He	$7x10^6$ years
He → C	$7x10^5$ years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Iron core leads to a supernova explosion (implosion and rebound)

The Crab Nebula: A remnant from a supernova in 1054.

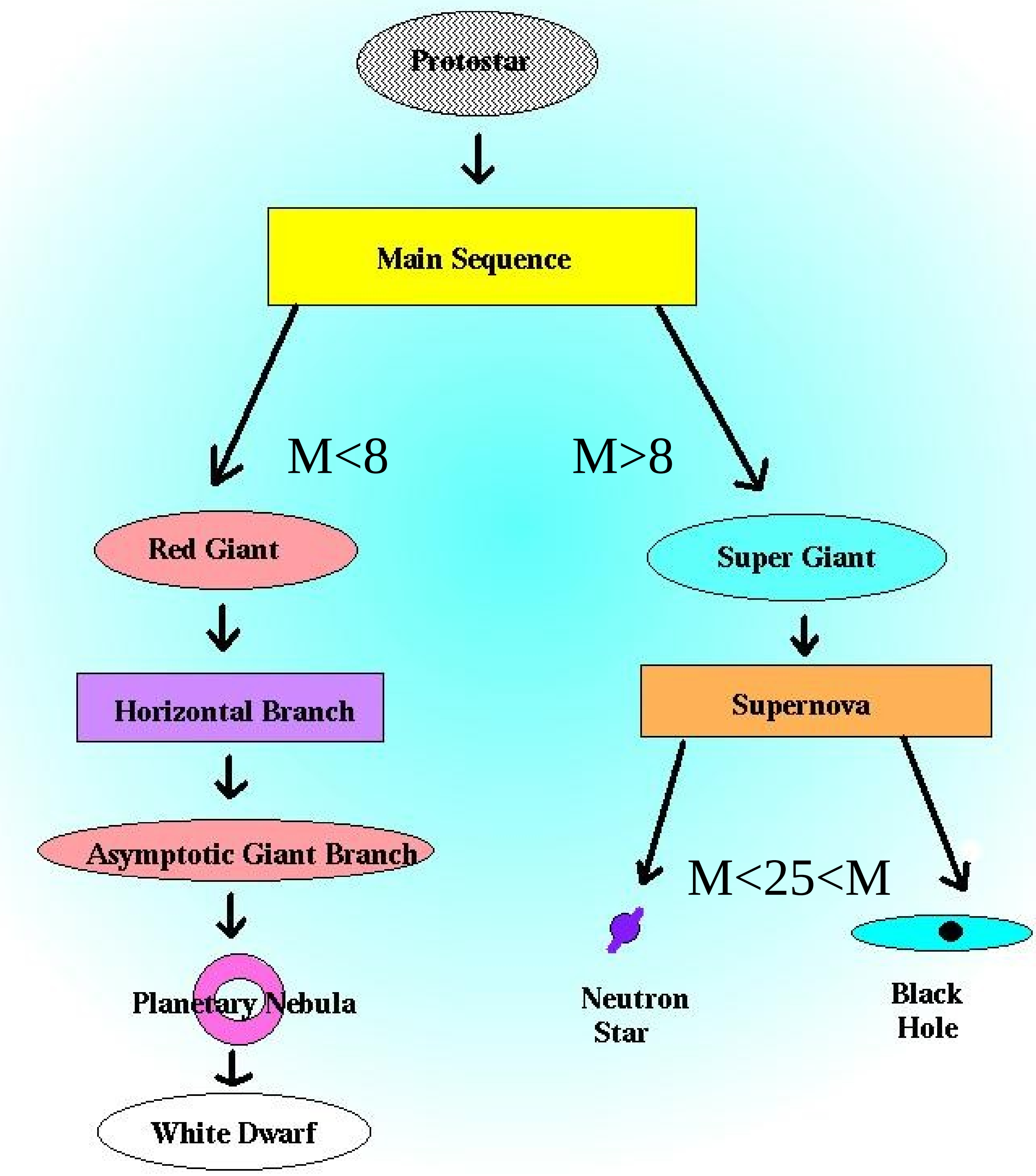
Supernova 1987a

Stellar recycling/ chemical enrichment

Supernova can create *any* element as atoms are smashing together at billions of degrees K.

60 to 90% of the original star is returned to space.

But what's left after the supernova of a massive star?



Protostar
Main Sequence
M<8
M>8
Red Giant
Super Giant
Horizontal Branch
Supernova
Asymptotic Giant Branch
M<25<M
Planetary Nebula
Neutron Star
Black Hole
White Dwarf

Massive stars (<2% of all stars)

- Do core fusion until the core is full of iron ash.
- The core collapses, creating a supernova.
- As the core collapses, eletrons (negative electric charge) and protons (positive electric charge) merge, forming neutrons (no electric charge).
- Neutrons have nuclear charge, which is much stronger than electric charge, and so neutrons repel each other, just like electrons did, but much, much stronger.
- Neutron degeneracy pressure supports neutron stars.

But what's left after the supernova of a massive star?

- A Neutron Star: Main sequence mass 8 - 25 M_{sun}
- A Black Hole: Main sequence mass >25 M_{sun}, there is no stopping the collapse.

