THE UNIVERSITY OF CHICAGO
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THE 82ND ARTHUR H. COMPTON LECTURE SERIES

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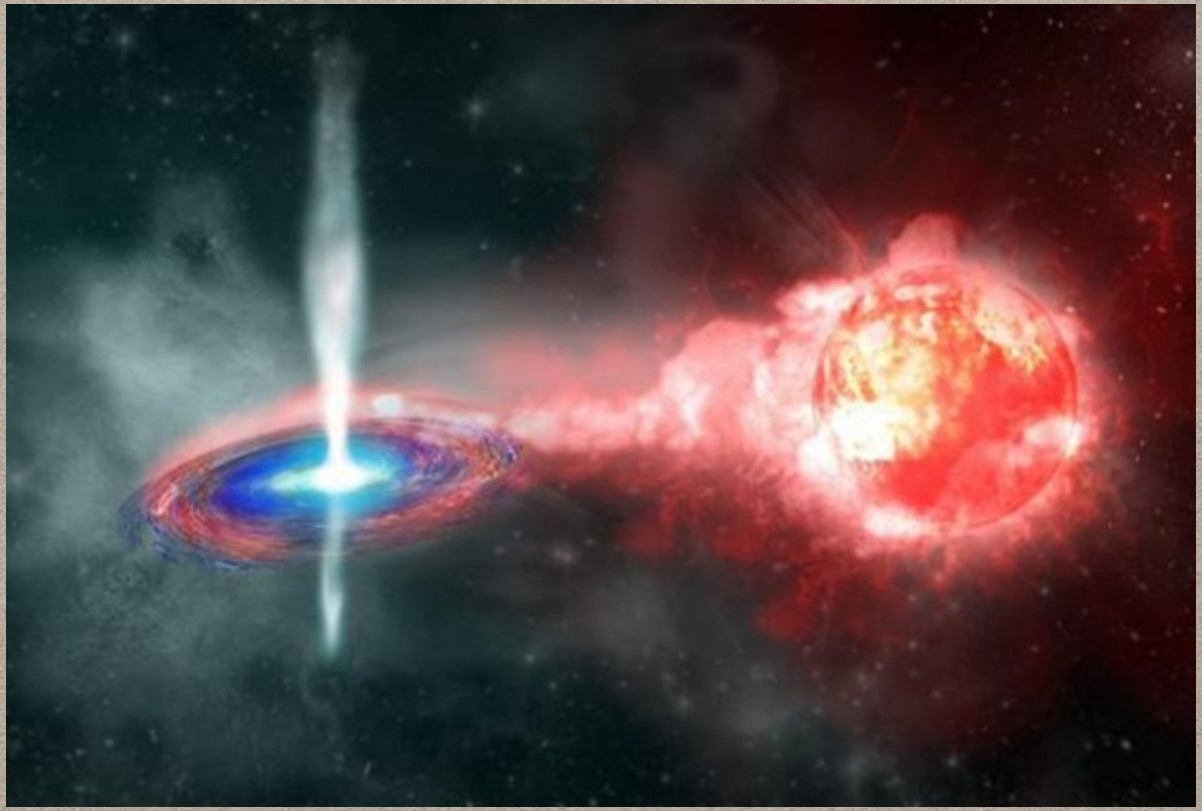


LECTURE 3

HANGING OUT WITH BAD COMPANY: TYPE-IA SUPERNOVAE

10/17/2015

WHITE DWARFS: THE PROGENITORS OF IA

What do we know about white dwarfs?

Mass ~ Sun

Most are **single**, 0.6 $M_{\odot}$ (solar masses)

Some in binary systems have **higher mass**

Size ~ Earth ~1% radius of Sun

$$\text{Density} = \frac{\text{mass}}{\text{volume}} \rightarrow \frac{10^6 \text{ grams}}{\text{c. c.}} \sim \frac{\textbf{tons}}{\textbf{cubic centimeter}}$$

OR MORE!

HUGE GRAVITY!

QUANTUM PRESSURE!

HOW CAN A WD EXPLODE?

- A normal star supported by thermal pressure regulates its temperature. If excess energy is lost, the star contracts and heats. If excess energy is gained, the star expands and cools. Feedback loop, akin to the furnace, thermostat in your house.

- A white dwarf, supported by the quantum pressure, cannot regulate its temperature. If excess energy is lost (the case for the vast majority of white dwarfs), they just get cooler. If excess energy is gained, they heat up and can explode.

Behavior of white dwarf, Quantum Pressure, worked out by S. Chandrasekhar (was at U Chicago) in the 1930's

Limit to mass the Quantum Pressure of electrons can support

Chandrasekhar mass limit ~ 1.4 $M_{\odot}$

density ~ billion grams/cc ~ 1000 tons/cubic centimeter

Maximum mass of white dwarf.

S. Chandrasekhar

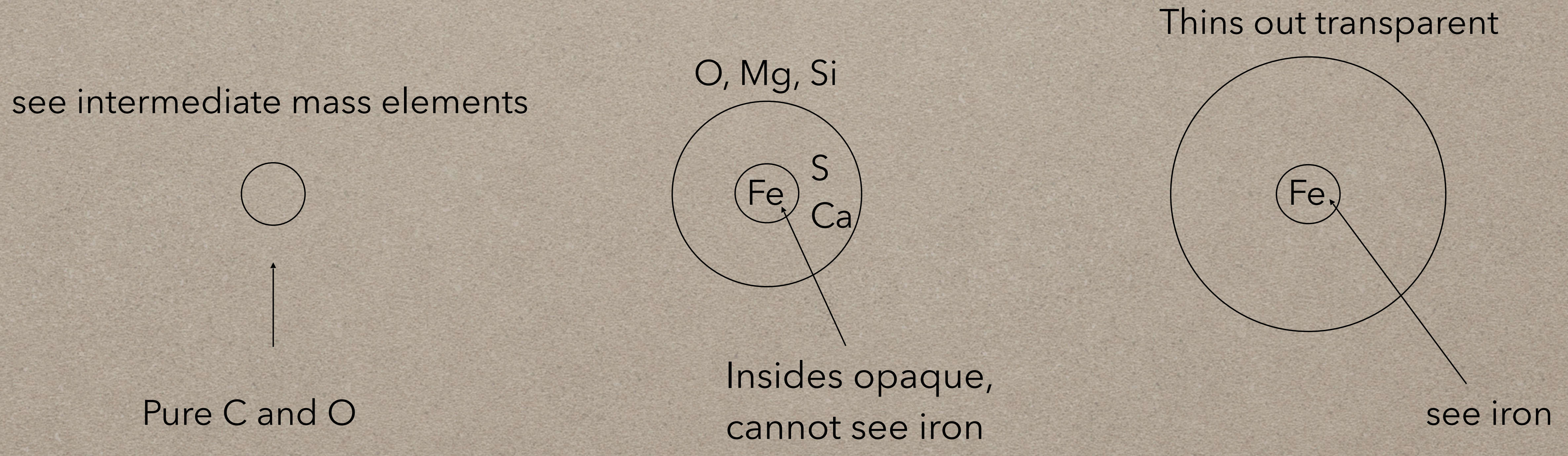
If more mass is added, the white dwarf must collapse or explode!

