THE BIRTH OF STELLAR-MASS BLACK HOLES

Lecture 6, Introduction to Black Hole Astrophysics (PHYS480)

Hsiang-Yi Karen Yang, NTHU, 3/30/2021

M87 SMBH with magnetic field measured from polarization [News link here]

ANNOUNCEMENTS

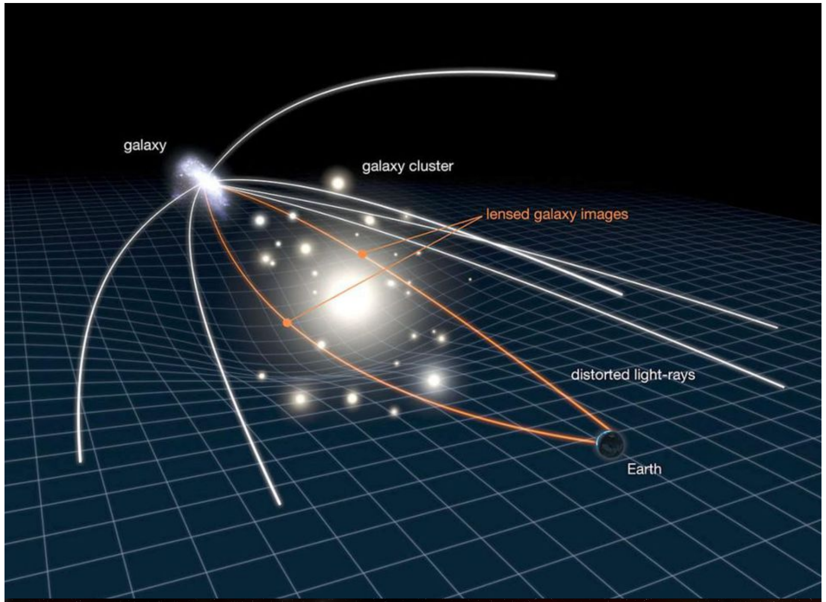
- HW2 solutions will be posted on iLMS today. TA and me will provide answers to Q1 & Q5 and share them on iLMS
- ***HW3 will be posted on iLMS and course website today. It is due next Wednesday (4/7) at 13:30, online or directly to TA/me***
- Please start searching for black hole news for the oral presentation. Once you decide on the topic, please paste the news link here:

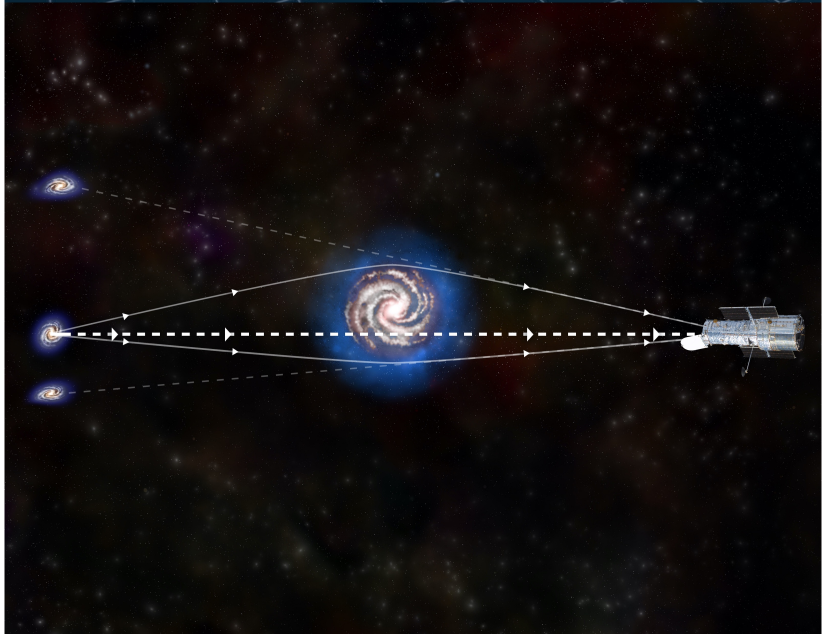
https://docs.google.com/spreadsheets/d/1_aYyMj1wf_uGheZ7zp_hvthmy4mdmPwIxFDdZOMG-nc/edit?usp=sharing

- The grading rubric for the oral presentation is available on iLMS. Please prepare your talk accordingly.
- Don’t forget to tell the TA if you’ve asked questions during or after class to receive the participation points (10 points in total)!

Q5 OF HW2 – MIRRORING EFFECT AROUND EINSTEIN RING?

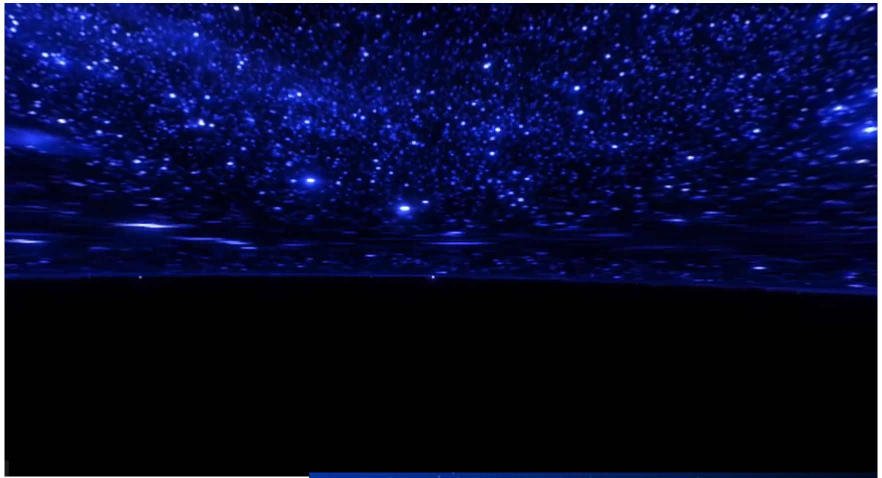
- Recall that the Einstein ring comes from the ***gravitational lensing*** effect
- The "ring" is a special case when the background source is exactly behind the lens
- If the source has an offset w.r.t the axis, it will create images on opposite sides of the lens, one within the Einstein ring, the other outside the Einstein ring
- As the source moves, these two images would move accordingly, called "***mirroring effect***"

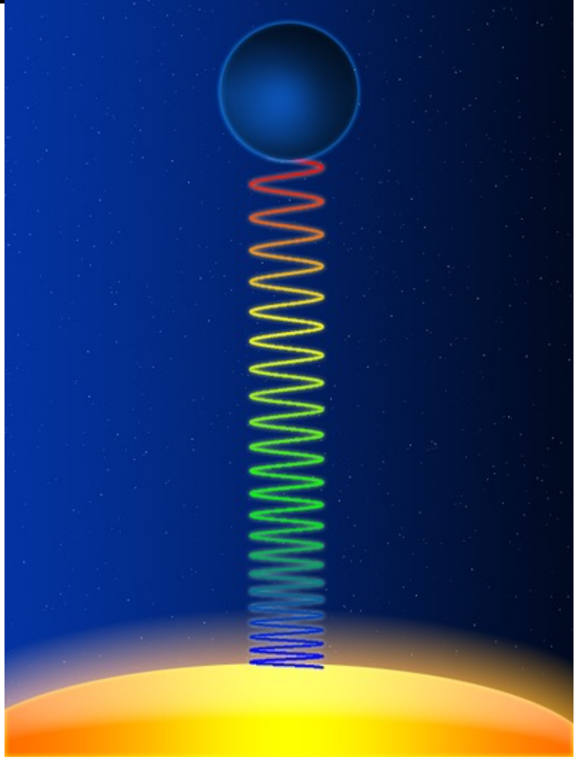




Q5 OF HW2 – WHY THE STARS APPEAR BLUE-SHIFTED?

- Recall ***gravitational redshift*** occurs because photons would lose energy when it climbs out of the curved spacetime of a massive object
- As we fall into the BH, the effect is inversed – photons emitted by distant galaxies gain energy as they approach the BH and would appear to be blue-shifted as viewed by us
- Note that in the video, Doppler's effect is ignored





REDSHIFT EFFECTS

- In reality, the amount of redshift/blueshift of light needs to account for all the following three effects, i.e., $z = z_g + z_d + z_c$

1) Gravitational redshift: $\boxed{z_g = \frac{1}{\sqrt{1 - r_S/r}} - 1}$ Steeply rising as r -> r_S

2) Doppler's effect: $\boxed{z_d \cong \frac{v}{c}}$ or $\boxed{z_d^{rel} = \gamma\left(1 + \frac{v}{c}\right) - 1}$ Steeply rising as v -> c

3) Cosmological expansion: $\boxed{z_c \cong \frac{H_0 D}{c}}$ or $\boxed{z_c = \frac{a_{now}}{a_{past}} - 1}$ Gradually rising

PREVIOUS LECTURE…

- ***Cygnus X-1*** is the first candidate of smbhs
  - Mass derived from orbit of the companion star
  - Size inferred from variability
  - X-ray properties different from accreting neutron stars (no pulses or X-ray bursts)
- So far dozens of smbhs (with dynamical masses) detected via X-ray, orbits, and gravitational waves
- X-ray binaries: accreting NSs or BHs, LMXB and HMXB, their distributions within the Milky Way and nearby galaxies
- Why study smbh? They are mini AGNs and they hold key for ***stellar evolution***

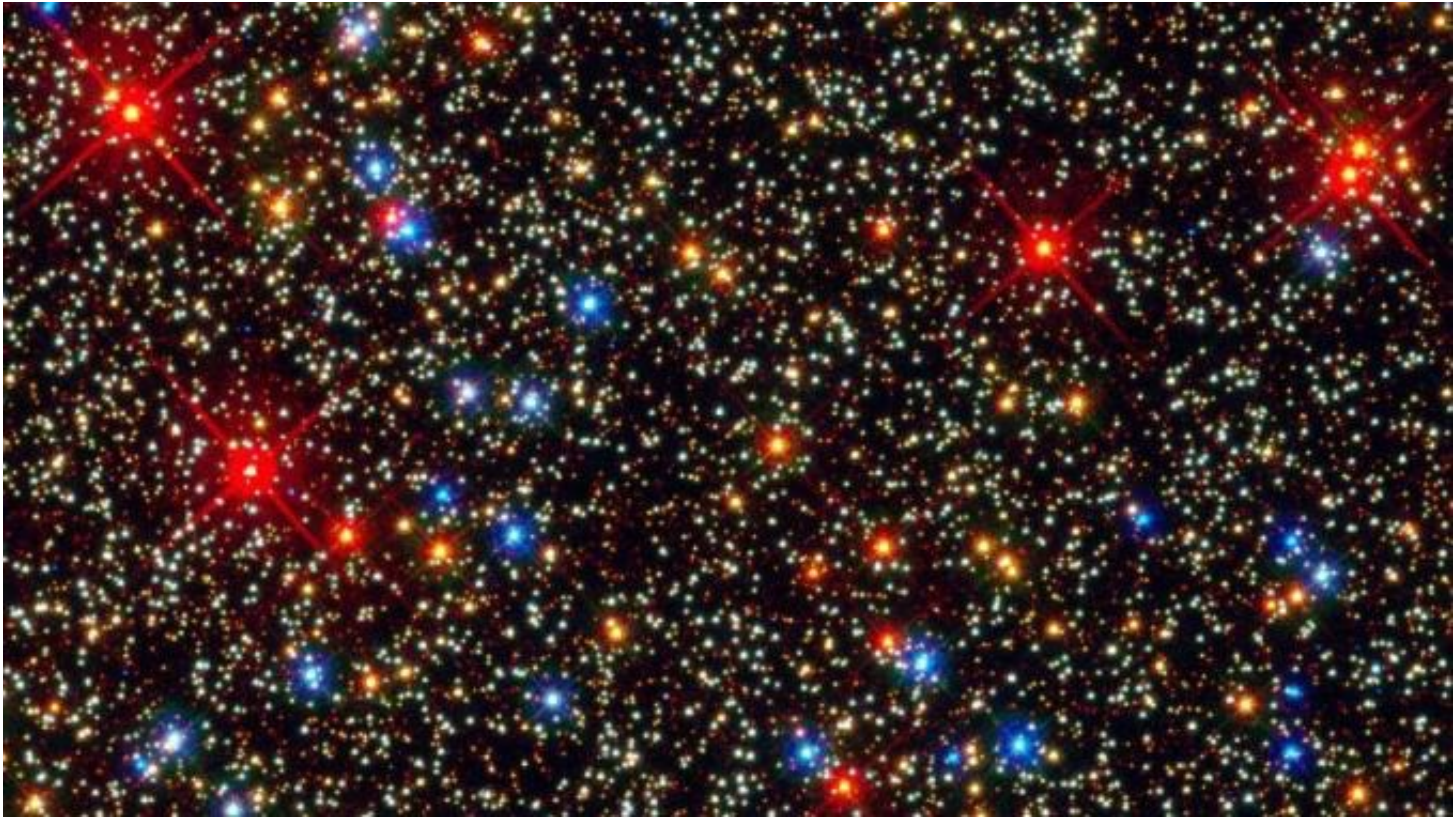
PREVIOUS LECTURE…

- ***Quasar 3C 273*** is the first candidate of SMBHs
  - Highly redshifted spectral lines -> distant and luminous
  - Variability and large luminosity consistent with a SMBH
- ***Sgr A* at the Galactic center*** is the first SMBH candidate with the accurate mass constraints
- ***M87 SMBH*** is the first confirmed BH with an event horizon
- Essentially every massive galaxy hosts a SMBH at the center, and they lie on the ***M-σ relation***
- SMBHs grow via mergers and accretion during the process of hierarchical galaxy formation
- However, quasars are more common in the early universe – "***downsizing***"
- Why study SMBHs?
  - Radiation and jet ***feedback*** of SMBHs are critical for understanding galaxy evolution
  - Their origin is still unknown!