End States of Stars

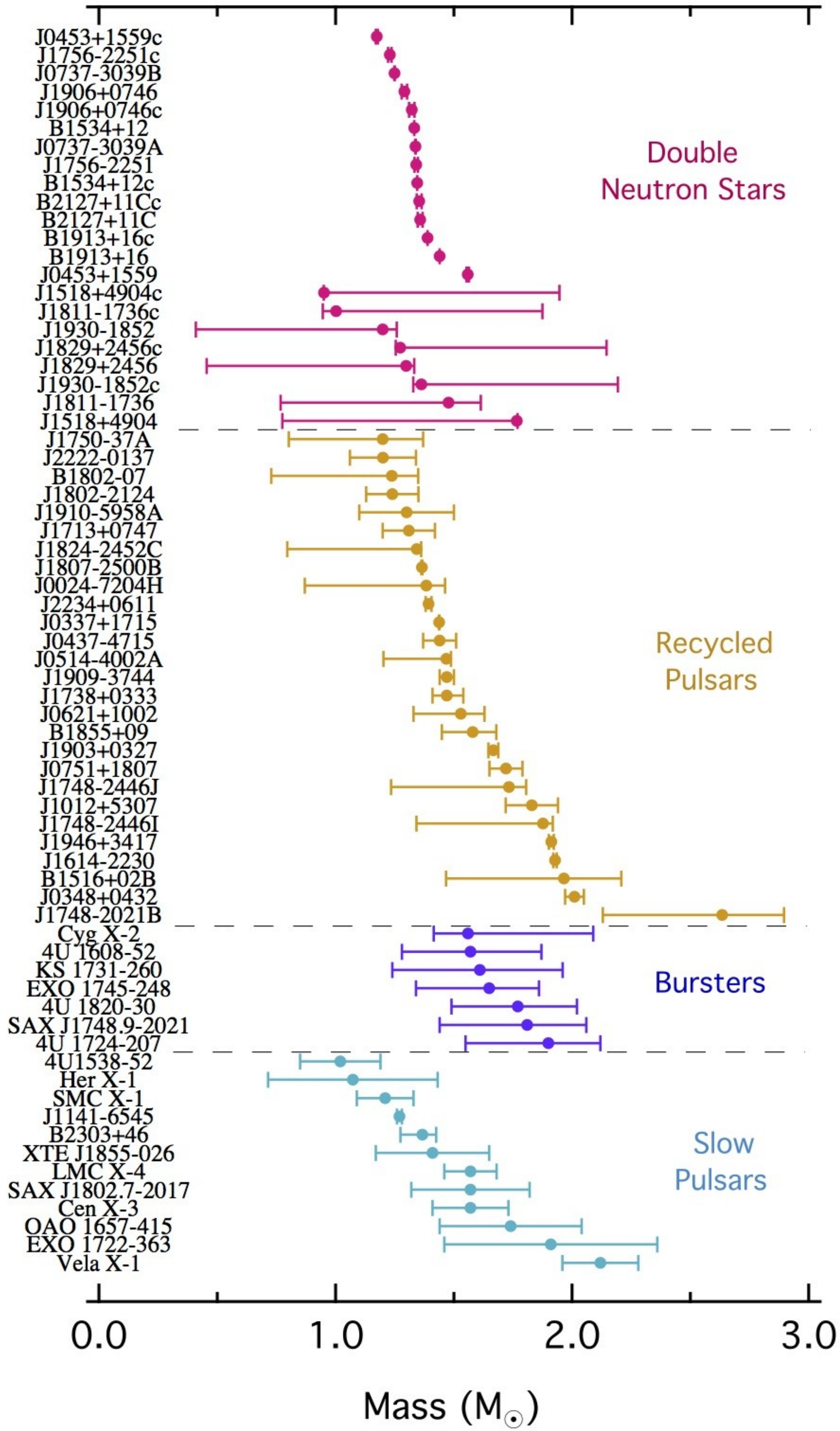
For main sequence stars with more than 8, but less than 25 solar masses:

-They end up as Neutron Stars.

-10 to 30km across. (City-sized)