TYPE IA VERSUS TYPE II: IRON PRODUCTION

Type II (Ib, Ic): energy from falling, gravity. Type Ia: energy from thermonuclear explosion.

For **core collapse**, iron is produced ***BEFORE*** the explosion in the progenitor star and triggers collapse. For **thermonuclear explosion** of carbon and oxygen, iron is produced ***DURING*** the explosion.

Type Ia - see O, Mg, Si, S, Ca early on, iron later => ***iron is inside***



Initial White Dwarf ***Near maximum light*** ***Weeks after maximum***

THE EXPLOSION PROCESS - I

1. Models based on Chandrasekhar-mass 1.4 solar mass C/O white dwarfs give observed composition structure!

2. Large quantum pressure deep inside the white dwarf -- high density and temperature overcome charge repulsion - **very unregulated.**

3. Ignite Carbon, temperature goes up, easier to overcome charge repulsion, more burning, higher temperature

$\Rightarrow$ runaway $\Rightarrow$ total explosion, no neutron star or black hole.

4. Models give thorough burning to iron on inside (important detail later), only partial burning of C and O leaving O, Mg, Si, S, Ca in outer layers.

THE EXPLOSION PROCESS - II

Two stages to explosion

Deflagration - slower than speed of sound, like a flame

Detonation – involves a supersonic shockwave, faster than the speed of sound.

Shock wave ignites the fuel, burning drives the shock. A detonation is self-propagating. Result is like a stick of dynamite or a bomb.

Force, acceleration are related to the change in pressure.

A shock wave involves a sharp, steep growth in pressure from in front to behind the shock front. Severe force and acceleration.

A detonation is faster and more violent than a deflagration since it involves a shock wave.

DEFLAGRATION AND DETONATION

Deflagration versus Detonation - Important Principles

Detonations, supersonic, do not give the white dwarf time to react.

⇒ For ***detonation alone***, the white dwarf would have no time to expand. It would burn entirely at the original high density and be turned essentially entirely to iron, but we observe intermediate mass elements on the outside, so ***Wrong!***

Deflagrations, subsonic, give the outer parts of the white dwarf time to expand, quench burning.

⇒ For ***deflagration alone***, the outer parts are never burned, explosion would be relatively weak, substantial unburned carbon and oxygen would be expelled.

Predict feeble explosion and observations show little or no remaining carbon, so ***Wrong!***

TRANSITIONING FROM DEFLAGRATION TO DETONATION (DDT)

Deflagration followed by Detonation Works

The ***deflagration*** starts the explosion:

- Produces iron on the inside
- Pressure waves push much of the unburned carbon and oxygen to lower densities.

The ***detonation*** catches up with the expanding outer parts

- Burns carbon and oxygen to oxygen, magnesium, silicon, calcium

Deflagration followed by detonation:

- Gives the right energy
- Gives the right elements on the inside and outside
- Predicts very little unburned carbon and oxygen.

Matches wide variety of observations!

All data, UV, optical, IR, X-ray are consistent with this picture

BUT HOW? HOT RESEARCH TOPIC...

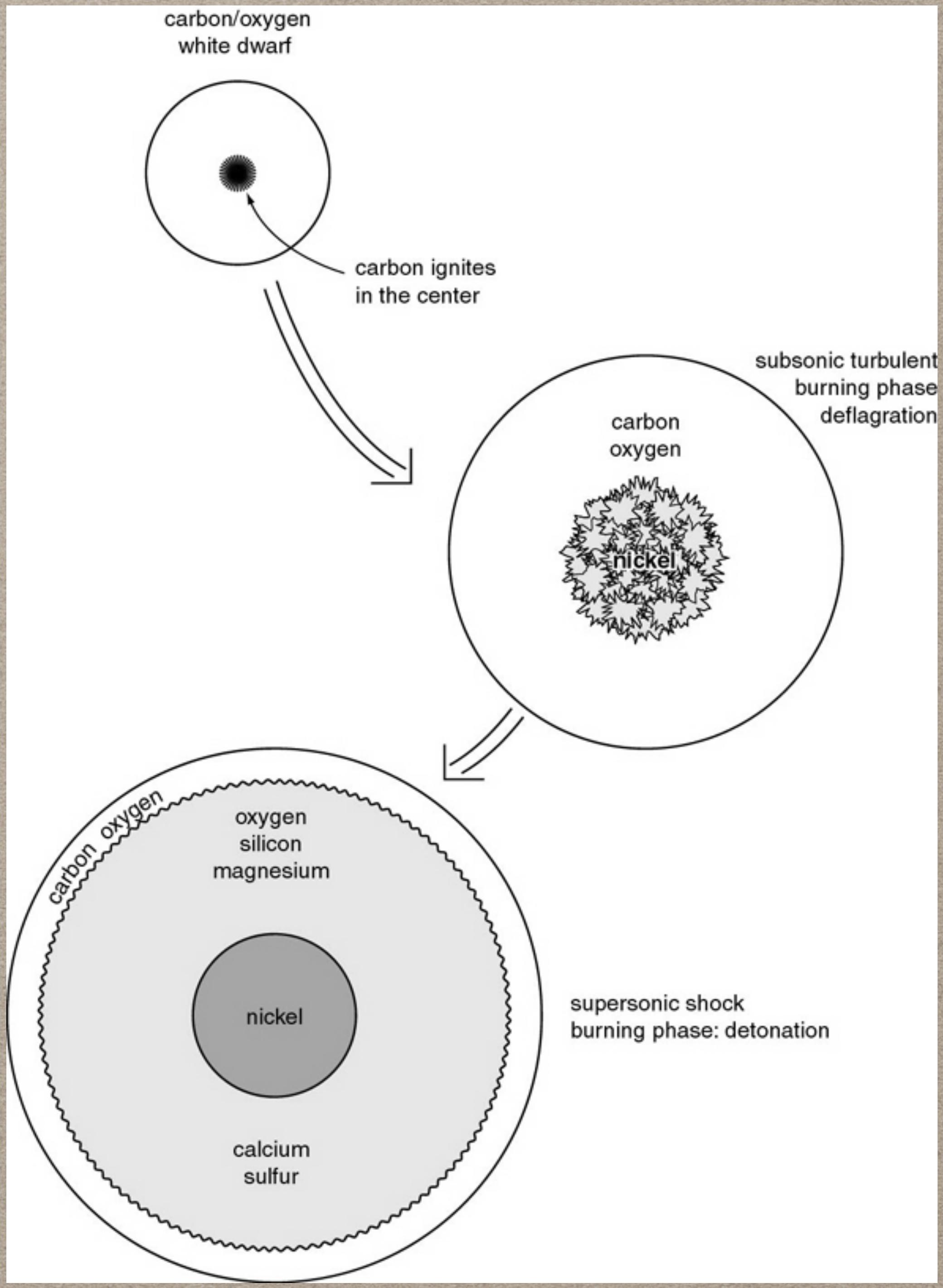
Physics problem - why does the subsonic deflagration change to a supersonic detonation?