THIS LECTURE

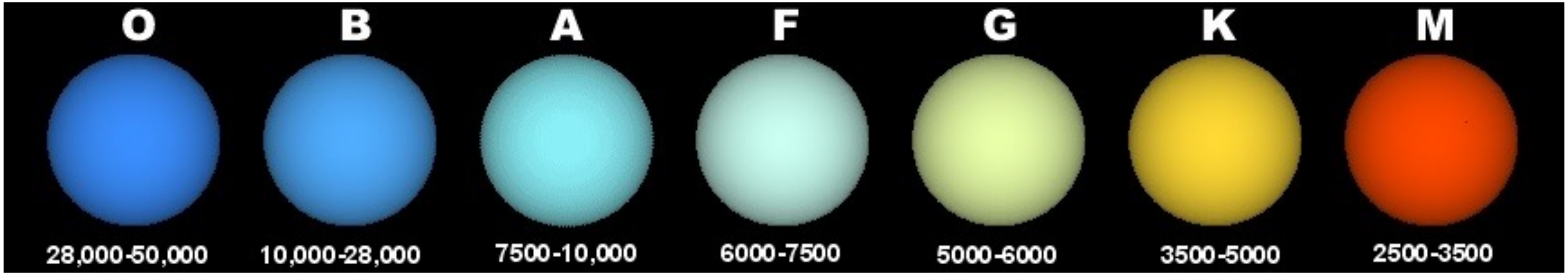
- A crash course on ***stellar evolution***!!
- How low-mass and high-mass stars evolve
- The different fate of stars and their properties
  - White dwarfs (WDs)
  - Neutron stars (NSs)
  - Stellar-mass black holes (smbhs)
- Evolution of binary stars

HOW STARS EVOLVE

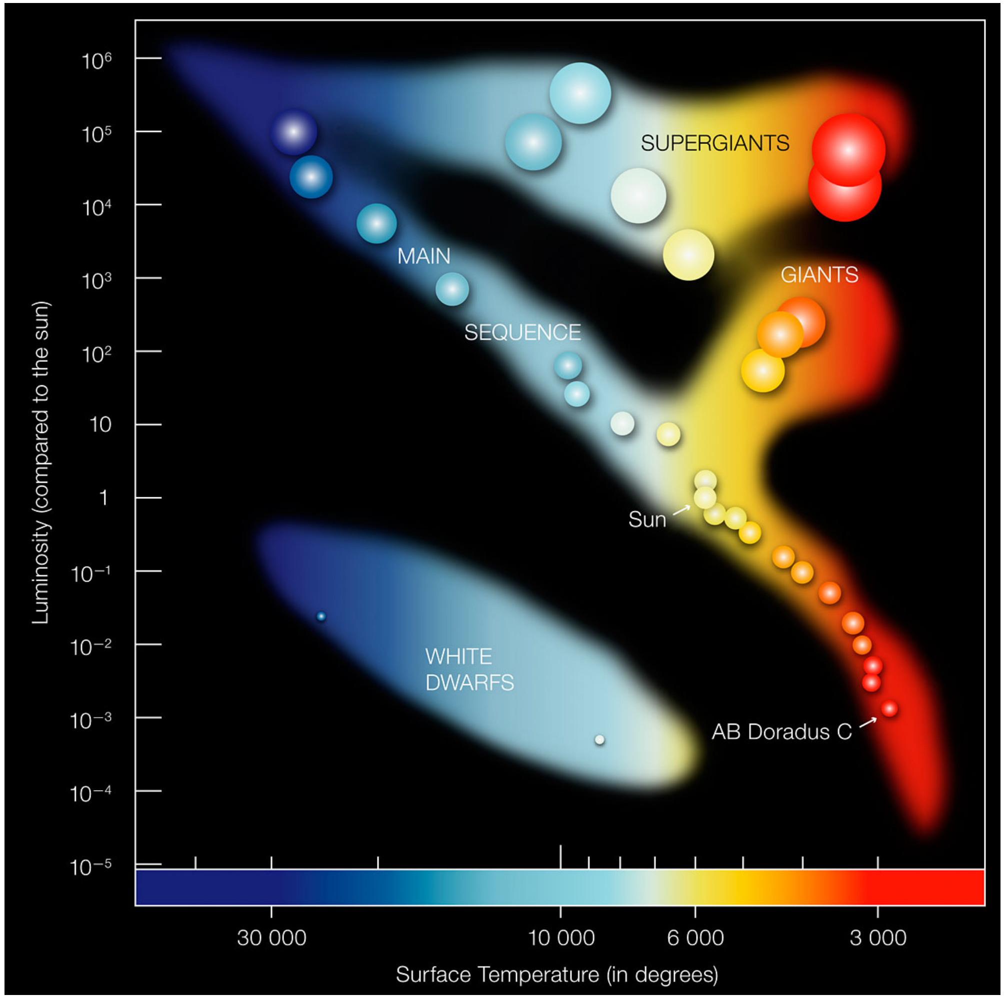


SOME REMINDERS ABOUT STARS

- Stars form in dense molecular gas (e.g., Orion nebula)
- Initial masses vary widely : 0.1-100 M_{sun}; high-mass stars are rare
- Stars have variety of ***colors*** -> ***temperature*** ranging from 3000K-30000K -> ***spectral types***: OBAFGKM
- Stars have variety of ***luminosity*** (0.001 L_{sun} ~ 100,000 L_{sun})



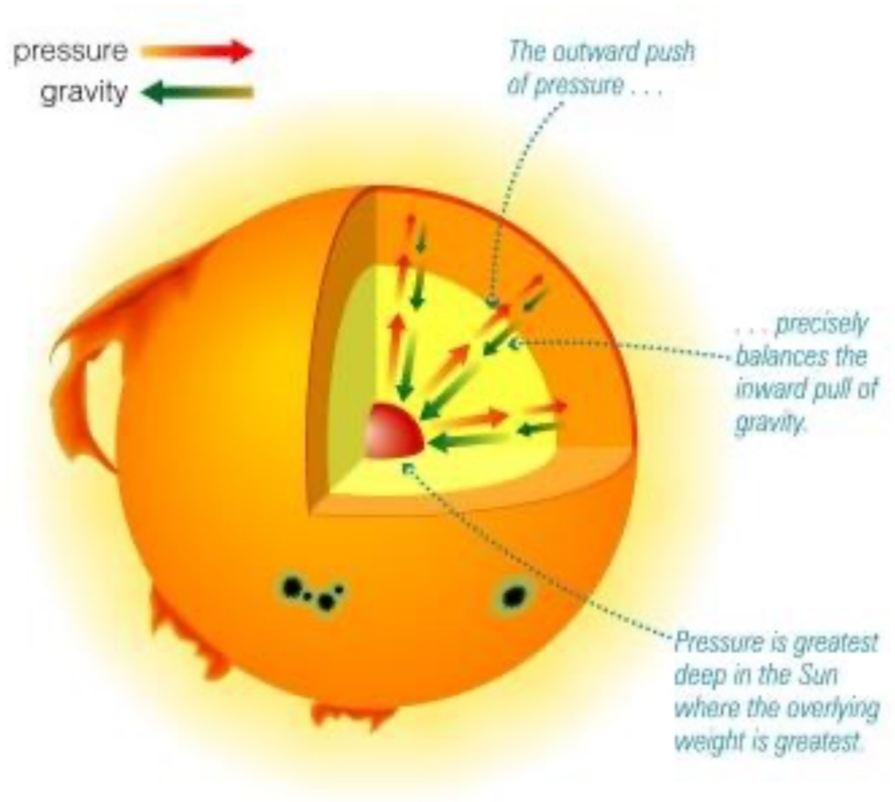
HERTZSPRUNG-RUSSELL (H-R) DIAGRAM



- Most stars lie on the ***main sequence (MS/主序帶)*** on the H-R diagram
  - Stars spend most of their lives on the MS
  - This is the H→ He fusion phase
- Locations on the H-R diagram determined by mass and age
  - On the MS, high-mass = hot, low-mass = cool
  - When stars get old, they leave the MS and flit around the H-R diagram
- When it comes to stellar evolution, ***mass*** is the single most important parameter!

WHAT SUPPORTS THE MS STARS AGAINST GRAVITY?

- If nothing opposed gravity, Sun would collapse within the free-fall time of ~20 minutes!
- For MS stars, gravity is withheld by a ***pressure gradient*** -- “***hydrostatic equilibrium (流體靜力平衡)***”
- This equilibrium is ***stable***
  - When gravity wins, core pressure grows, thereby increasing the pressure gradient that pushes outward



WHAT'S PROVIDING THE PRESSURE?

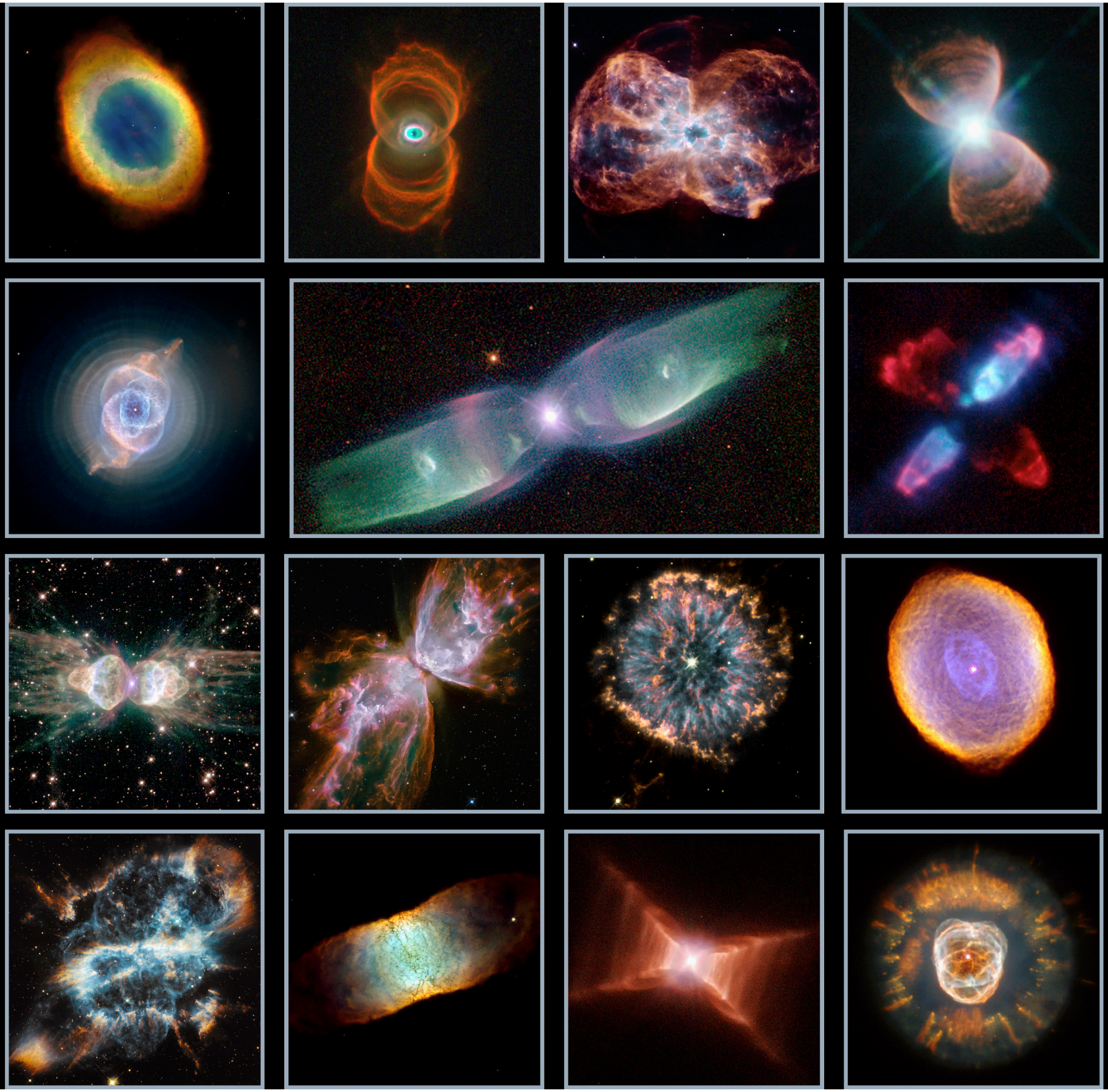
- Hydrogen burning during the MS: 4H -> He
  - 0.7% of mass is converted to energy
  - ~10^6 times more efficient than chemical burning
- Eventually, the star runs out of hydrogen in its core. The time it takes until the star runs out of hydrogen is approximately

$$\tau \approx 1.0 \times 10^{10} \left(\frac{M}{M_\odot} \right)^{-2.5} \text{yr}$$

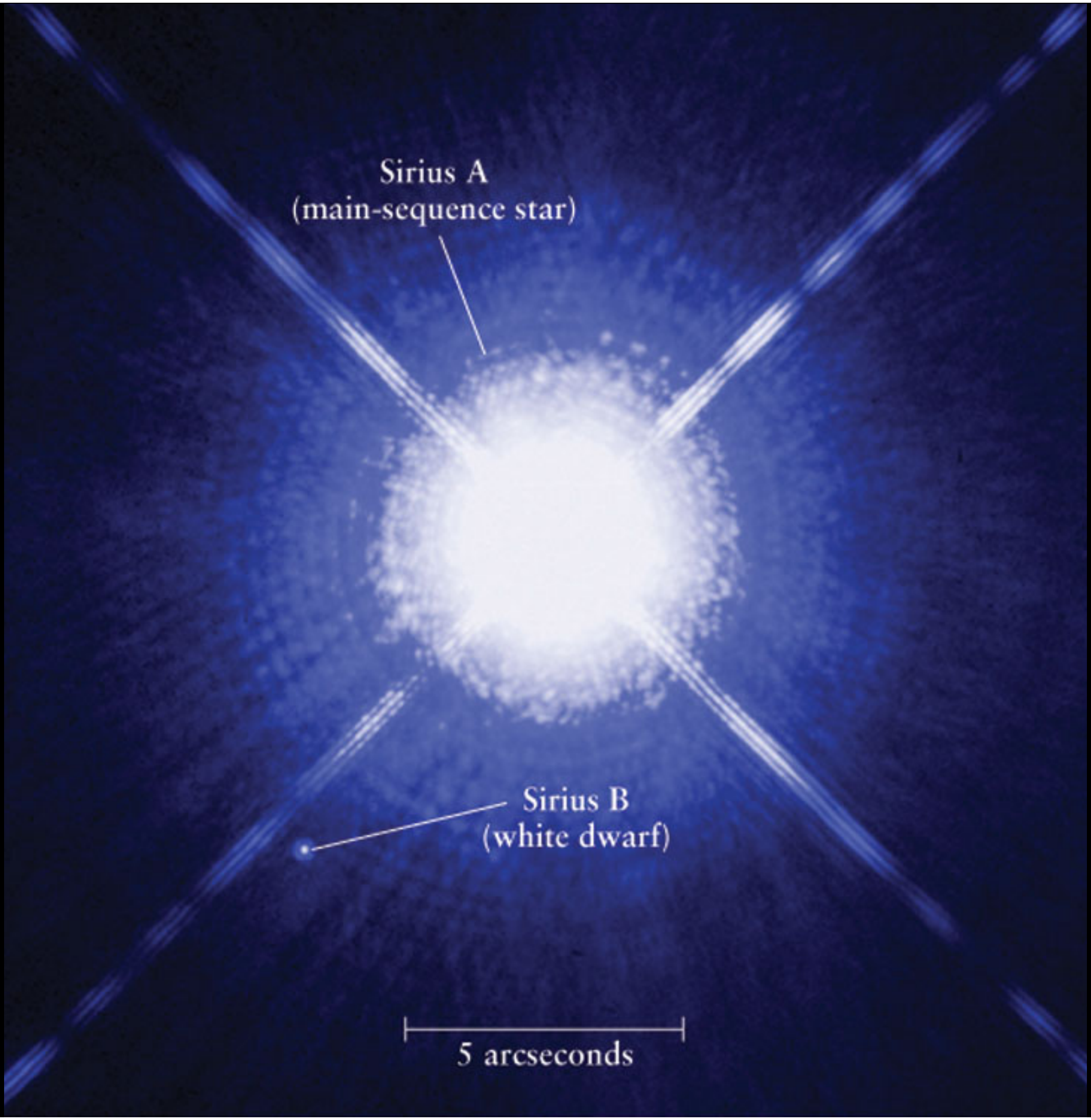
- Sun's lifetime on the MS is about 10 billion years (5 more billion years to go)
- Typical lifetime of a massive star (~40 M_{sun}) is about Myr