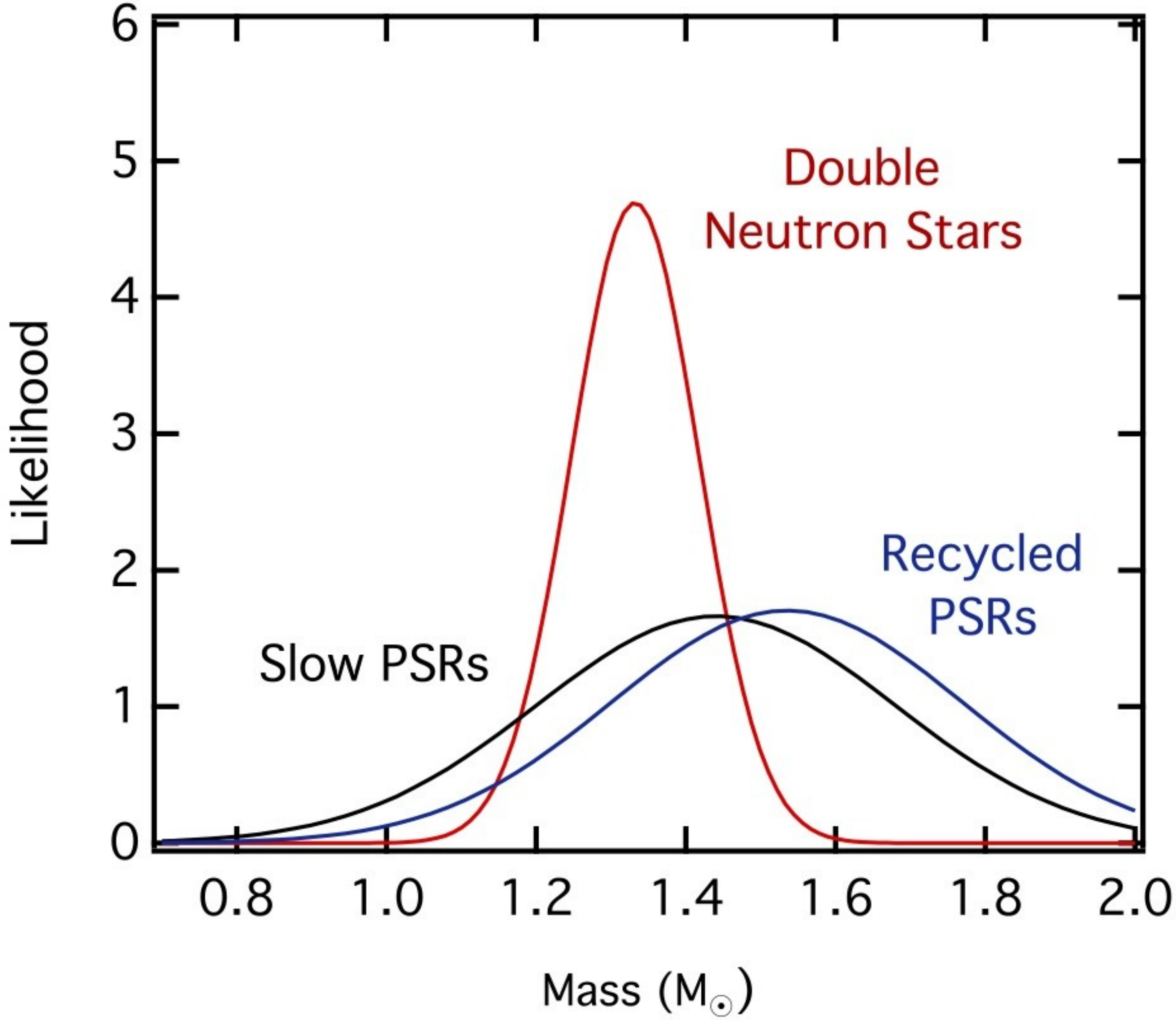
-Neutron stars have an average mass of 1.4 solar masses.

-Neutron stars cannot get larger than about 2.5 solar masses.



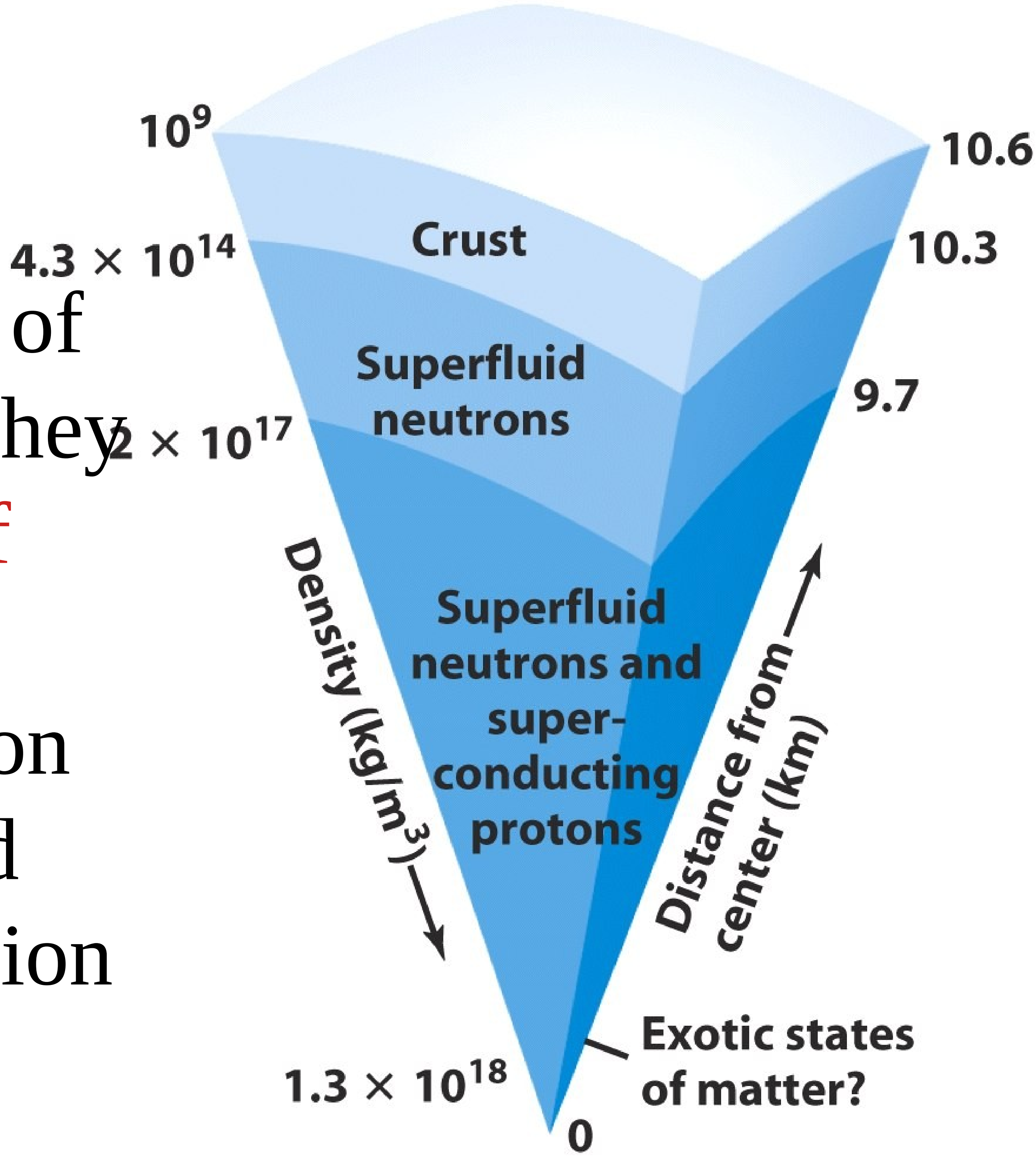
Detected masses of neutron stars: determined from binary stars (of course!). ‘Double neutron stars’ are binaries where both stars are neutron stars, whereas the rest have non-neutron star companions.