Important problem of terrestrial physics as well as supernovae.

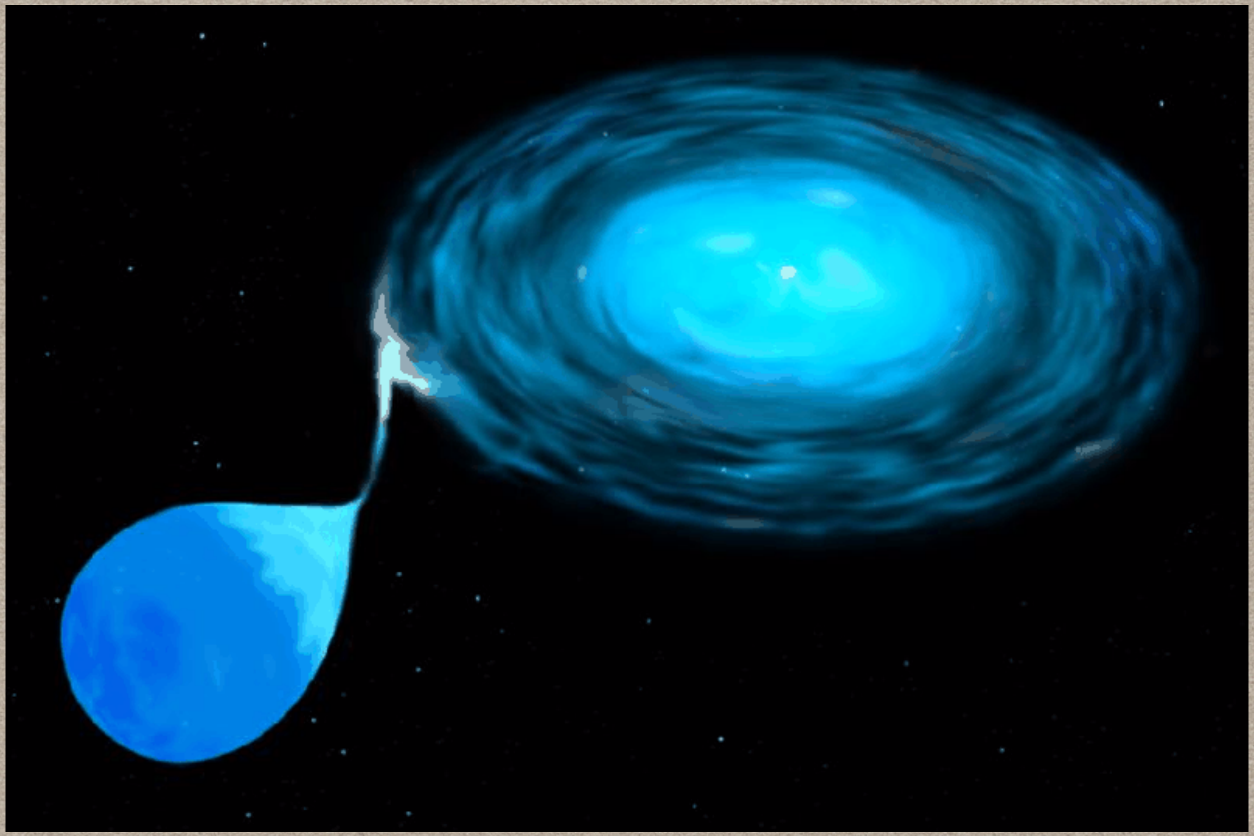
Pipeline, mine, tanker car explosions – the recent disasters in San Bruno, California, 2010, Upper Big Branch mine in West Virginia, 2010, West, Texas fertilizer explosion 2013, oil train explosions involved a detonation, more violent, dangerous than a "flame."'

Very recent, highly detailed **supercomputer simulations** suggest that turbulence packs the subsonic flame until no matter which way it goes, it runs into another flame.

Rapid burning of turbulent, packed region triggers detonation.



HOW TO GROW A WD TO THE CRITICAL MASS



Most popular model: Type Ia are Chandrasekhar mass, 1.4 $M_\odot$, carbon/oxygen white dwarfs; many, if not all, are old.