POST-MS EVOLUTION OF LOW-MASS STARS

- Low-mass stars: $M \lesssim 8\,M_{sun}$
- Once hydrogen runs out in core…
  - Energy production stops and pressure gradient reduces
  - Core contracts due to gravity and heats up
  - Envelope of star expands and cool -> becoming a "***red giant (紅巨星)***"
  - Core keeps contracting and ignite helium fusion: 3He -> C
  - Outer atmosphere is expelled as a "***planetary nebula (行星狀星雲)***"
  - When He runs out in the core, core contracts again but temperature not enough to trigger the next fusion process
  - Core collapses into a "***white dwarf (白矮星)***"



Hubble Views Of Planetary Nebula

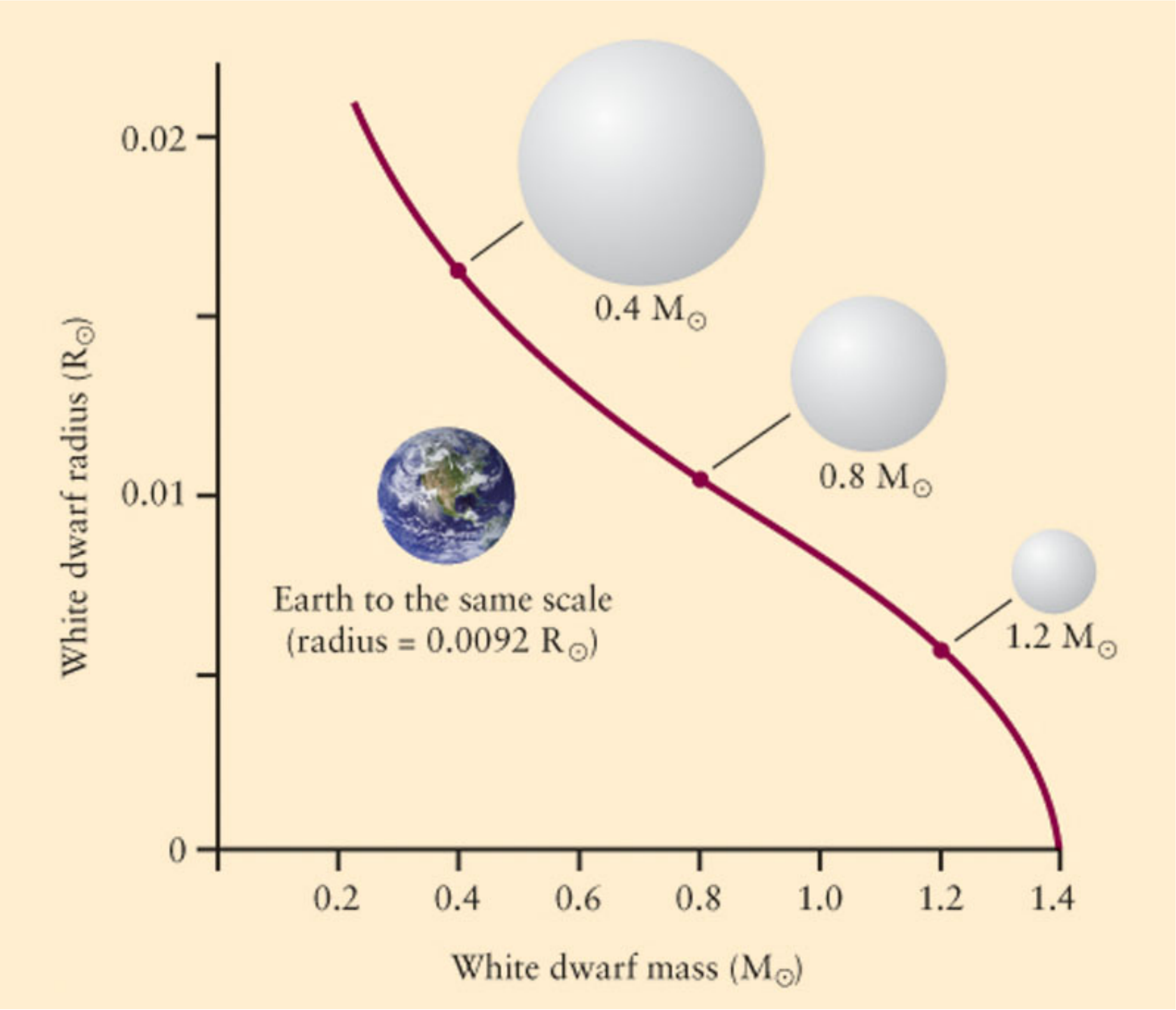

Sirius A
(main-sequence star)
Sirius B
(white dwarf)
5 arcseconds

WHITE DWARFS

Subrahmanyan Chandrasekhar, Age 21

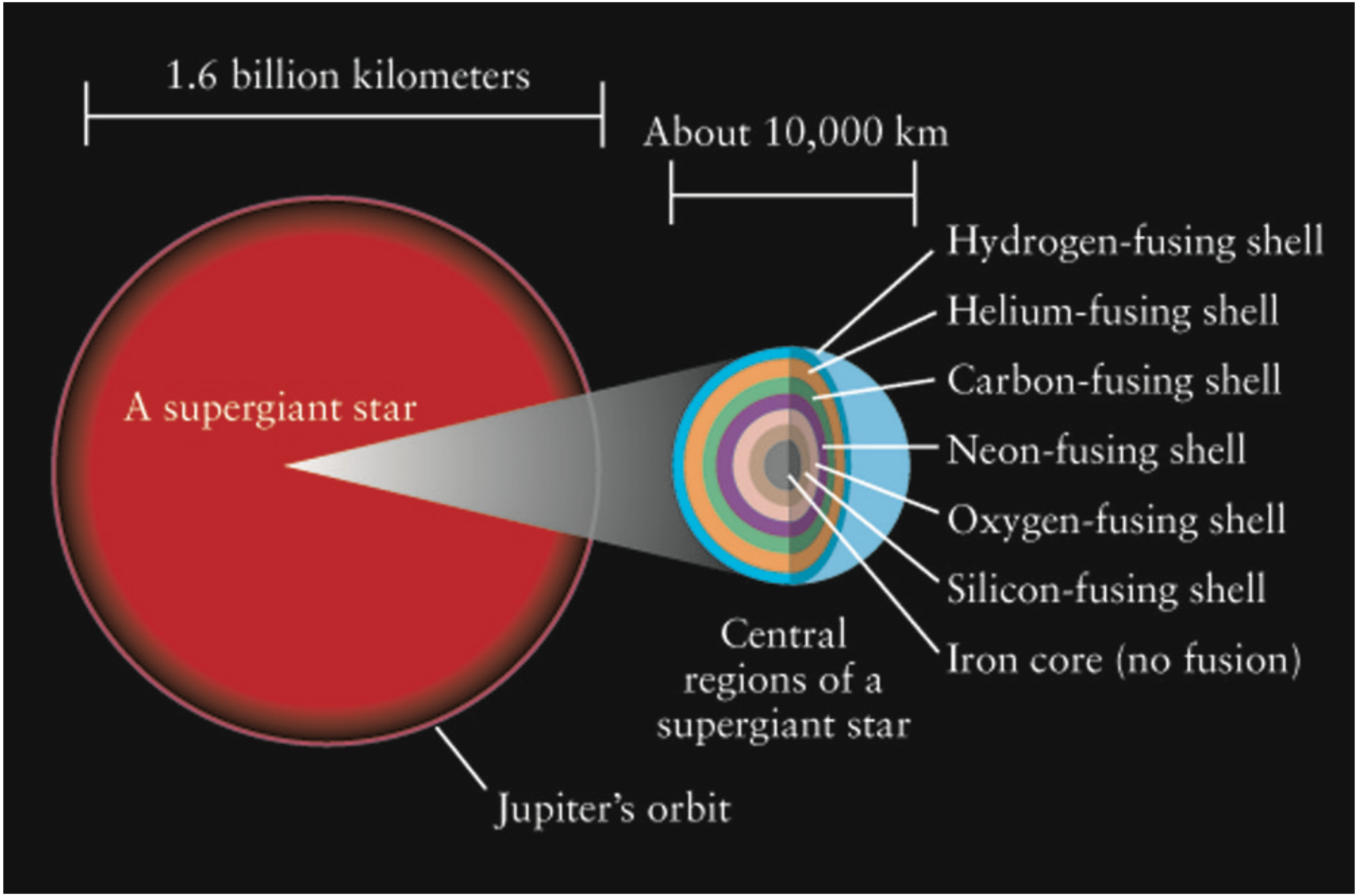
- A compact stellar remnant ("***compact object /緻密天體***") where the gravity is supported by "***electron degeneracy pressure***"
- The degeneracy pressure comes from the Pauli exclusion principle of fermions
  - As the electrons are squeezed into a more and more compact region, they can no longer stay at the ground state but have to occupy higher and higher energy levels
- For more and more massive stars, gravity would squeeze the electrons so that they become relativistic
- Since velocity of electrons has to be < c, there is a mass limit where the above mechanism could work
- In 1931, Subrahmanyan Chandrasekhar derived the "***Chandrasakhar limit***": upper limit of mass of WDs $\sim 1.4\,M_{sun}$

WHITE DWARFS: MASS~SUN, RADIUS~EARTH



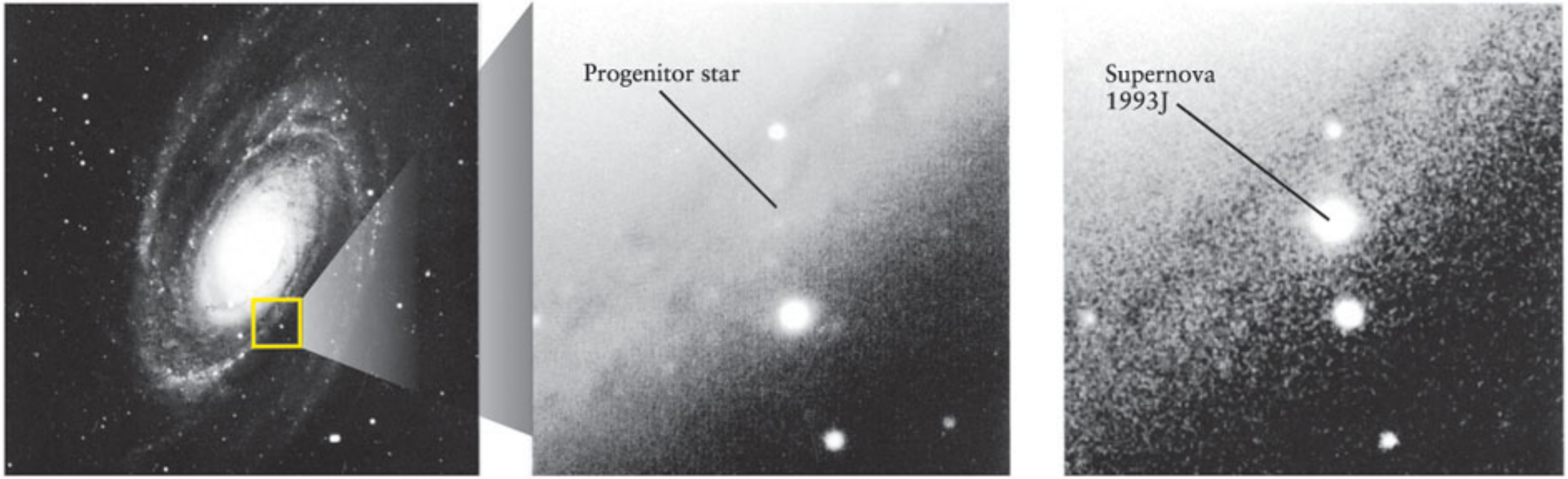
EVOLUTION OF A HIGH-MASS STAR

- Stars with $M \gtrsim 8\,M_{sun}$ take a different path
- Core gets hot enough to trigger nuclear fusion beyond Carbon
  - There is a sequence of reactions that go all the way from H to Fe (iron)
  - The reactions become less and less efficient, so mass must be consumed at a faster rate
  - Iron is the end product as it is the most stable nucleus (fusing it won't generate more energy)
  - End up with an onion-like structure

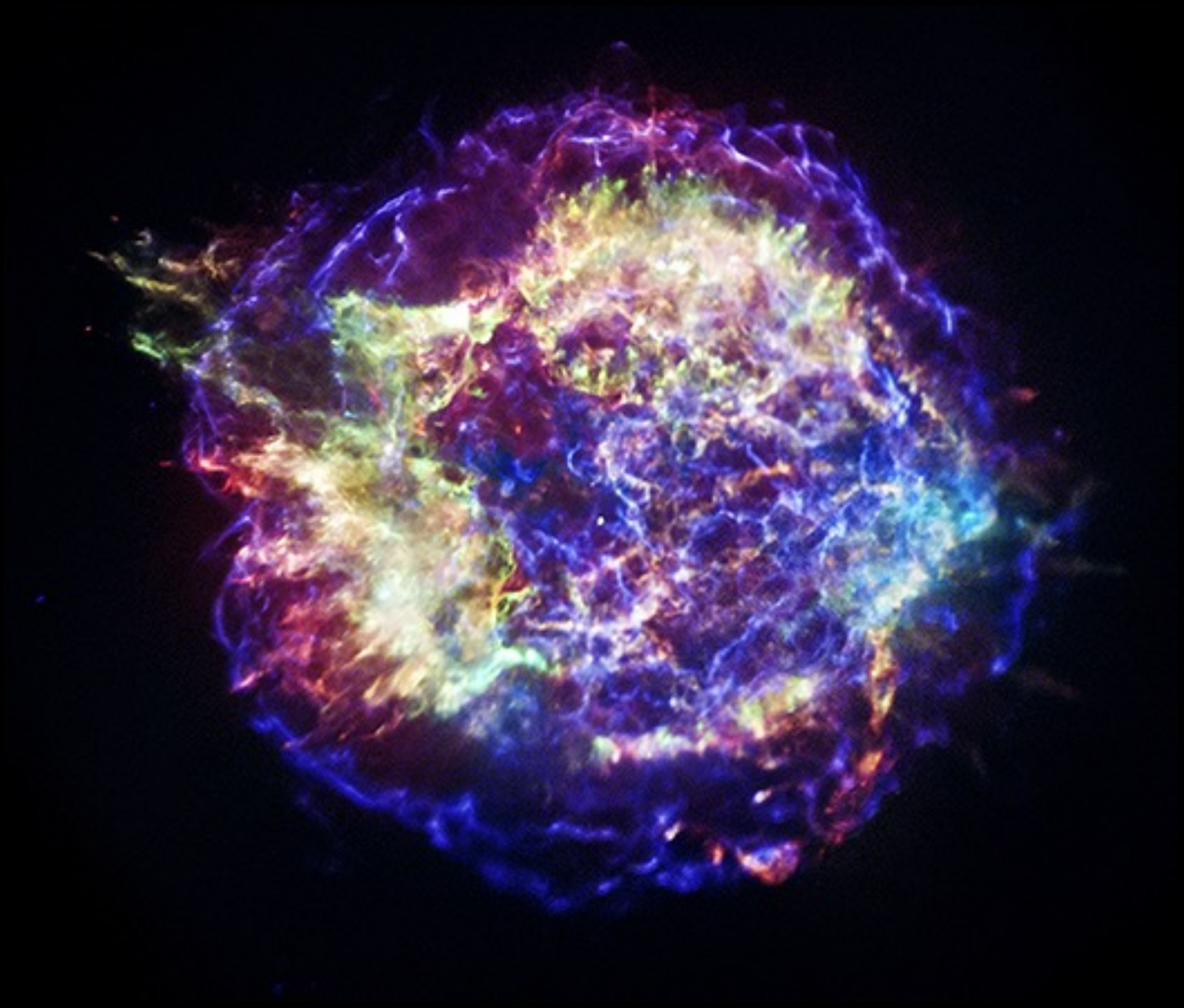

1.6 billion kilometers
About 10,000 km
A supergiant star
Hydrogen-fusing shell
Helium-fusing shell
Carbon-fusing shell
Neon-fusing shell
Oxygen-fusing shell
Silicon-fusing shell
Iron core (no fusion)
Central regions of a supergiant star
Jupiter's orbit

WHAT HAPPENS NEXT?