Masses are surprisingly tight around 1.4 solar masses with very few above 2 solar masses.



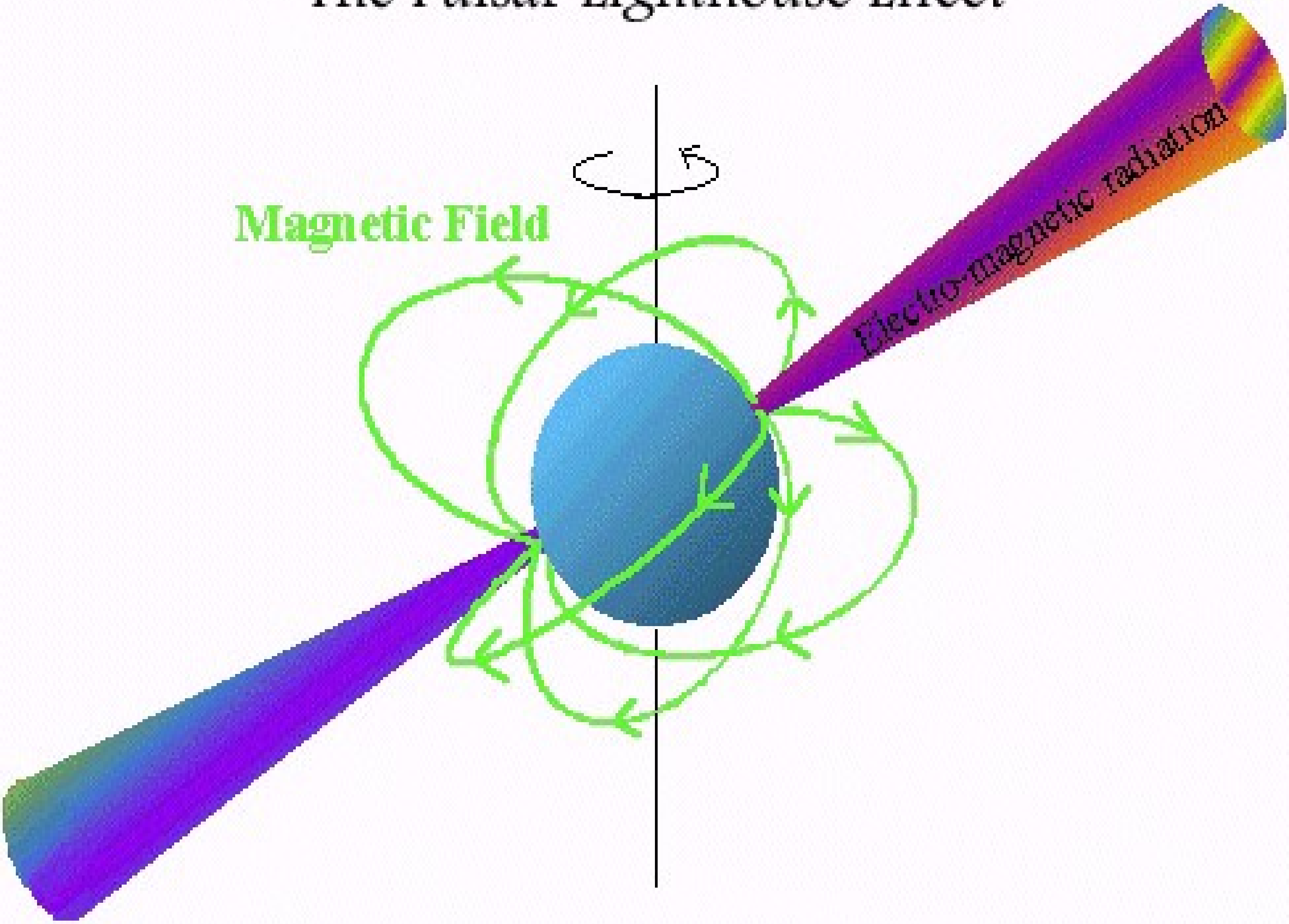
The structure of neutron stars: they are made of neutrons!

A 1cm cube on Earth would weigh 400 billion tons.



How do you detect something 20km across?