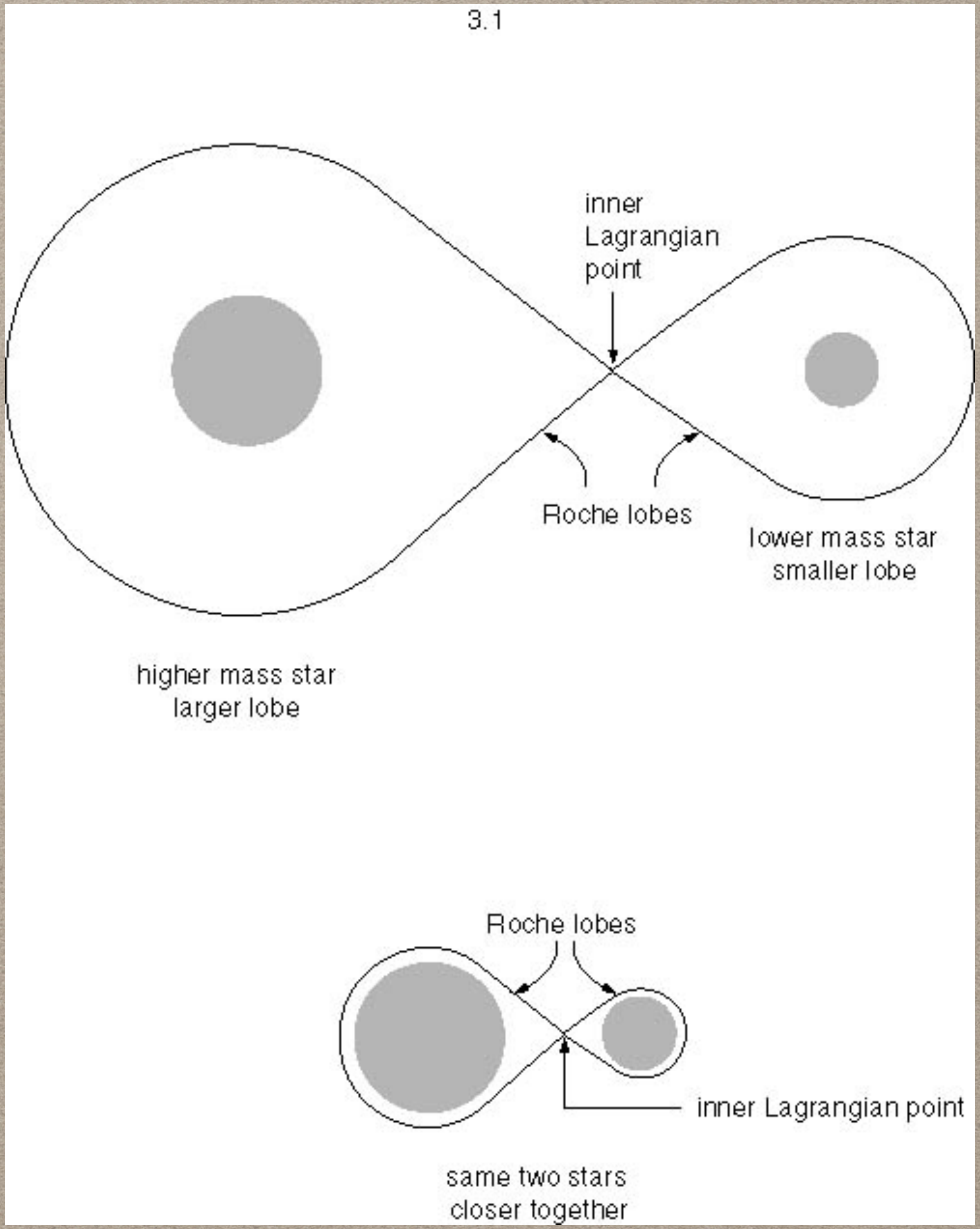
Only credible idea is to grow a white dwarf by **mass transfer in a binary system**.

No direct evidence in Type Ia explosions for binary systems, some recent indirect hints.

How does nature grow a white dwarf to 1.4 $M_\odot$?

MASS TRANSFER IN BINARIES - I

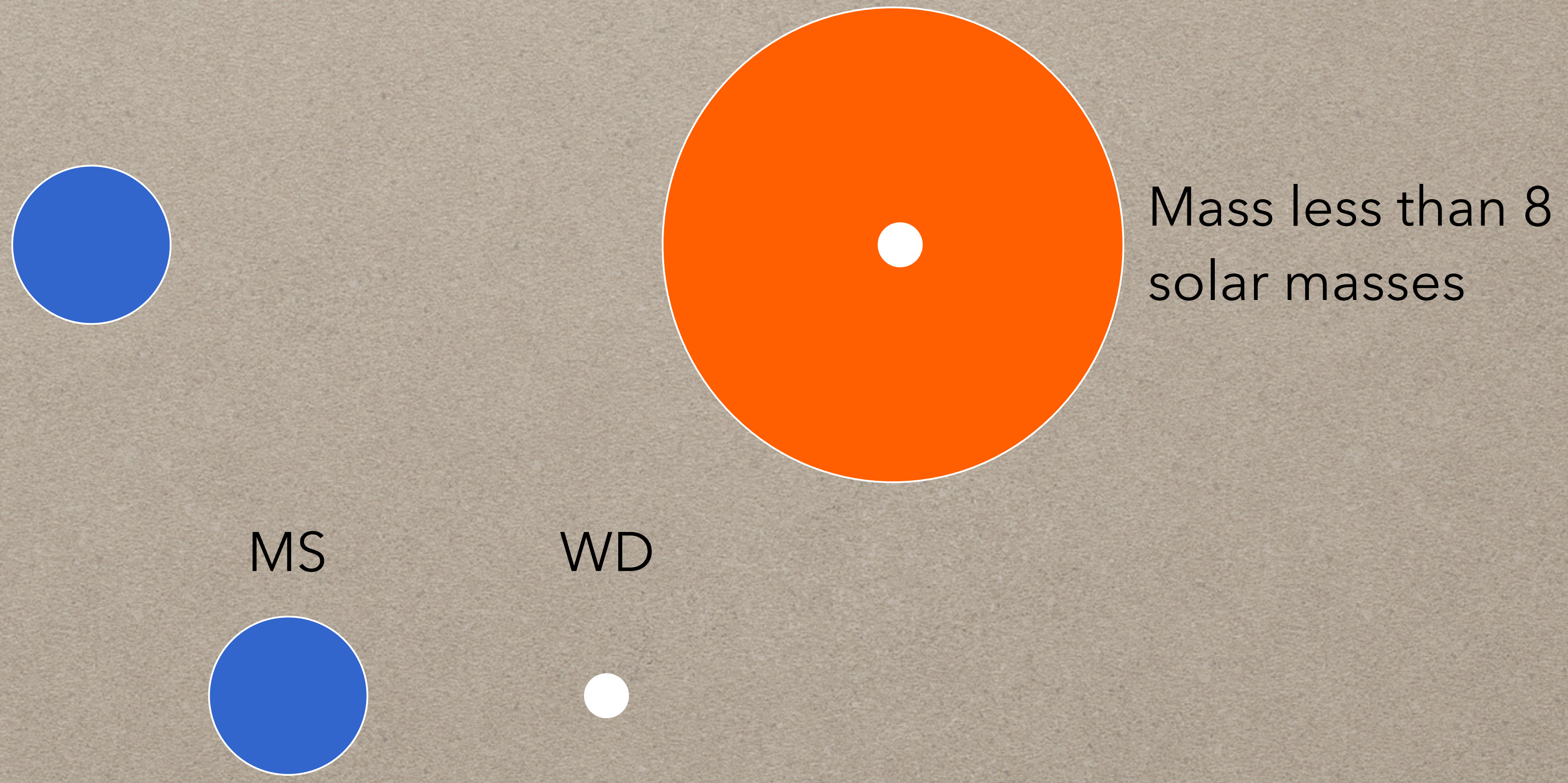
Roche lobe is the gravitational domain of each star. Depends on size of orbit, but more massive star always has the largest Roche lobe.