- Once iron is reached, fusion stops in core
- Without energy production, core is slowly crushed
- When core mass > 1.4 M_{sun}, pressure forces become incapable of supporting core, and the core undergoes catastrophic gravitational collapse in < 1 second
- Core collapse:
  - Releases about 10^{46} J
  - 99% emerge as neutrinos
  - 1% of energy (10^{44} J or 10^{51} ergs) emerges as radiation and kinetic energy
  - Star is blown apart – "***core collapse supernova***" or "***Type II supernova***"
- Supernova explosion is an important mechanism for distributing heavy elements synthesized in massive stars to the universe



(a) Spiral galaxy M81 (b) Before the explosion (c) After the explosion



Chandra X-ray View of Cassiopeia A Supernova Remnant

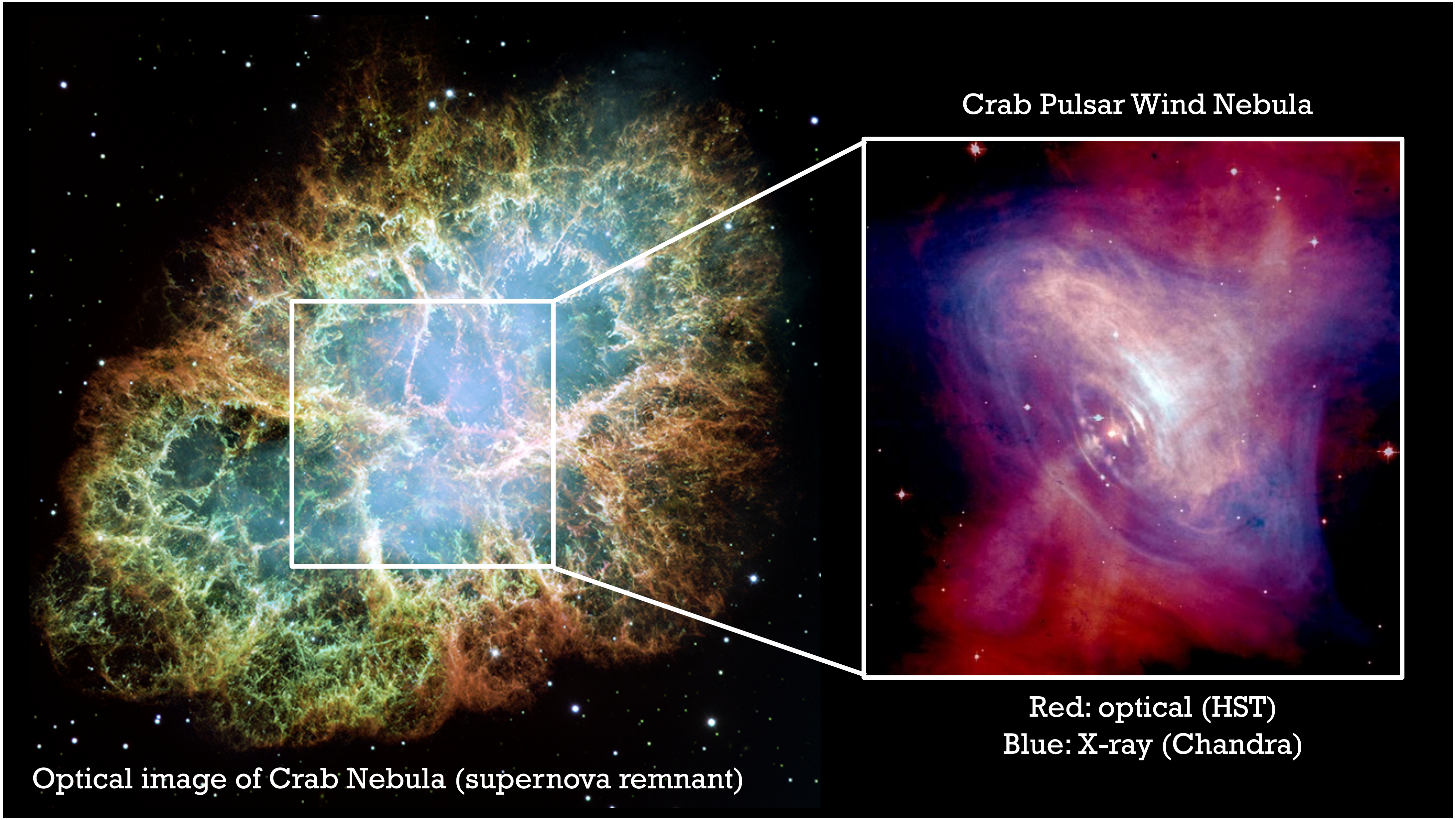
IN TERMS OF SIMULATING SUPERNOVAE…

- It had been a long standing problem in the simulation community to successfully make a star explode as a supernova
  - When core collapses, the bounced materials generate shock waves that propagate outward
  - But the shock waves are always stalled by the infalling materials at outer layers -> no explosions ☹
- Improvements of modeling in recent years
  - 1D -> 2D -> 3D
  - Detailed modeling of interactions between neutrinos and matter
  - Instabilities (by neutrinos, turbulence, etc) are necessary to raise the shock and make the explosion happen
  - **Recent News: Secret Ingredient Found to Power Supernovas**

WHAT HAPPENS TO THE CORE?

- If initial mass M < 20 M_{sun}, become a ***neutron star***
  - Final mass M ~ 1.5 – 3 M_{sun}, R ~ 10 km
  - Matter gets "neutronized": $\boxed{p + e^- \rightarrow n + \nu}$

- If initial mass M > 20 M_{sun}, core collapses all the way to a ***black hole***
  - Final mass M ~ 3 – 100 M_{sun}, r_S ~ 9 – 300 km

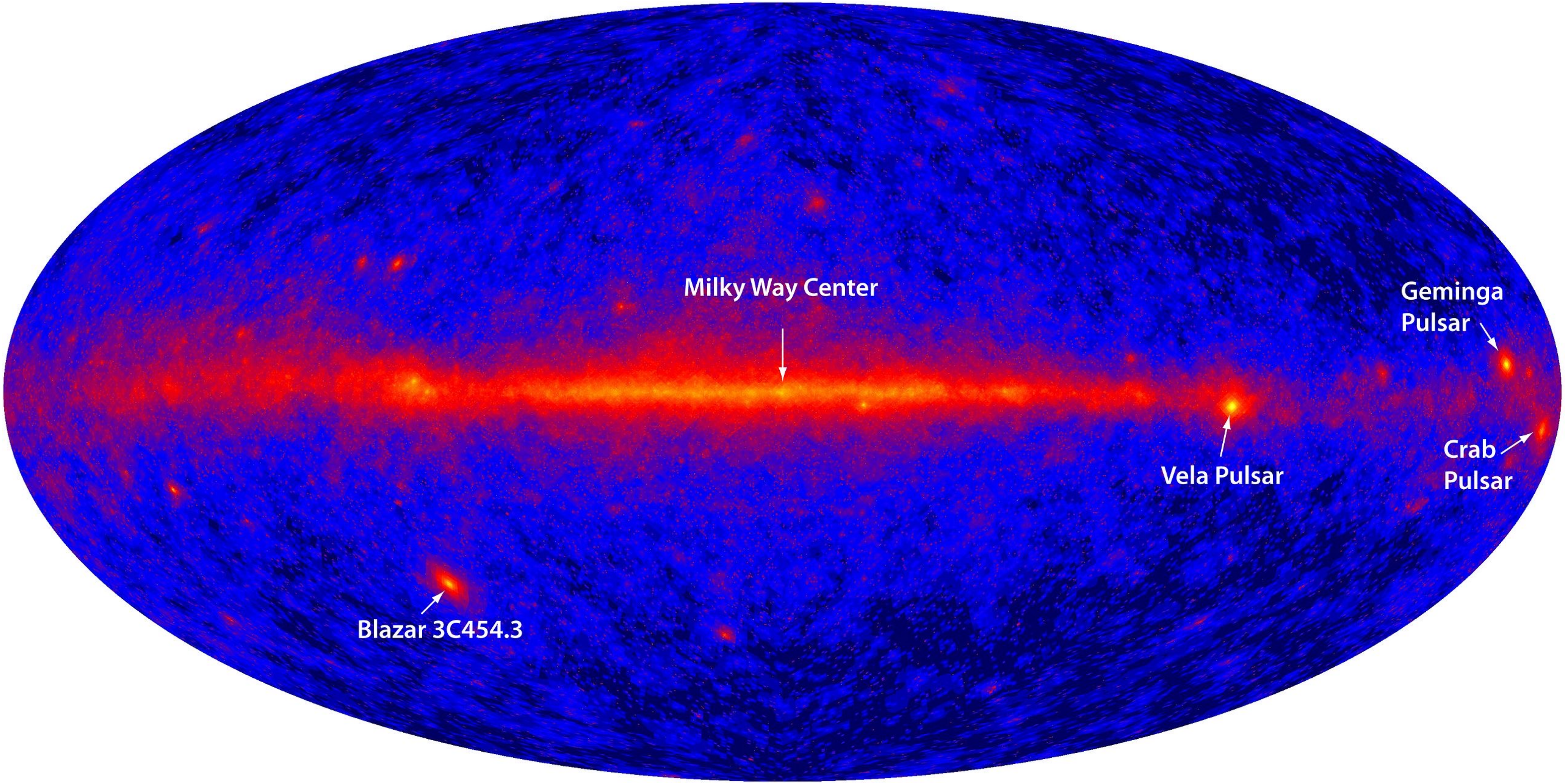


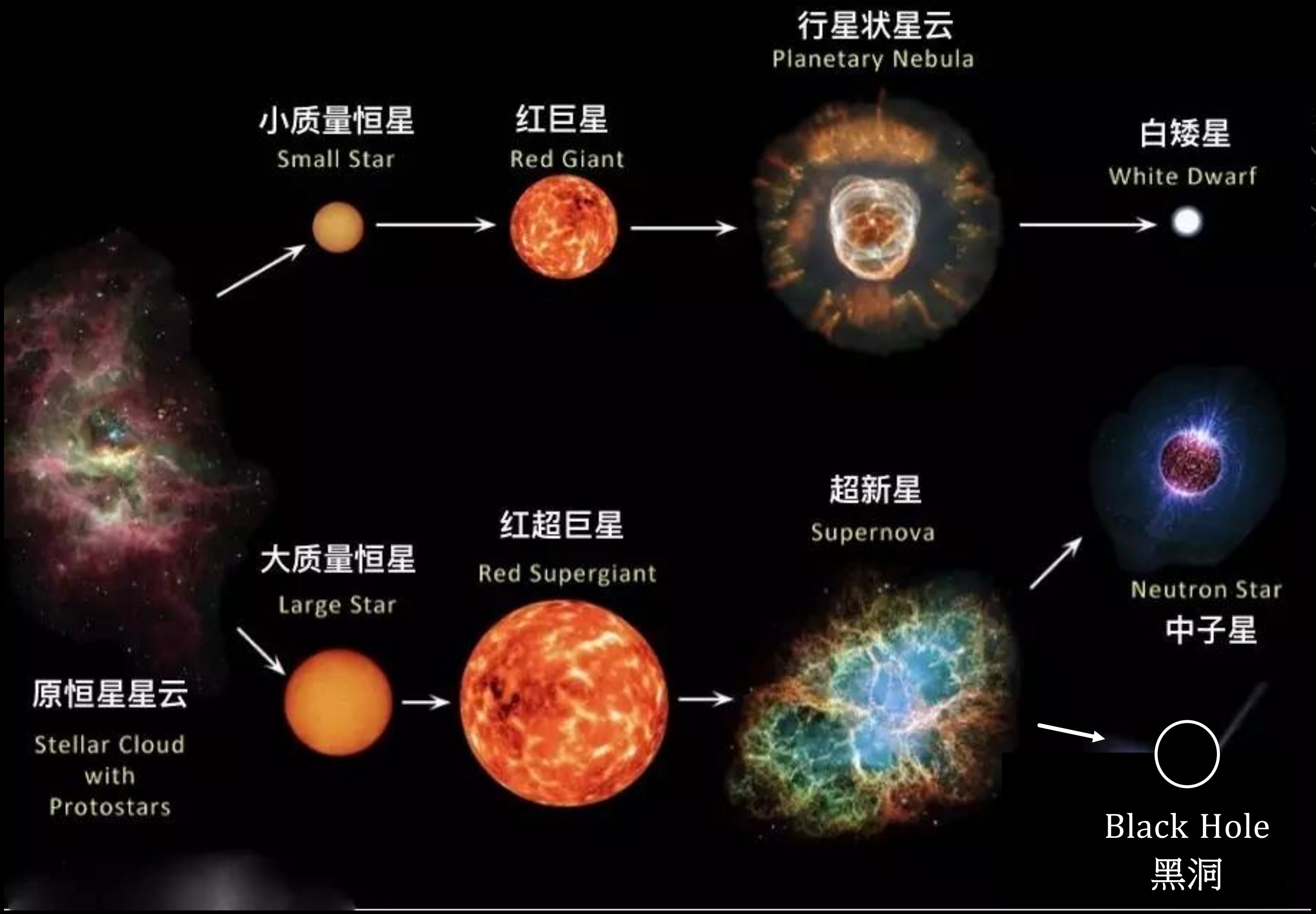
Crab Pulsar Wind Nebula

Red: optical (HST)
Blue: X-ray (Chandra)

Optical image of Crab Nebula (supernova remnant)