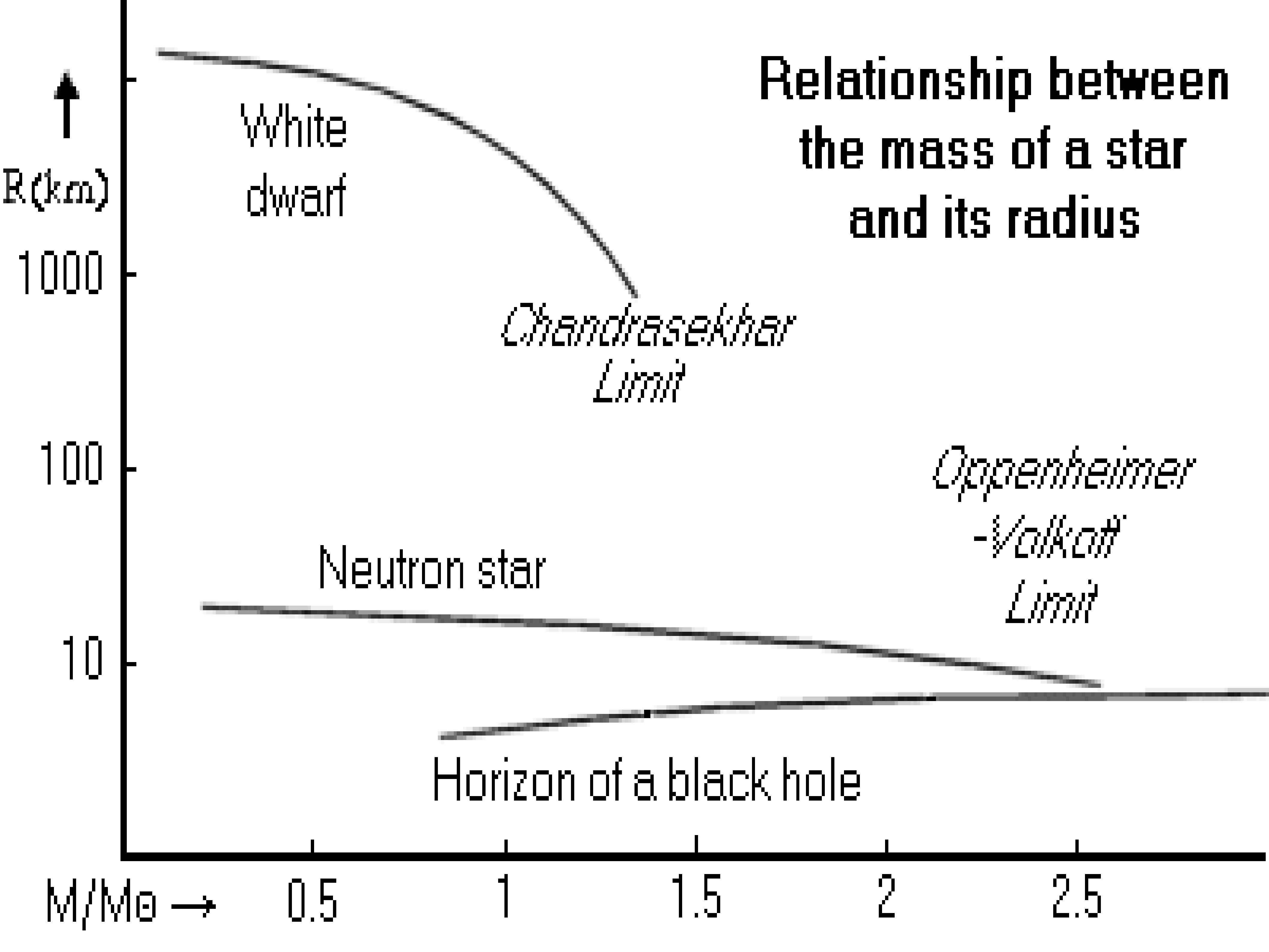
The Pulsar Lighthouse Effect



How do you detect something 20km across?
Pulsars

- A special kind of neutron star that "beams" radio waves in our direction.
- Spin (on average) once per second.
- Strong magnetic fields cause the "beam"

Why do pulsars spin so fast?


Relationship between the mass of a star and its radius
R(km)
1000
100
10
White dwarf
Chandrasekhar Limit
Neutron star
Oppenheimer -Volkoff Limit
Horizon of a black hole
M/M⊙ →
0.5
1
1.5
2
2.5

It is estimated that our galaxy already has about 100 million neutron stars.

Only about 1,000 have been detected.

Black Holes

- The end product of main sequence stars with mass >25 M_{sun}.
- Nothing can escape- not even light.

Black Holes

- Size;

-The black hole itself is a point at the center.

-Nothing can travel faster than light.

-Light travels at a fixed speed: c

-Set the escape velocity to c and solve for size.

-Schwarzchild radius: $R_{sch}=3M$ for mass in solar masses you get size in kilometers.