Caution: the most massive star may not have the largest radius!

MASS TRANSFER IN BINARIES - II

In common circumstances for binary star systems, all the hydrogen envelope is transferred to the companion (or ejected into space), leaving the core of the red giant as a white dwarf orbiting the remaining main sequence star (if the red giant were more massive, the helium core would evolve to be a Type Ib/c).



ACCRETION DISKS

First star evolves, sheds its envelope, leaves behind a white dwarf.

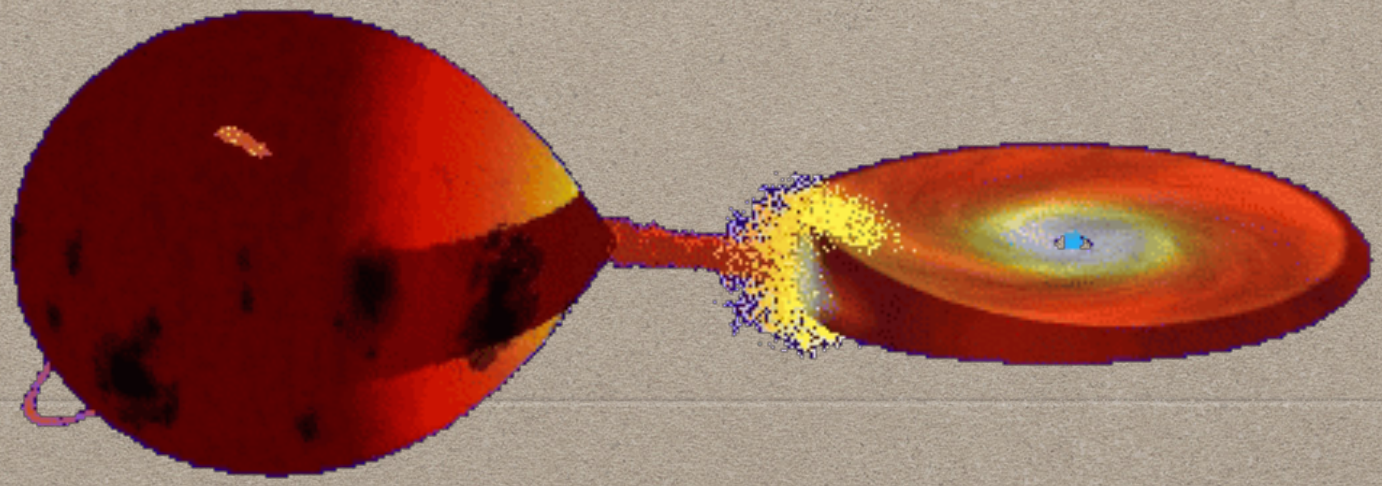
Then the second star that was ***originally*** the less massive evolves, fills its Roche Lobe and sheds mass onto the white dwarf.

The white dwarf is a tiny moving target, the transfer stream misses the white dwarf, circles around it, collides with itself, forms a ring, and then settles inward to make a flat disk.

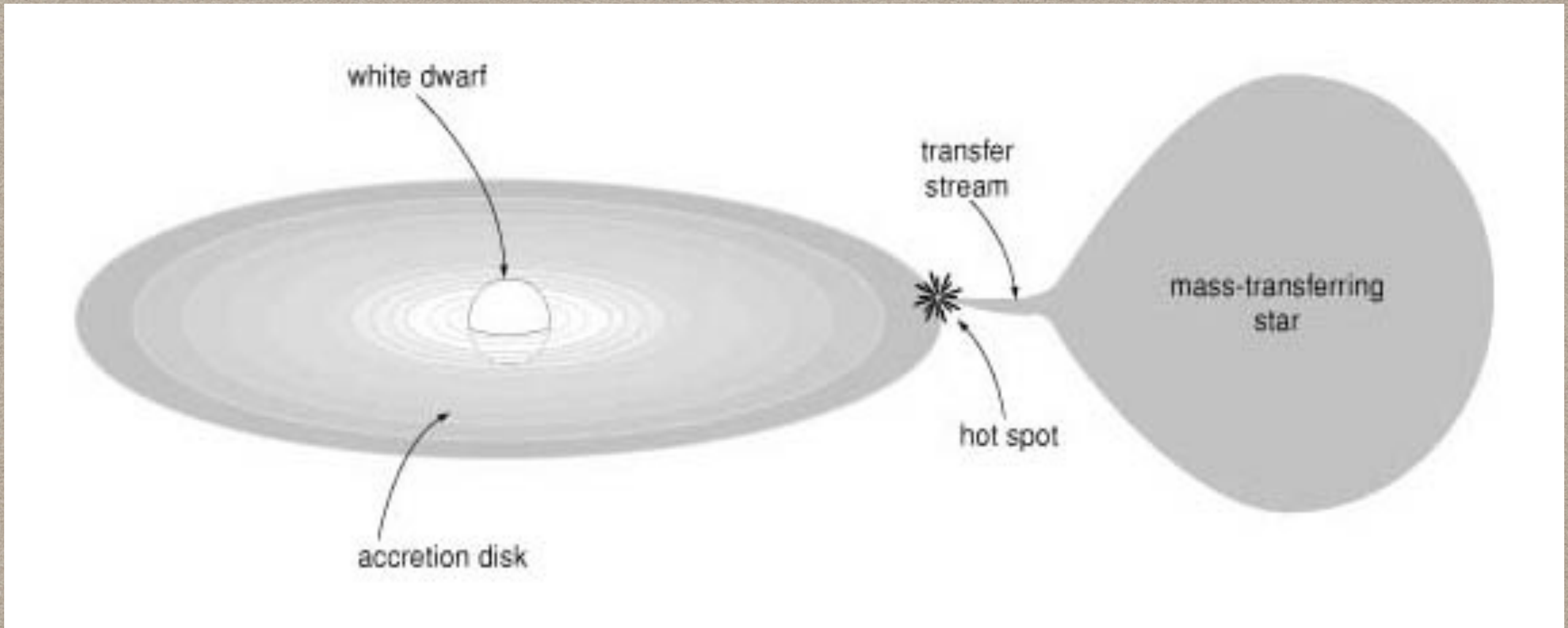
Matter gradually spirals inward, a process called ***accretion.***