GAMMA-RAY ALL-SKY MAP BY FERMI TELESCOPE



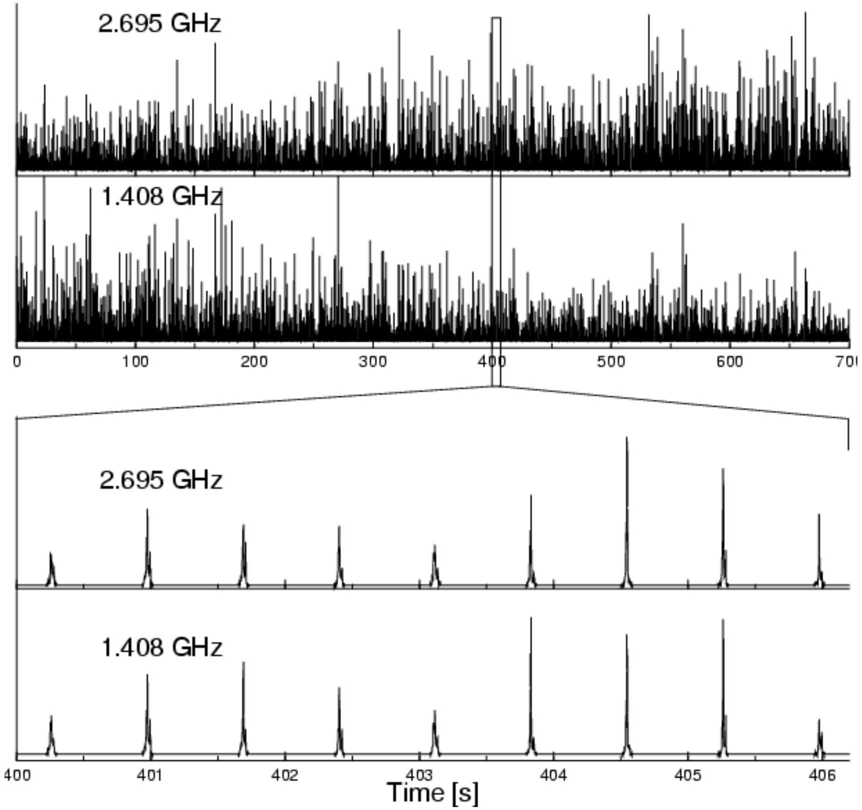

小质量恒星
Small Star
红巨星
Red Giant
行星状星云
Planetary Nebula
白矮星
White Dwarf
原恒星星云
Stellar Cloud with Protostars
大质量恒星
Large Star
红超巨星
Red Supergiant
超新星
Supernova
Neutron Star
中子星
Black Hole
黑洞

NEUTRON STARS

DISCOVERY OF PULSARS

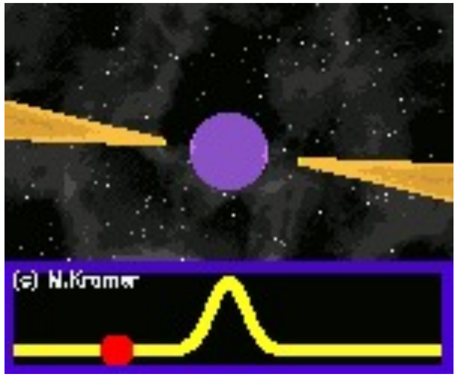
Jocelyn Bell Burnell (Age 24)

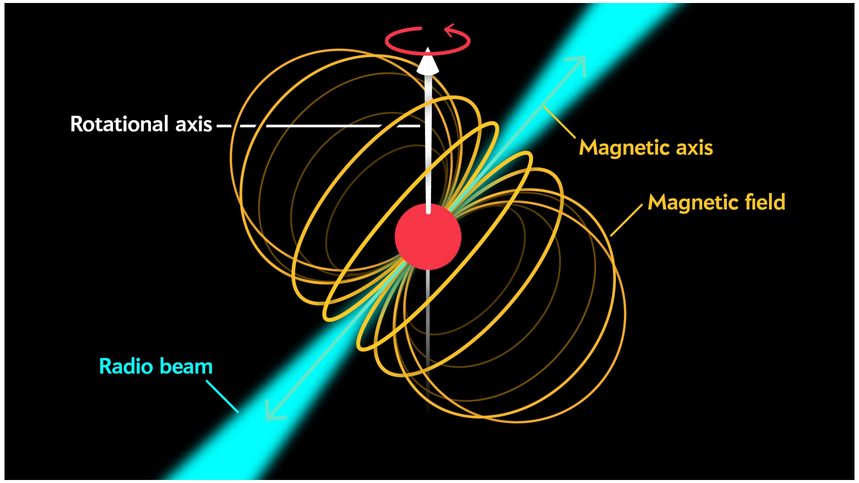
- Bell & Hewish (1967)
    - Constructed new type of radio telescope to study radio emission from quasars
    - Bell noticed a periodic signal pulsing every 0.71 seconds
- A rotating star will fly apart if the centrifugal force exceeds gravity
    - Many pulsars are rotating so rapidly that even a dense WD would fly apart
    - This led people to seriously consider the idea of a NS (first hypothesized by Zwicky in 1930s)



PULSARS

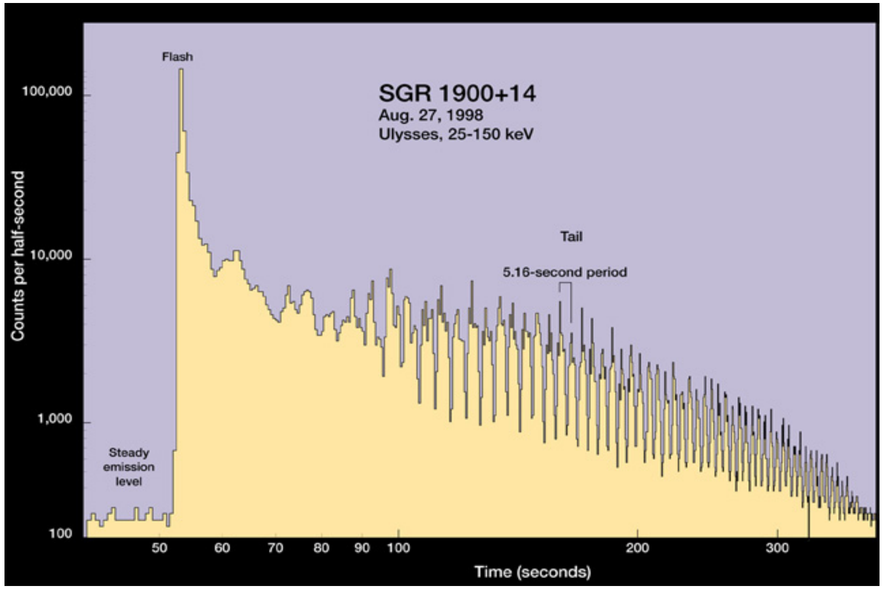
- Magnetized, rotating NSs
- At the magnetic poles, magnetic field is strong enough to produce high-energy particles, creating beams of light in radio and X-ray
- The beam can be seen from Earth as periodic pulses like a lighthouse
- Their pulses are precise clocks
  - Shapiro time delay to probe spacetime curvature
  - Pulsar navigation (similar to GPS)
- Rotational period ranges from milliseconds to seconds



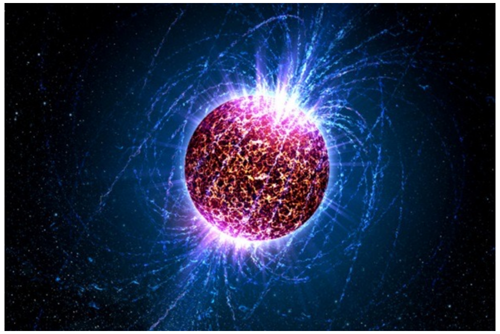


MAGNETARS

- A particular class of NSs that have extremely strong magnetic fields (up to 10^{11} Tesla!)
- Sometimes, these enormous magnetic fields "snap", leading to intense explosions
  - A dramatic example occurred on 8/27/1998
  - During a 0.2s period of time, it produced 100x the total luminosity of our galaxy
  - It produced a major disturbance of our upper atmosphere (despite a distance at 20000 lyrs)
  - Every X-ray/gamma-ray satellite detected it
  - Good that it wasn't closer!



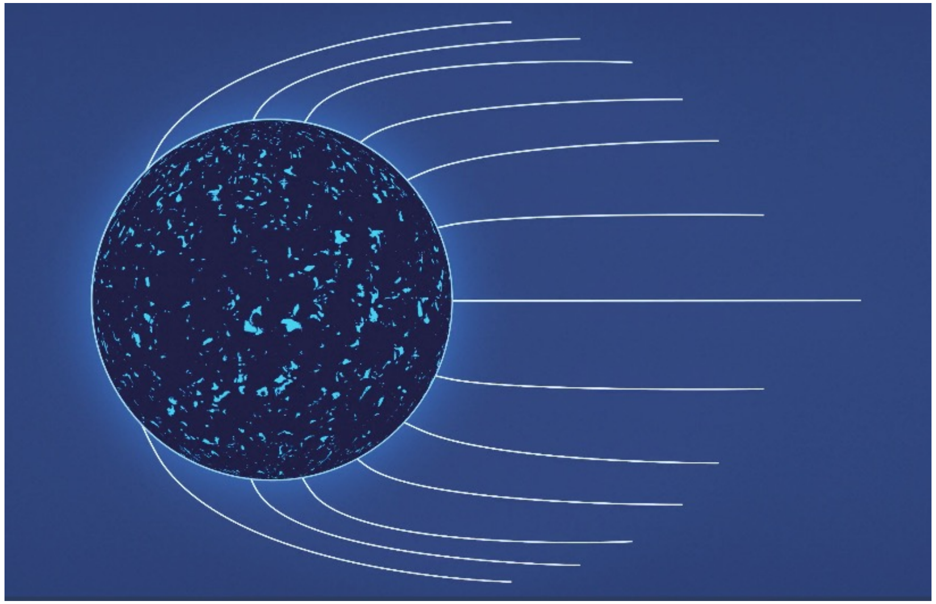
PROPERTIES OF NS



- A star made almost entirely out of neutrons $\boxed{p + e^- \rightarrow n + \nu}$
  - Neutrons normally decay, but at high densities they can't
- Gravity supported by ***neutron degeneracy pressure***
- It is close to being a black hole
  - Size close to the Schwarzschild radius; escape velocity close to c
- Surface gravity is so large that any mountain higher than a mm would crash!
  - Surface gravity ~ 10^{13} of that on Earth!
  - Anything would be crashed onto the surface – let's call it "Lasagne effect"

GRAVITATIONAL LENSING OF NS

- Light bending effect is so strong that it is possible to see the back side of a NS!



Each patch represents 30 deg x 30 deg

EXTREME CONDITIONS OF NS

- ***Extreme gravity***
- ***Extreme density***
  - M ~ 2 M_{sun}, R~10km, density ~ 5 x 10^{17} km/m^3 – as dense as an atomic nucleus
  - A teaspoon of NS material would weigh ~100 million tons!!
- ***Extreme temperature***
  - T ~ 10^{11-12} K for a newly formed NS
  - As neutrinos take energy away, T ~ 10^6 K, emitting in X-ray
- ***Extreme rotation***
  - Record holder: PSR J1748-2446ad with 716 times per second, rotational velocity ~ 0.24c!
- ***Extreme magnetic field***
  - Typical NSs: 10^{4-8} Tesla
  - Magnetars: 10^{8-11} Tesla
- These extreme conditions cannot be probed on Earth!

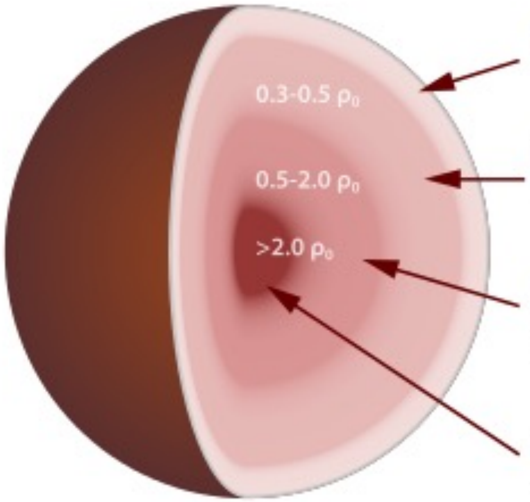
NS CAN BE SEEN IN X-RAY OR OPTICAL IF CLOSE ENOUGH

Neutron Star RX J185635-3754

NASA and F. Walter (State University of New York at Stony Brook) • STScI-PRC00-35

STRUCTURE OF NS

- State of matter at the core of a NS is still unknown
  - Cannot be probed in labs on Earth
  - May be new and exotic states of matter
- This is why it is crucial to measure the ***"equation of state"*** (EOS) of NSs
  - EOS is relationship between pressure and density
  - Different matter would have different levels of "squishiness", hence different EOS
  - Given an assumed EOS of any theoretical model, one can compute the expected ***mass-radius relation***
  - Comparing with the observed mass-radius relation could constrain the EOS of NSs



outer crust 0.3-0.5 km
ions, electrons

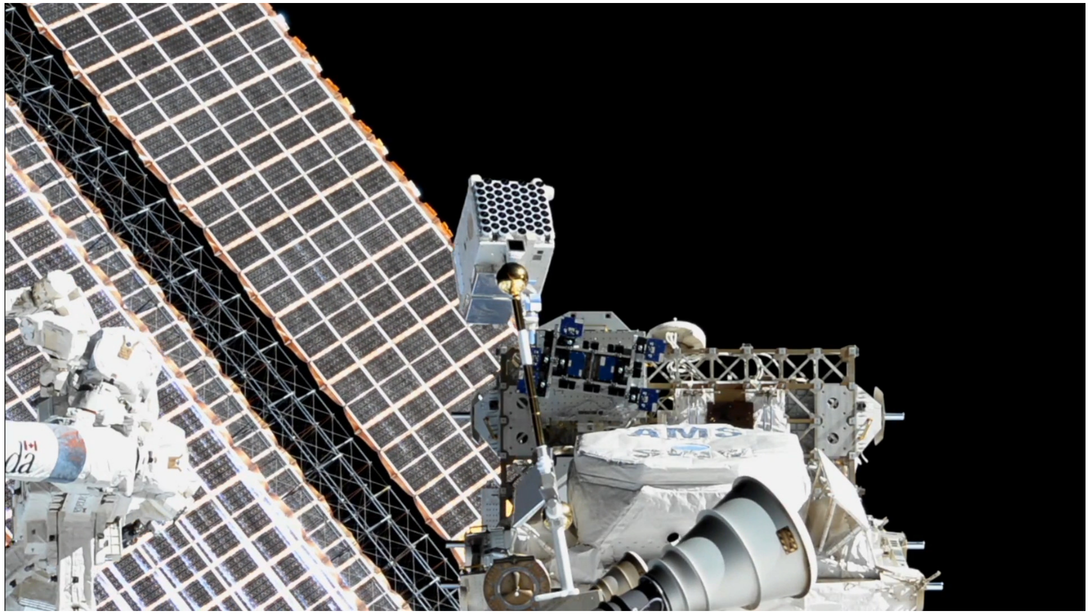
inner crust 1-2 km
electrons, neutrons, nuclei

outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas

inner core 0-3 km
quark gluon plasma?