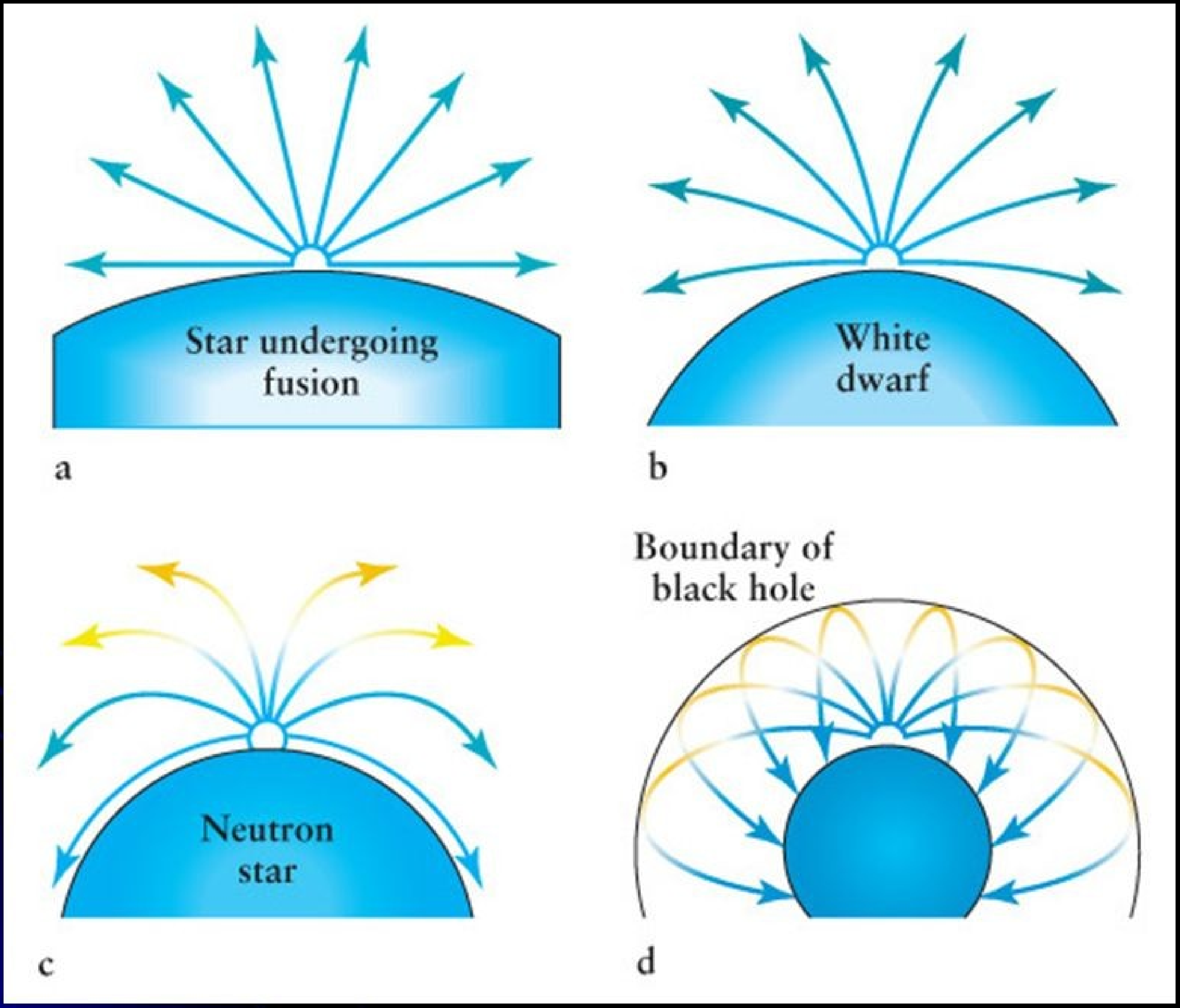
- Also called the event horizon.

To launch a rocket from any object, that object needs to reach escape speed. Otherwise, it just falls back down.

Listed below are how fast rockets must go if launched from planets in our solar system.

Graphic from Skye Gould/Business Insider

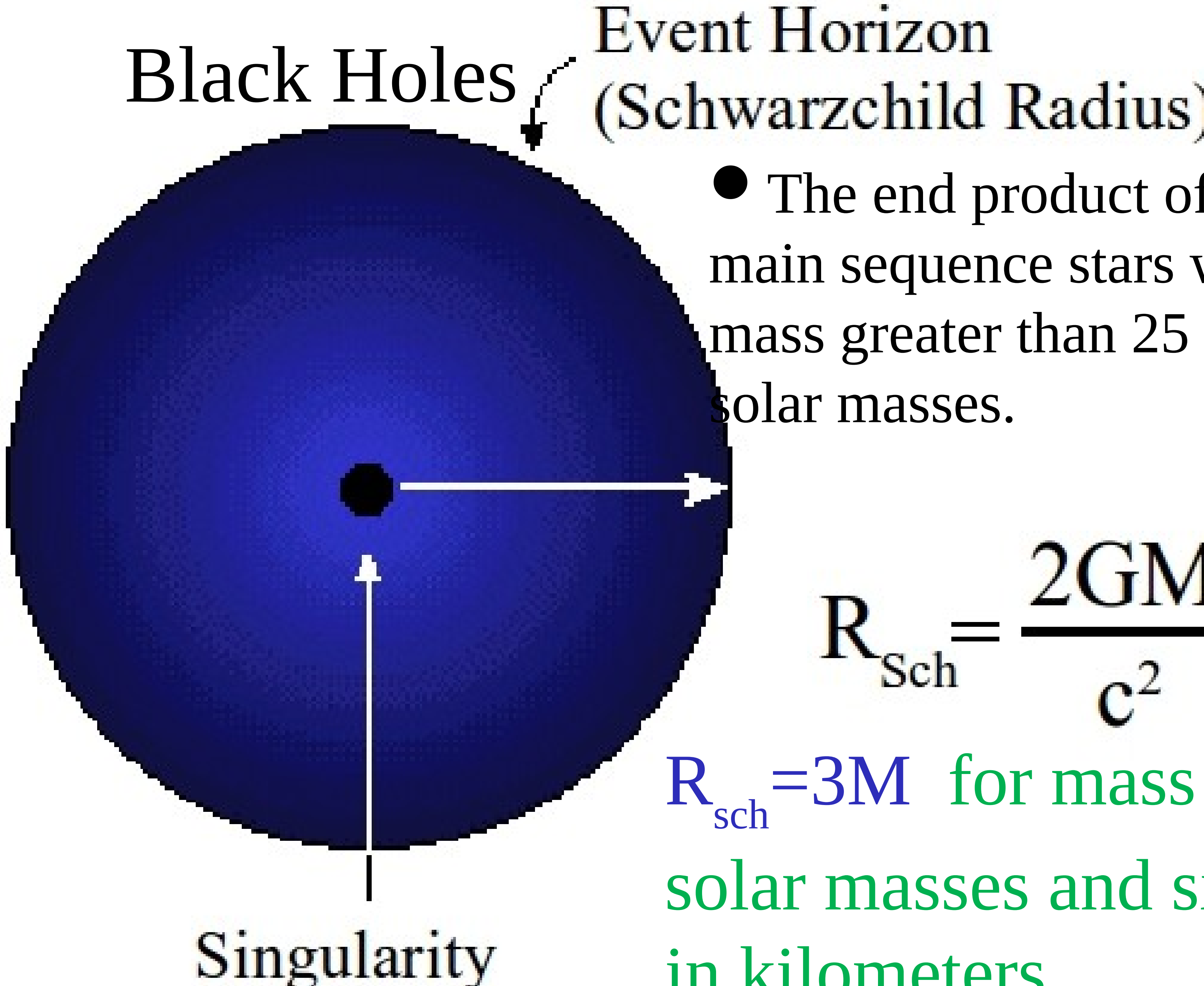
So if we make objects more and more massive, the escape speed gets higher and higher. If that escape speed is larger than the speed of light, then nothing can get out, not even light.