$\Rightarrow$ the result is an ***Accretion Disk***

An accretion disk requires a transferring star for supply and a central star to give gravity, but it is essentially a separate entity with a structure and life of its own.



CATACLYSMIC VARIABLES



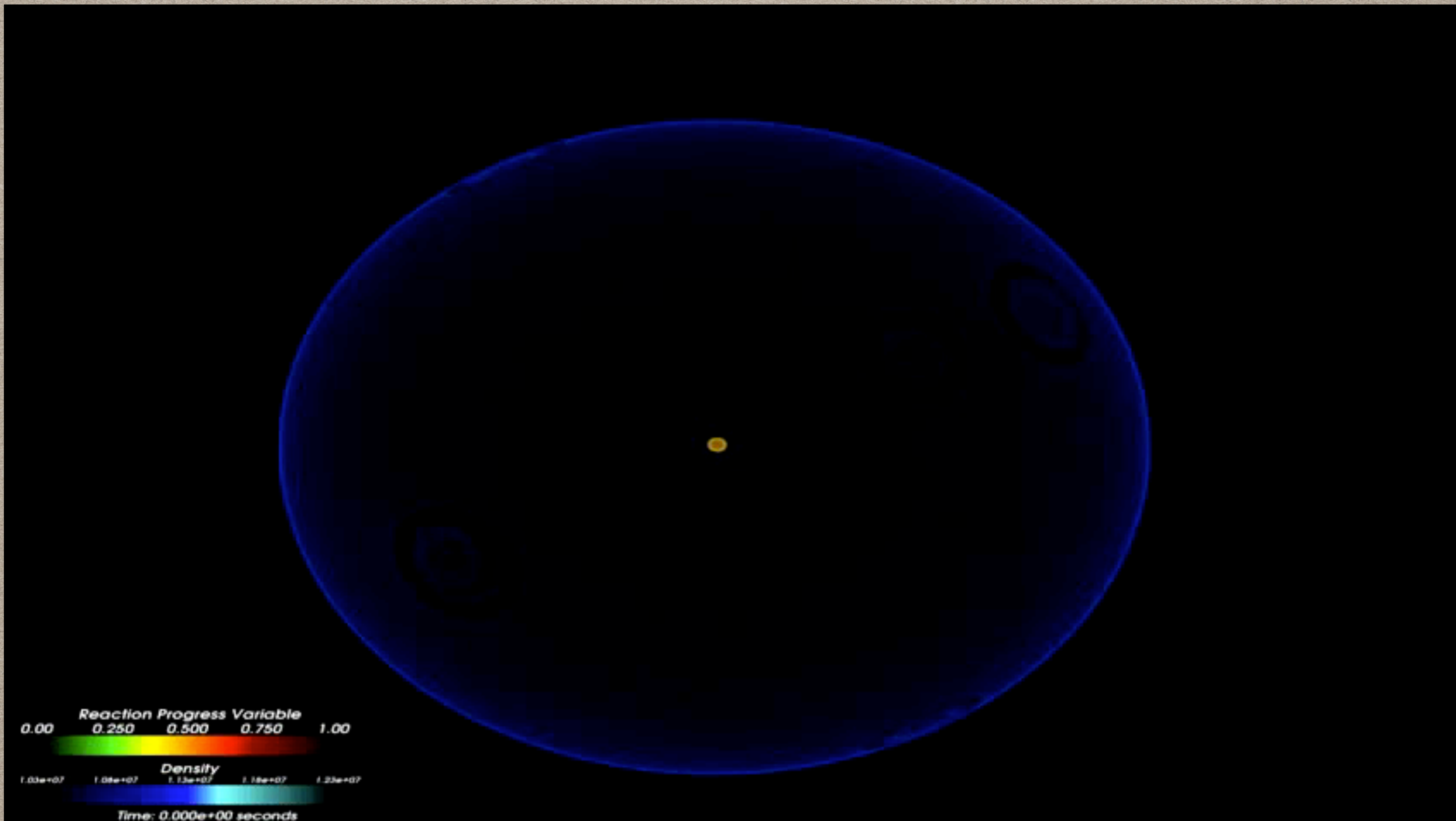
Second stage of mass transfer

General Category "Novae"

"New" stars flare up, see where none had been seen before.

All CVs share same general features: ***transferring star***, ***transfer stream***, ***hot spot***, ***accretion disk***, and ***white dwarf***.