NS INTERIOR COMPOSITION EXPLORER (NICER)

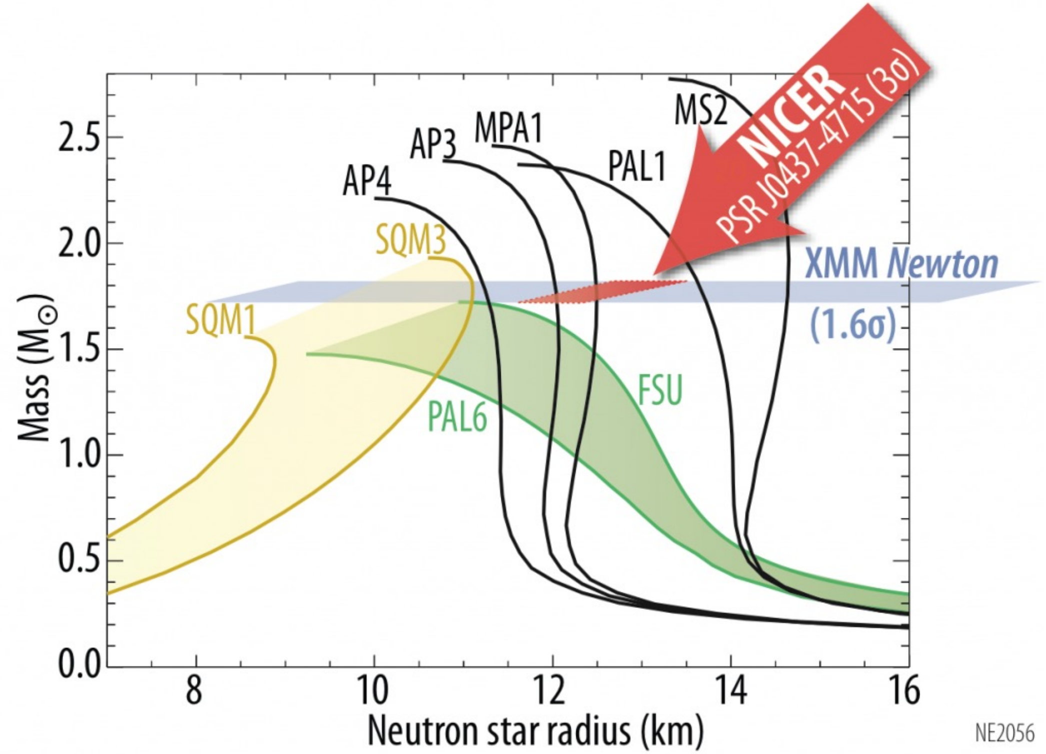
- NASA’s X-ray instrument to probe the composition of NSs
- Installed on the ISS since 2017
- It has the capability to take rotation-resolved spectra in the soft (0.2-12keV) X-ray band
- It will measure the mass-radius relation for nearby pulsars and constrain their EOS



OBSERVING PULSAR J0030+0451

- Figure compares two models of the pulsar's hotspots
- Due to gravitational lensing, it is possible to see both hotspots of the pulsar
- The modeled locations, shapes, and numbers of hotspots are surprising, suggesting that magnetic field configurations are even more complex on NSs!
- **NASA's NICER Delivers Best-ever Pulsar Measurements, 1st Surface Map**

CONSTRAINING EOS IN THE FUTURE



- NICER will measure the mass and radius to high precisions, constraining the state of matter in the cores of NSs
- Left figure shows the ***predicted*** uncertainty levels of NICER measurements
- EOS constraints coming soon – stay tuned!!

UPPER LIMIT OF NS MASSES?

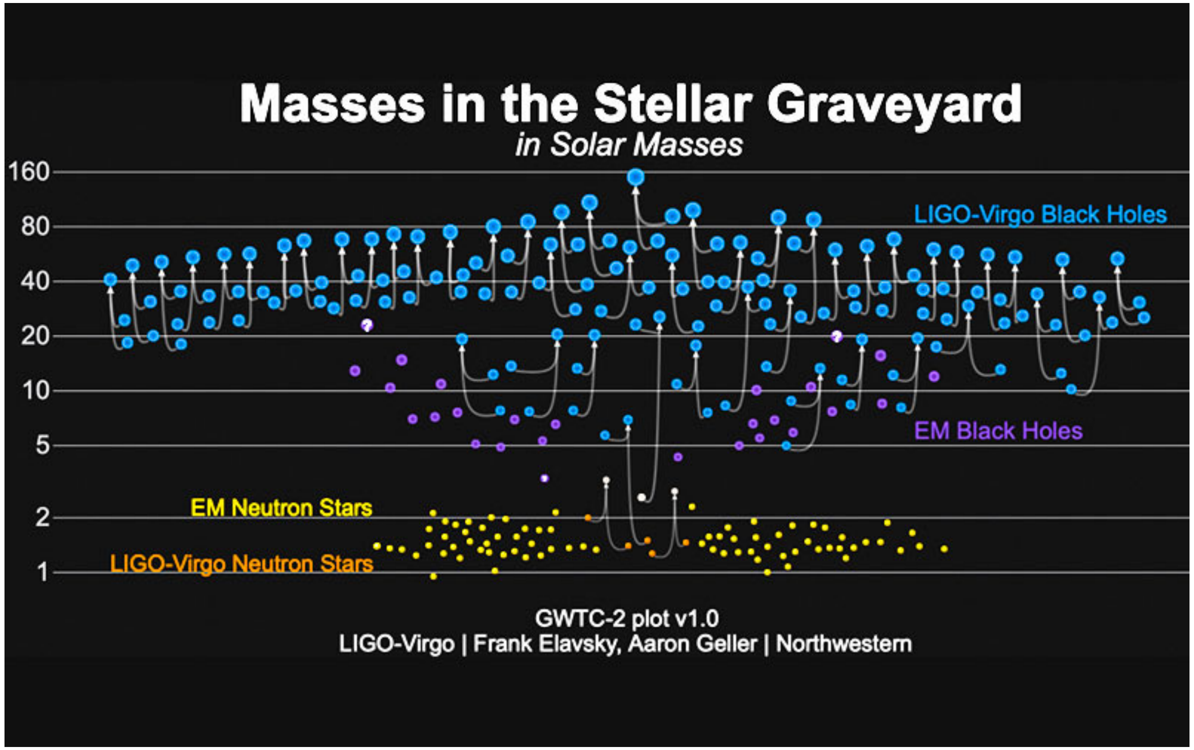
- Maximum mass of a NS is not known exactly
  - Limit could be derived in a similar way to the Chandrasakhar limit for WDs
  - But details depend on the unknown EOS
- In 1939, Robert Oppenheimer and others predicted the upper limit of NS masses to be ***~2.1 M_{sun}*** above which stars would collapse and no known forces could prevent it from collapsing into black holes (i.e., ***the Tolman-Oppenheimer-Volkoff or TOV limit***)
- In 2018, using the NS-NS merger event GW170817 detected by LIGO, the upper limit is updated to ***~2.16 M_{sun}***
- Most massive NS found to date: 2.14 M_{sun} in 2019 **[Here's the news link]**
- Working assumption: > 3 M_{sun} defined as stellar-mass BHs

WHY STUDY NEUTRON STARS?

- It allows us to probe physics in extreme conditions!
- Spacetime is almost as curved as BHs -> can be used to probe effects of GR
- NSs are governed by the same physics laws as BHs and can thus offer cross-checks of our understanding
- NSs have more ”hair” and are more complex than BHs, it allows us to have more ways to study them
- For example, NS-NS mergers would have electromagnetic counterparts to the GWs, enabling multi-messenger astronomy!
- **Article -- ”Golden Age of Neutron Stars”**

STELLAR-MASS BLACK HOLES

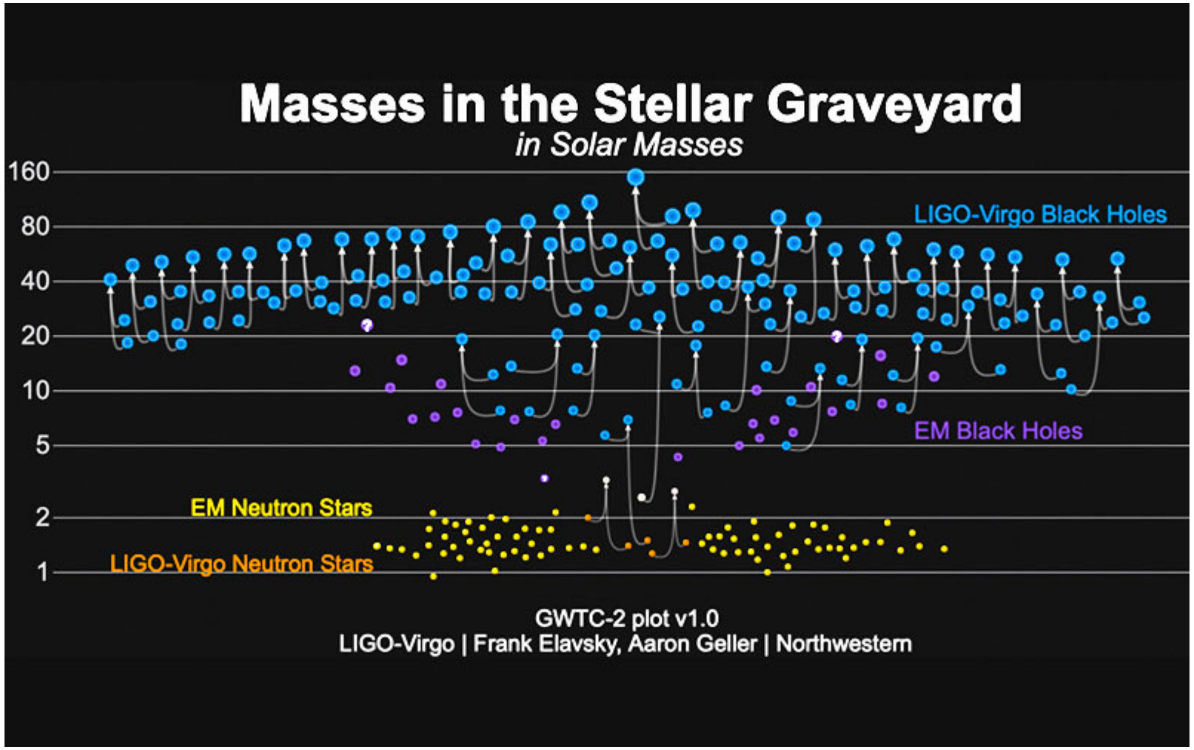
STELLAR-MASS BH INVENTORY TO DATE



- Observed number of smbhs is determined by
  - ***Intrinsic distribution*** of smbhs
  - Observational ***selection effects***
- Selection effects:
  - GWs tend to detect more massive smbhs because they could more easily produce spacetime ripples above the current sensitivity
  - For EM sources, fluxes decay with $1/r^2$, so can only detect nearby sources

*EM black holes: BHs that produce EM waves, i.e., light (e.g., X-ray binaries)

STELLAR-MASS BH INVENTORY TO DATE

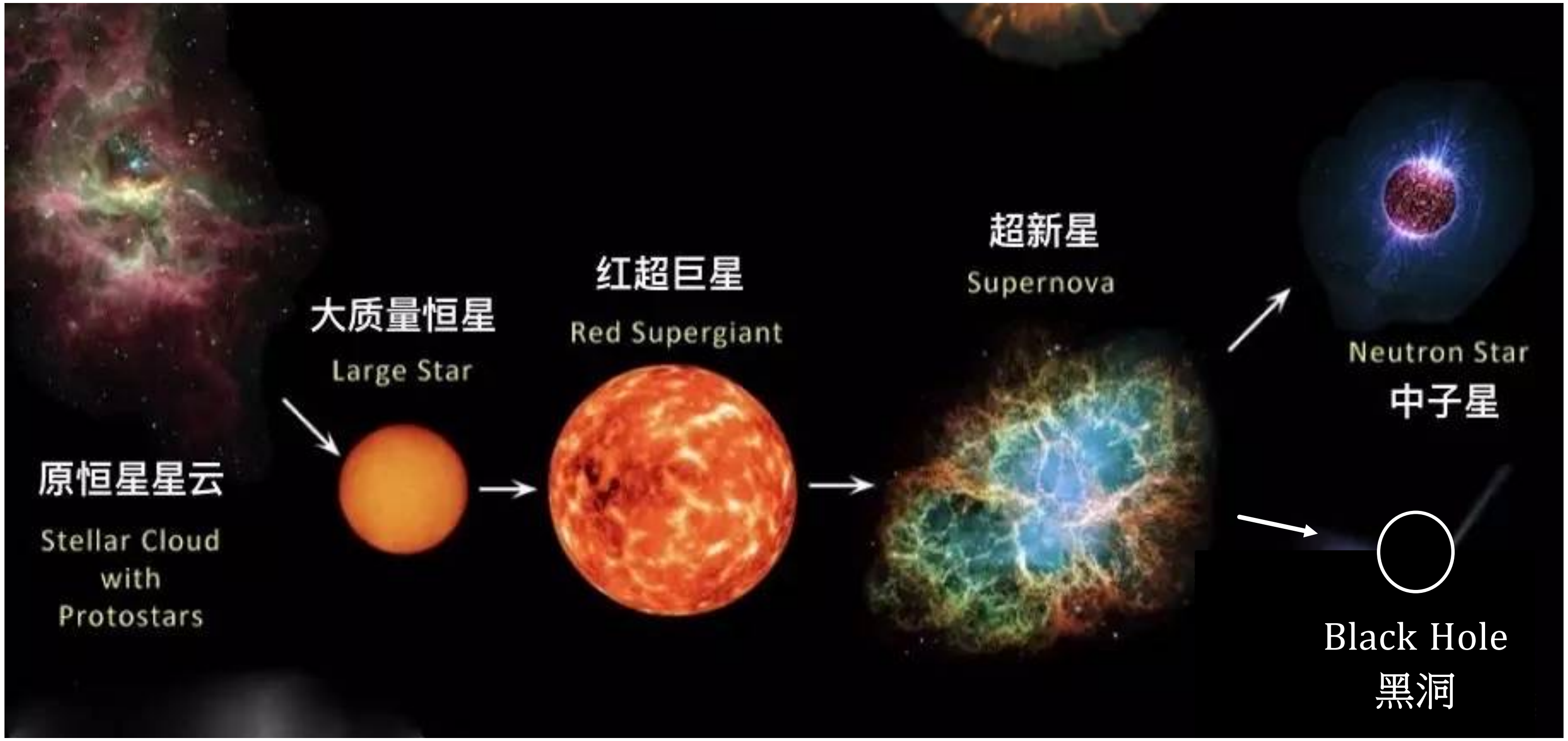


Important questions to address:

- Can stellar evolution models predict intrinsic distributions consistent with the observed distribution?
- Can models explain the ***range of masses of smbhs (~5-160 M_{sun})*** that are observed?

WHAT DO WE KNOW ABOUT THE INTRINSIC DISTRIBUTION OF BHS?