The figure has arrows, showing how light would leave increasingly massive stars.

Graphic from Tabitha Norris

Black Holes



- The end product of main sequence stars with mass greater than 25 solar masses.

$$R_{Sch} = \frac{2GM}{c^2}$$

$R_{sch}=3M$ for mass in solar masses and size in kilometers

How do you detect something that doesn't emit light?

X-7 in M33. The black hole is estimated at 15.7 solar masses and the star at 70 solar masses!

If the star is 70 solar masses, yet less evolved than the companion, how massive must the other star have been on the main sequence?

If the star is 70 solar masses, yet less evolved than the companion, how massive must the other star have been on the main sequence?

It must have been more than 70 solar masses, which only leave behind black holes.

If nothing gets out, what can we measure?

1) Mass. From their gravity.
2) Rotation. This changes the shape of the Schwarzchild radius- making it wider along the spin axis. This has been done by mapping the event horizon.
3) Charge. There's no reason to believe black holes have charge (more positive or negative material falls in), but if they do have charge, it could be measured from outside the event horizon.

The Wacky World of Black Holes

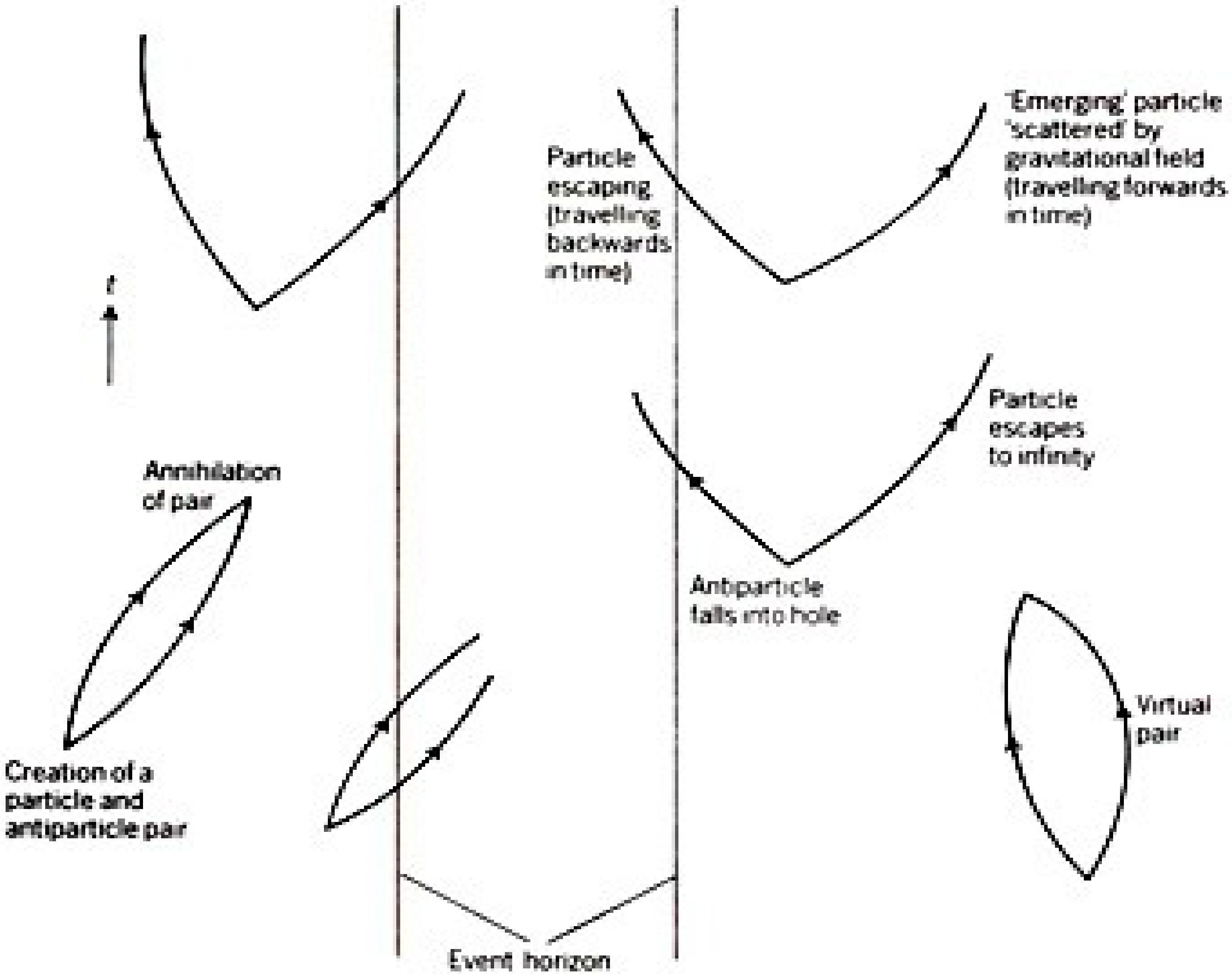
Takeaways:

1) Eventually black holes evaporate (go away).
2) Black holes are not vacuum cleaners, they cannot 'suck in' the Universe.

If our Sun became a black hole (which it won't), the Earth would still orbit exactly as it does now.

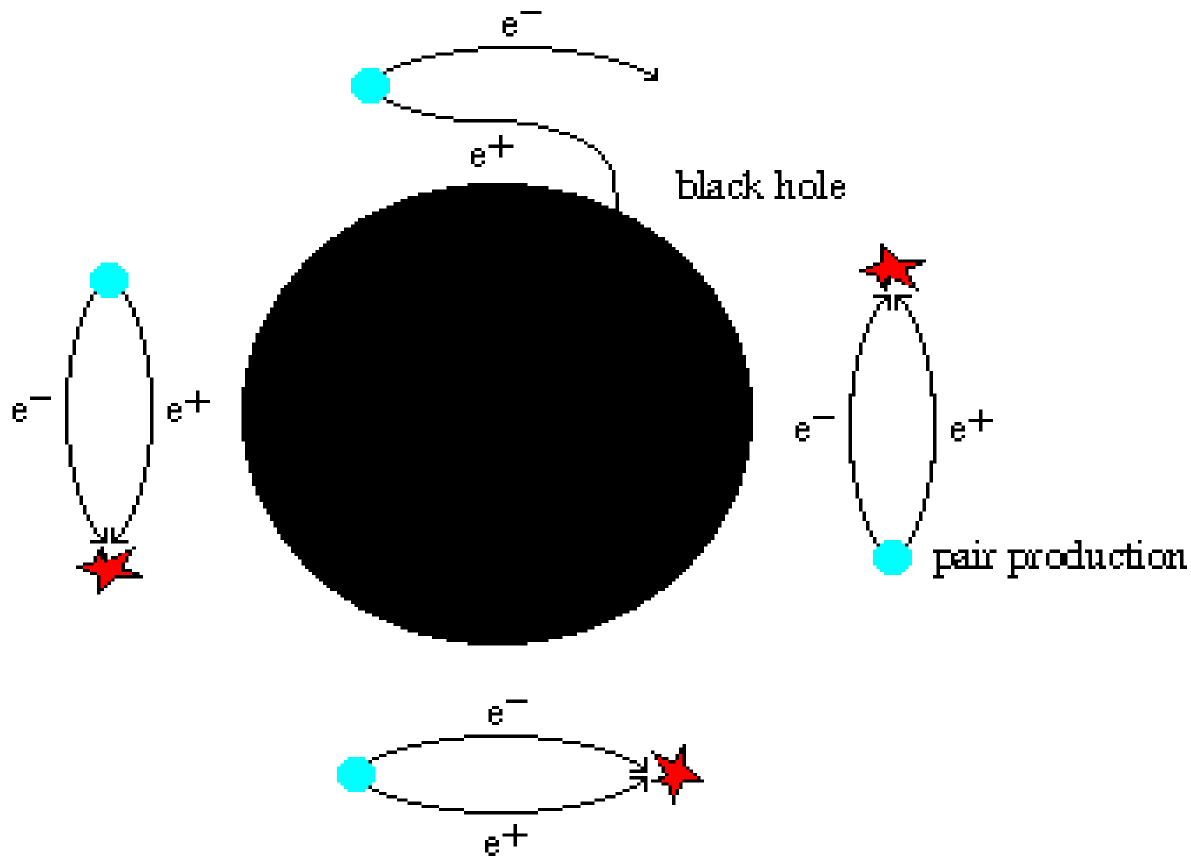
Hawking Radiation

Black holes evaporate!



Hawking Radiation

the strong gravitational field around a black hole causes pair production



if a pair is produced outside the event horizon, then one member will fall back into the black hole, but the other member will escape and the black hole loses mass

the amount of mass lost is greater for small black holes, therefore quantum sized black holes disintegrate in very short timescales

Eventually, all black holes evaporate.

Test 2 material stops here