SUPERCOMPUTER SIMULATION OF SD MODEL



Full three-dimensional simulation performed with the University of Chicago FLASH code at the Argonne National Lab supercomputing facilities

AN ALTERNATIVE: DOUBLE WD MERGERS

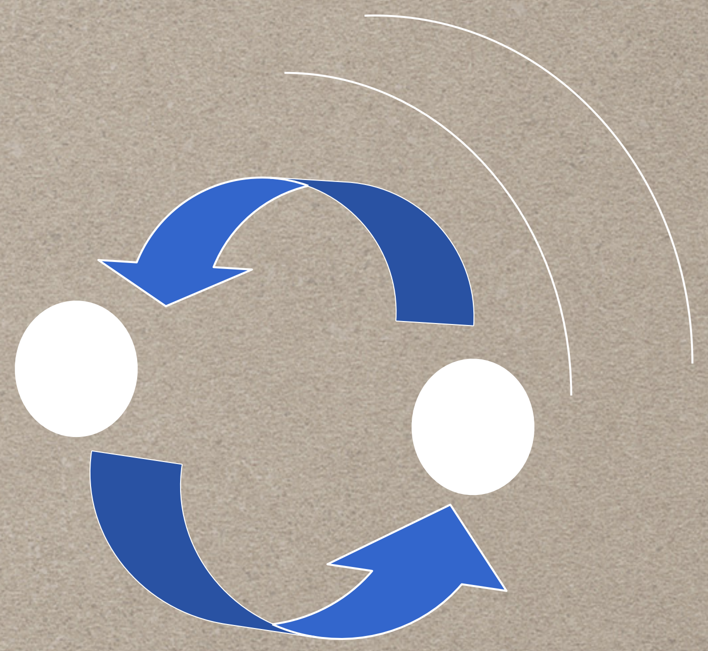
We do observe 2 white dwarfs in orbit in some cases - is that the end?

No: ***gravitational radiation***

ripples in curved space-time

like paddle on surface of pond

remove energy from orbit - acts as drag



If you try to slow down an orbiting object what happens?

Falls inward, speeds up,
Get more gravitational radiation, more in-spiral

Given enough time (billions of years) 2 white dwarfs must spiral together!

SPIRALING DOWN INTO THE ABYSS

What happens when two white dwarfs spiral together?

New physical fact: Larger mass WD has smaller radius

- *Which WD has the smaller Roche lobe?*

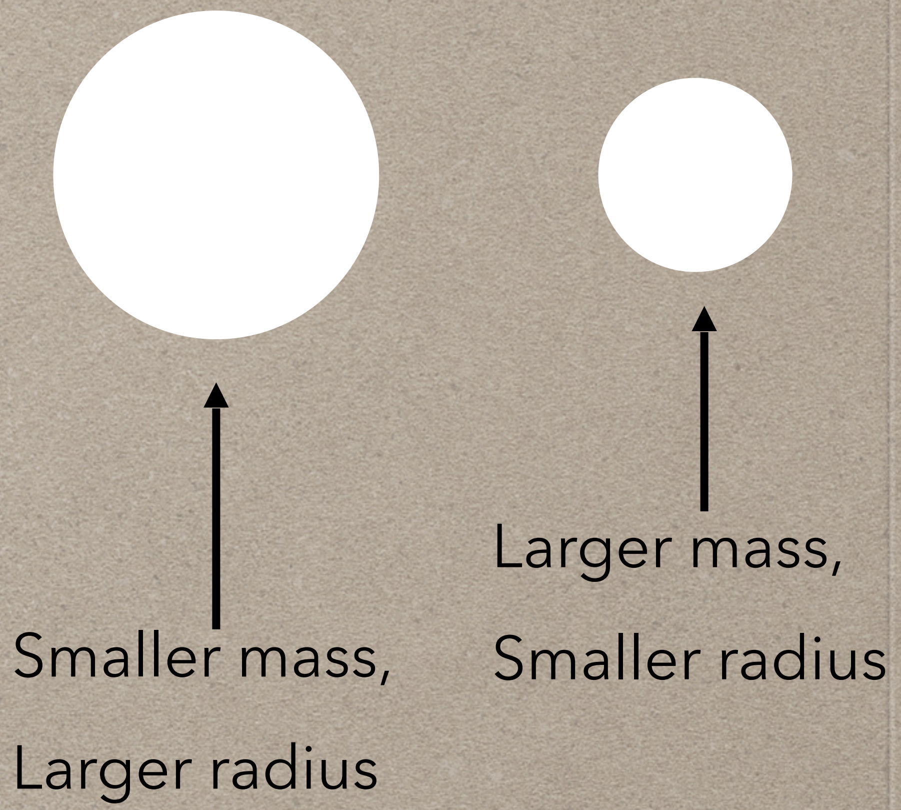
  The smaller mass

- *What happens to the Roche lobes as the WDs spiral closer by gravitational radiation?*

  They both get smaller

- *Which fills its Roche Lobe first?*

  Must be the smaller mass



As small mass WD loses mass, its ***radius gets larger***, but its ***Roche Lobe gets smaller***! Runaway mass transfer.

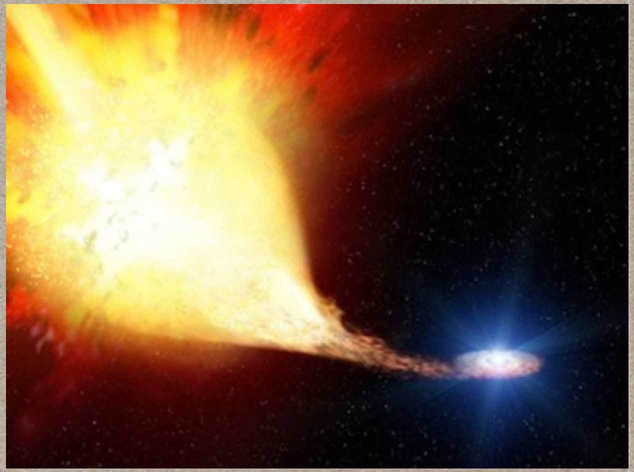
Small mass WD transfers essentially all its mass to larger mass WD

Could end up with one larger mass WD

If larger mass hits M_{ch} → could get explosion => **Supernova**

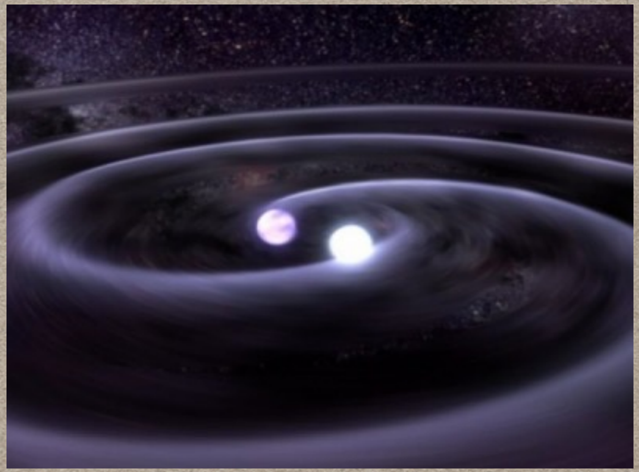
THE TWO COMPETING MODELS FOR SN IA

1) The first white dwarf to form, from the originally most massive star, grows to very near the Chandrasekhar mass, ignites carbon and explodes while the other star is still transferring mass. Models give good spectra, but no companion yet seen before or after the explosion.