- Recall the formation process of smbh:



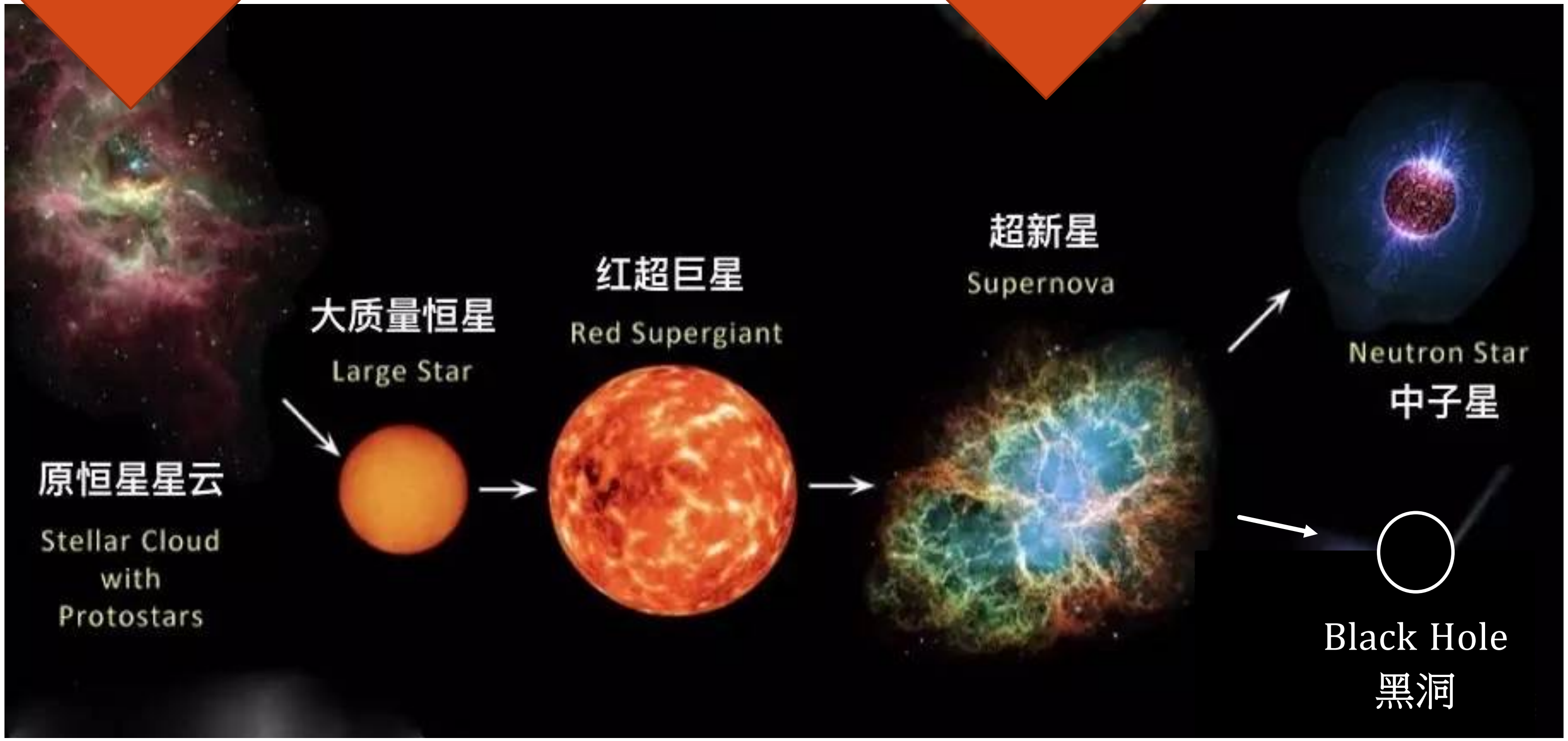
$M_{core} > 3\ M_{sun}$

O WE KN … IC DISTR … S?

Q1: What is the mass distribution of stars when they are formed?

Q2: How much mass is left in the core during supernova explosions?

- l the formation process of smbh:



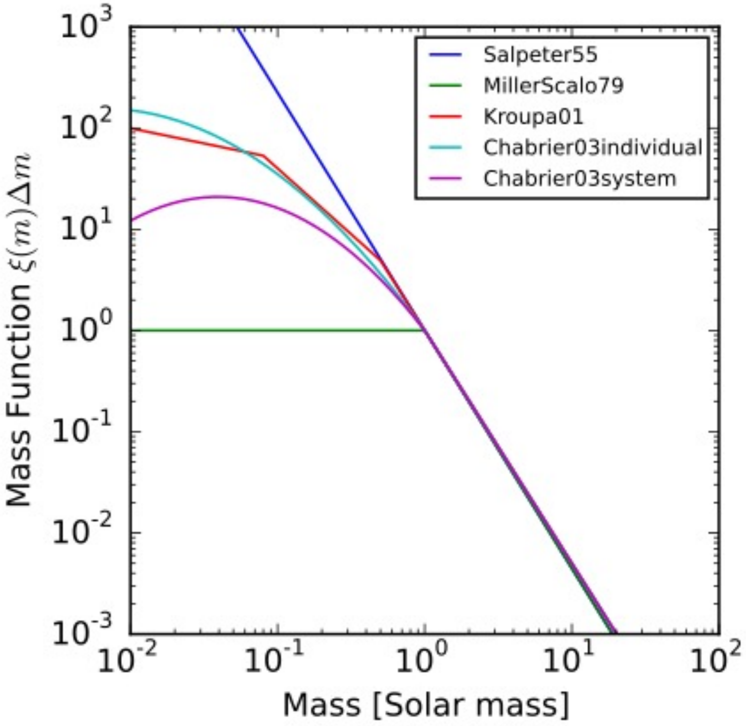
$M_{core} > 3\ M_{sun}$

Q1: WHAT IS THE MASS DISTRIBUTION OF STARS WHEN THEY ARE FORMED?

Star forming region in M17

- Stars form in dense, molecular gas
- They often form in groups
- The mass distribution of stars for a population is called the "***initial mass function (IMF)***"
- The IMF can be empirically inferred

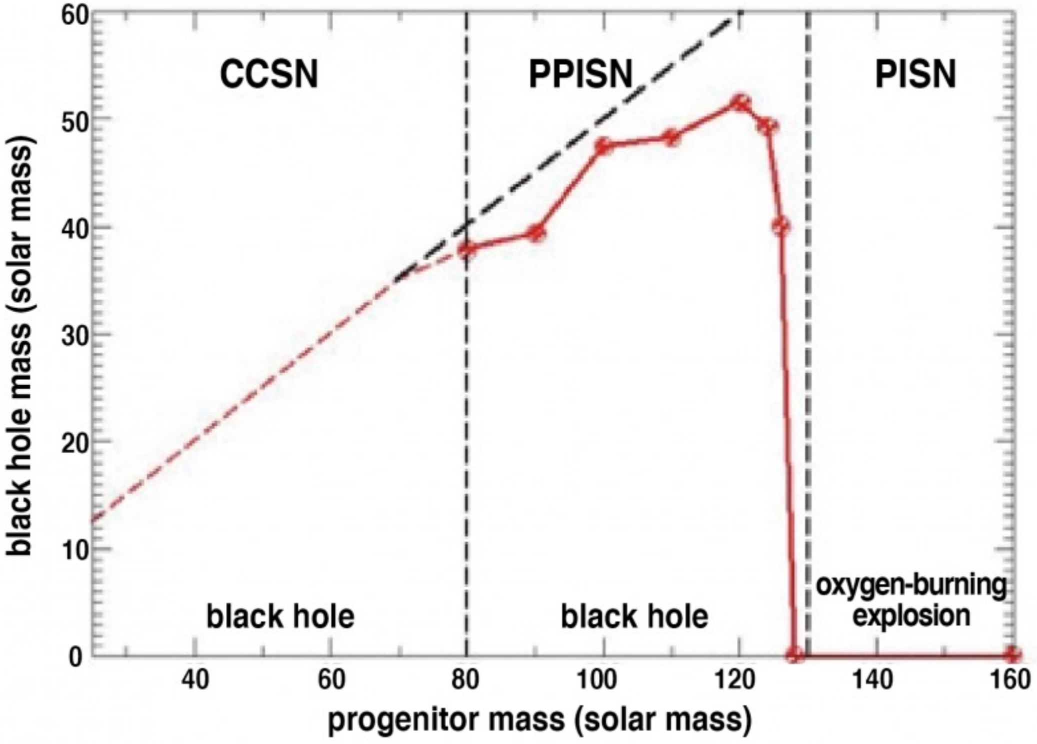
INITIAL MASS FUNCTION



- In general, low-mass stars are abundant, and high-mass stars are rare
- Despite uncertainties for $M < M_{sun}$, for high-mass stars, the number density of stars is well described by a power-law with slope of -2.3

Q2: HOW MUCH MASS IS LEFT IN THE CORE DURING SUPERNOVA EXPLOSIONS?

Predicted relation between initial stellar mass and BH mass

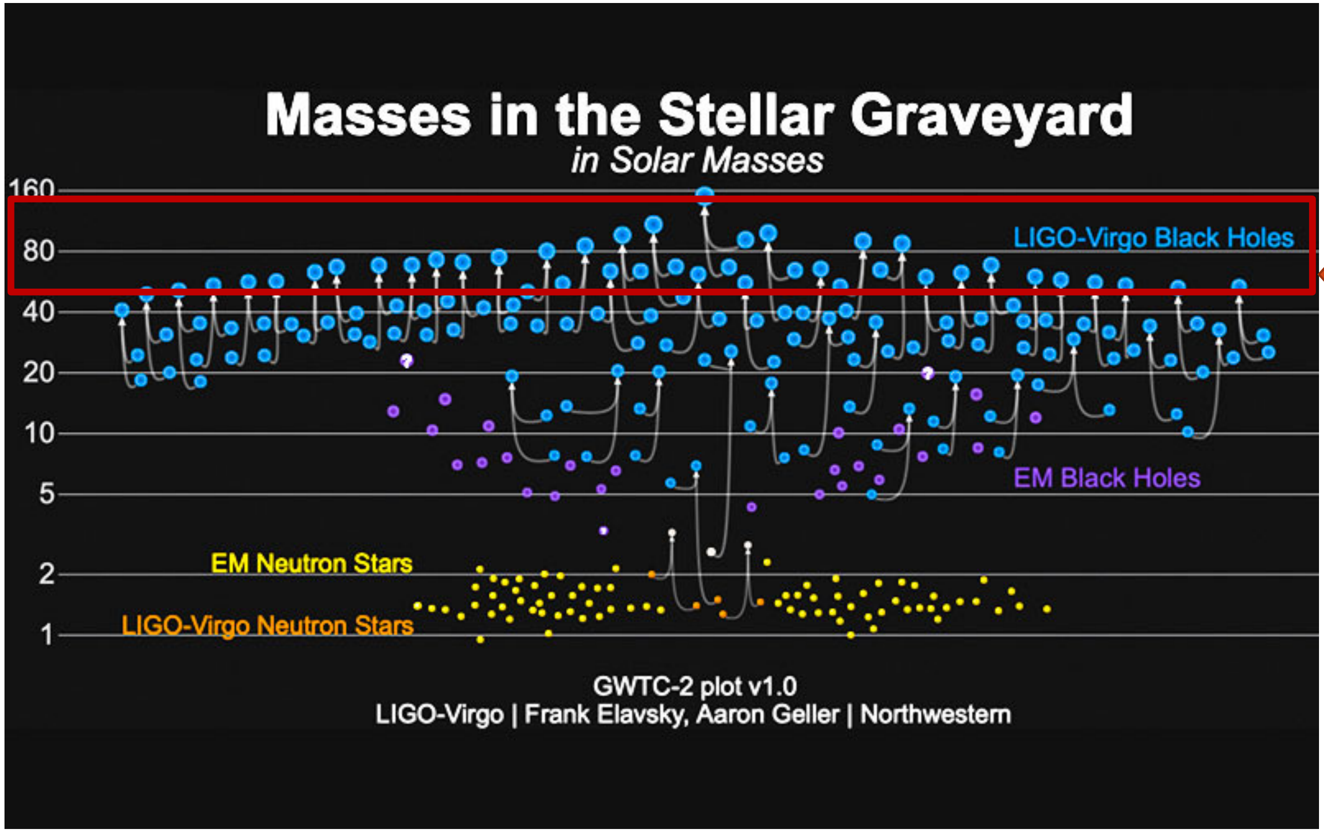


- PPISN = Pulsational Pair-Instability Supernova
  - Initial mass ~ 80-130 M_{sun}
  - Creation of electron-positron pairs induce pulsations that cause mass loss
- PISN = Pair-Instability Supernova
  - Initial mass ~ 130-250 M_{sun}
  - Creation of electron-positron pairs make the star unstable
  - The explosion is so violent that no remnant is left
- For stars with initial mass > 300 M_{sun}, it is possible to directly collapse into a BH with M~150 M_{sun} without going through an explosion
- Therefore, ***models predict a gap of BH masses between ~50-150 M_{sun}!!***

NEWS ABOUT A STELLAR-MASS BH THAT IS SO MASSIVE THAT IT SHOULDN'T EXIST?

- On 11/27/2019, a Nature paper claimed discovery of a smbh of M ~ 70 M_{sun}
  - It made the news because the mass is within the "gap" of smbh formation
- But, two weeks later, two other groups found mistakes in their measurements – the smbh found turned out to be just a normal one…
- Great example of how science proceeds
- Read more from this news: **Impossibly Big Black Hole Was Probably Impossible After All**

BACK TO THE BHS FOUND BY GWS…



These guys were totally unexpected and have sparkled great interests to revise the stellar-evolution models!!

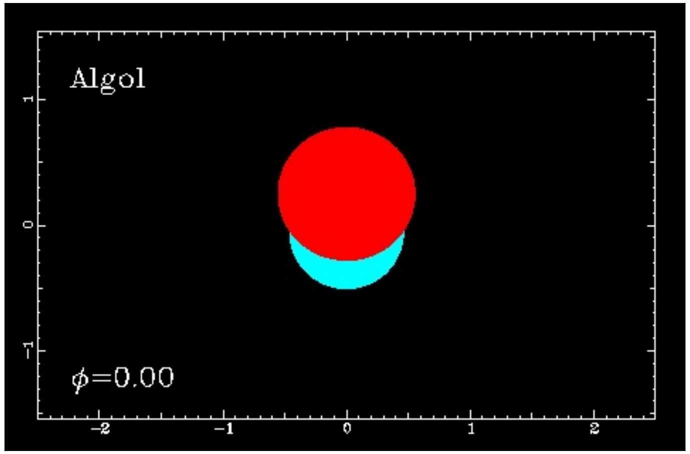
EVOLUTION OF BINARY STARS

BINARY STARS

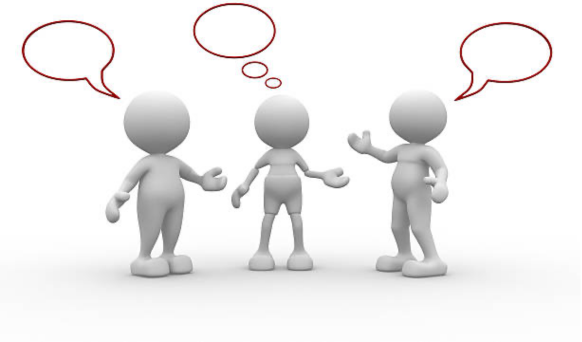
- Most stars in the Solar neighborhood are part of binaries (fraction ~2/3)
- Separations range from almost touching "***contact binaries***" to thousands of AU
- Majority are far enough apart that the stars evolve independently
- Binary paradoxes – some observed binaries have properties that are hard to understand in terms of the known evolution of single stars