Single Degenerate

2) Two white dwarfs form, spiral together, the least massive one is torn apart when it fills its Roche lobe and the most massive one grows to near the Chandrasekhar mass, ignites carbon and explodes. Expect not to see a companion, people pessimistic that these models predict the right spectra.



Double Degenerate

Astronomers are still trying to determine which (if either or both) works.

SN IA AS TOOLS TO MEASURE DISTANCES IN THE UNIVERSE

Edwin P. Hubble

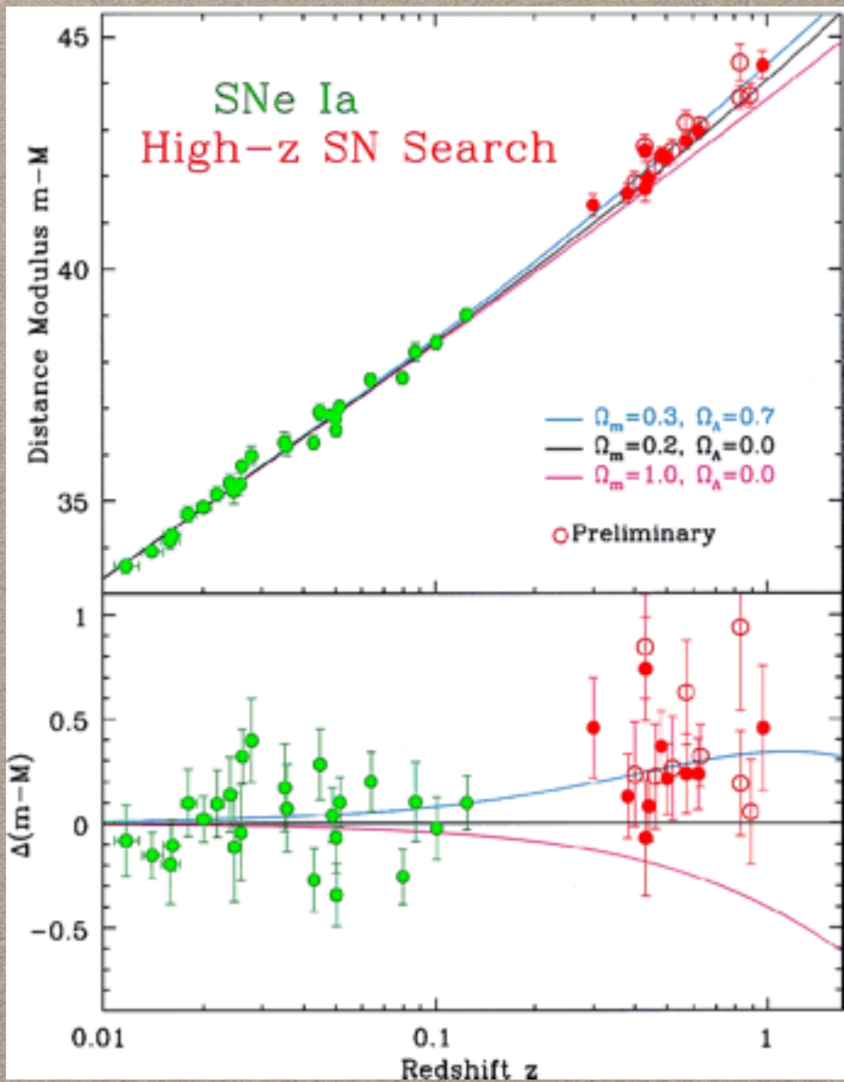
>> The WD progenitors of SN Ia are very similar mainly due to the Chandrasekhar limit requirement for explosion

>> As such they produce explosions with very similar luminosities and durations.

>> In astronomy, if we measure the *observed* brightness of an object and we also know it's *intrinsic* brightness we can measure its distance!

>> SN Ia -> "**Standard candles**"

>> **Hubble law**: Distance vs recession velocity.



COSMOLOGY WITH TYPE IA SUPERNOVAE

Type Ia Supernovae: the distant light posts of the Universe

- ➢ Type Ia Supernovae are even brighter than Type II Supernovae by almost 100 times!
- ➢ As such, they can be found at great, cosmological distances.
- ➢ Observing Type Ia supernovae at large distances help constrain the properties of the Universe itself.
- ➢ Research led to Nobel prize in physics in 2011.

From left to right: S. Perlmutter, A. Riess & B. Schmidt

SN 2014J: HAPPENED LAST YEAR IN OUR GALACTIC NEIGHBORHOOD!

SUMMARY

- Type Ia supernovae result from the explosions of degenerate white-dwarf stars.
- WDs explode when their mass exceeds the critical "Chandrasekhar limit" of 1.4 Msun.
- To grow the mass of a white dwarf to that limit it has to gain mass via mass transfer.
- To match the observations of SN Ia the explosion of the white dwarf must involve transition from deflagration (subsonic burning) to detonation (supersonic burning).
- The Single Degenerate (SD) scenario for SN Ia involves mass transfer to the white dwarf from a giant star in a binary system.
- The Double Degenerate (DD) scenario involves the merger of two white dwarfs in a binary system.
- Astronomers are still debating what channel is more relevant to SN Ia.
- SN Ia have very similar luminosities and can be observed at large distances due to their brightness. As such cosmologists use them as "standard candles" to measure distances in the Universe and determine its fate.