Binary star Albireo

BINARY PARADOX -- ALGOL

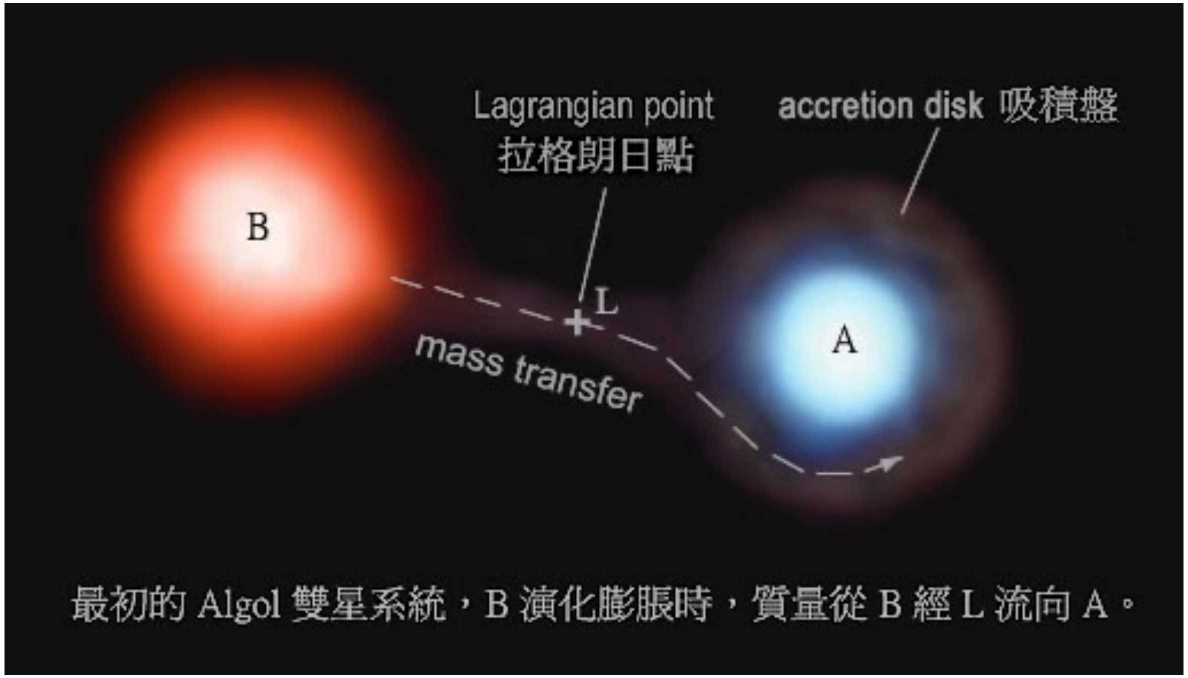


- Algol binary system consisting of:
  - Star A – a massive blue star on the MS
  - Star B -- a less massive red star that is on the way to becoming a red giant
- But shouldn't the more massive star evolve faster and become a giant first?



Group discussion (Q1):
Please break into groups of 3-4 people. Discuss your answers and provide an explanation. Write down your names and answers on a piece of paper and submit it to the TA after class.

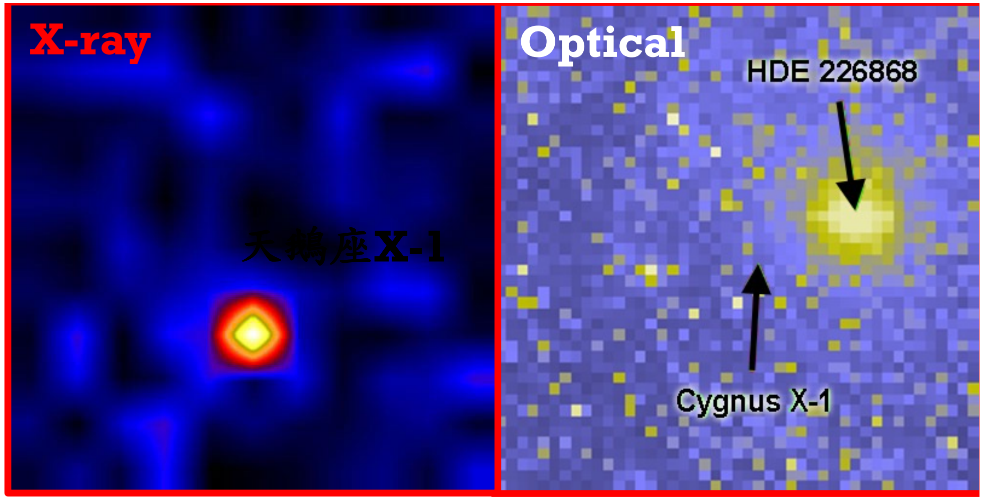
THE KEY IS MASS TRANSFER!



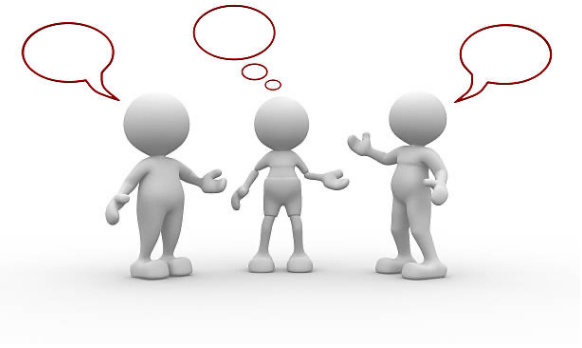
最初的 Algol 雙星系統，B 演化膨脹時，質量從 B 經 L 流向 A。

- In the beginning, B was in fact the most massive star
- As B evolves faster and became a giant star, its outer atmosphere flowed to A
- This is why A is more massive now, but still on the MS

RECALL CYGNUS X-1

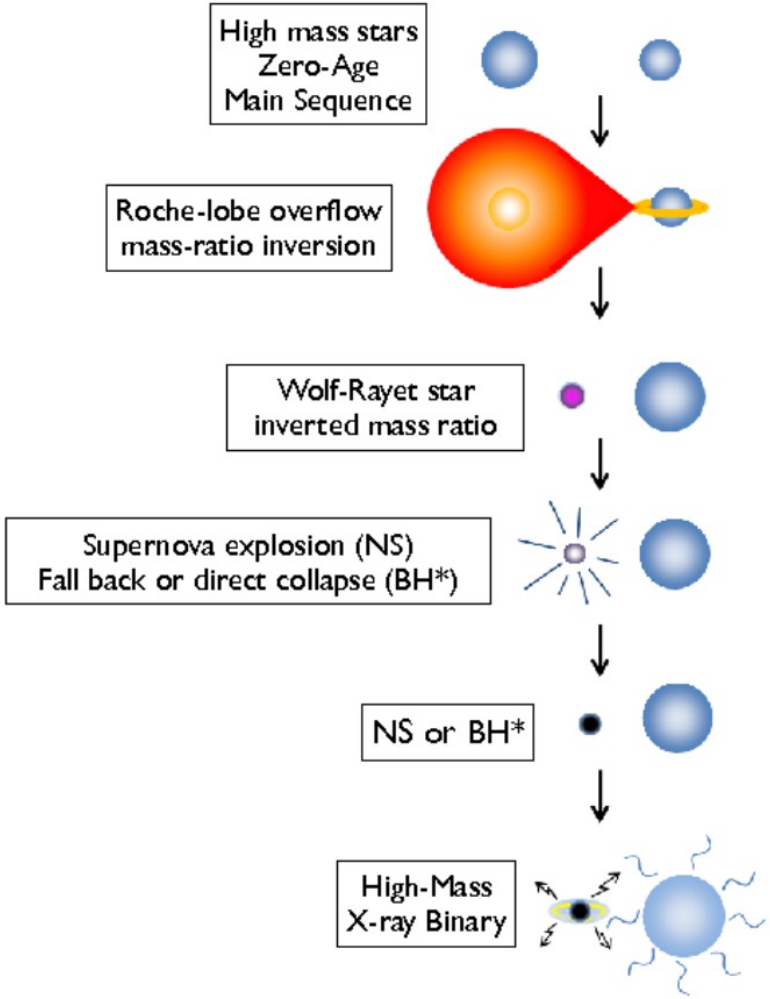


- It is a BH X-ray binary
- This system has two stars:
  - Cygnus X-1: a stellar-mass BH with $M \sim 21.2\ M_{sun}$
  - HDE226868: a blue supergiant star with $M \sim 40\ M_{sun}$
- How exactly did the system evolve from its formation to the current stage? Please write down or draw the different stages of its evolution.



Group discussion (Q2):
Please break into groups of 3-4 people. Please discuss and write down/draw how this system evolved. Write down your names and answers on a piece of paper and submit it to the TA after class.

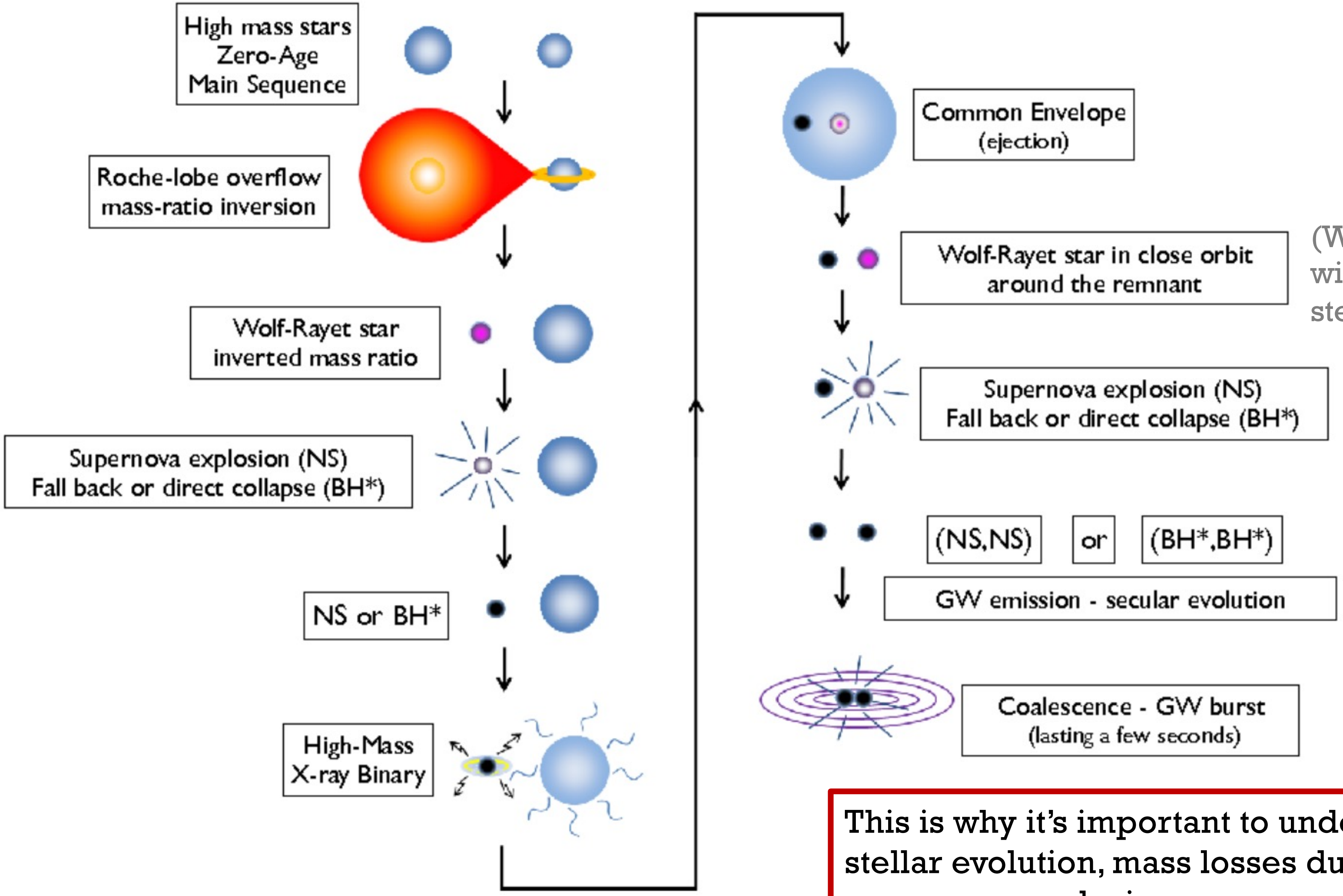
EVOLUTION OF CYGNUS X-1



Two critical roles of ***mass transfer***:

1) Need mass transfer to the lower-mass star so that it is not disrupted by the SN explosion of the higher-mass star
2) Need further mass transfer onto the NS/BH to produce observable emission via accretion

FUTURE OF CYGNUS X-1

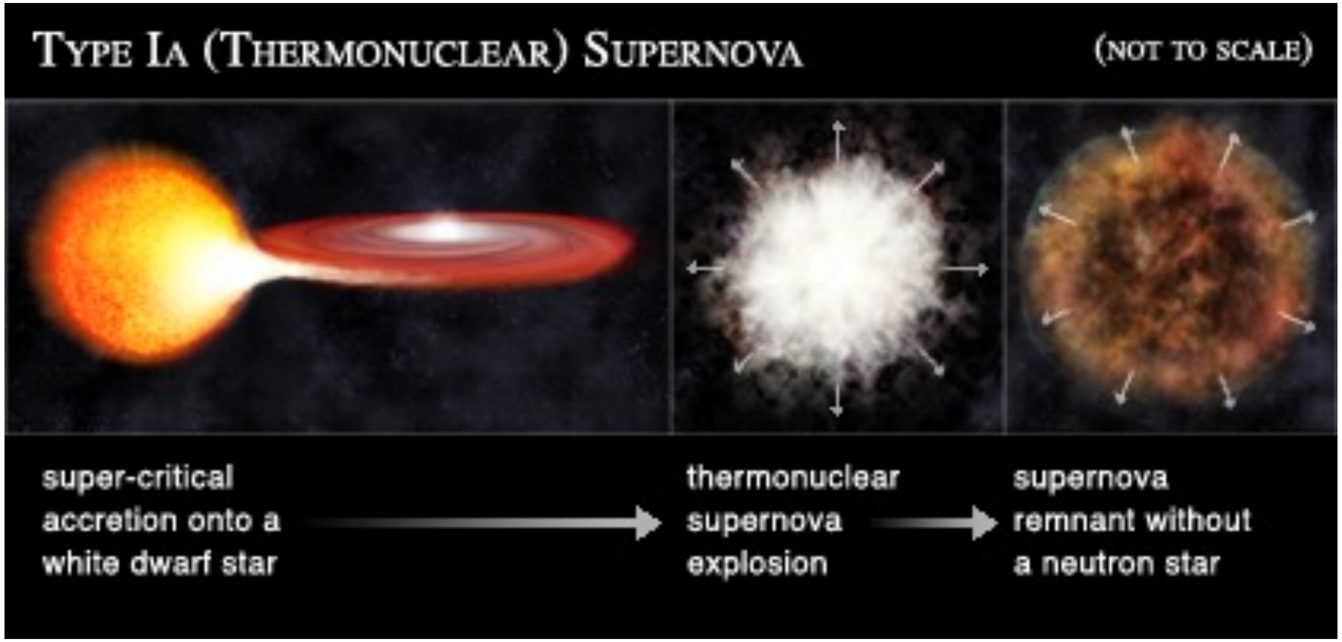


(WR stars: massive, hot stars with heavy elements & strong stellar winds)

This is why it's important to understand details of stellar evolution, mass losses due to stellar winds, supernova explosions, common envelopes, etc!

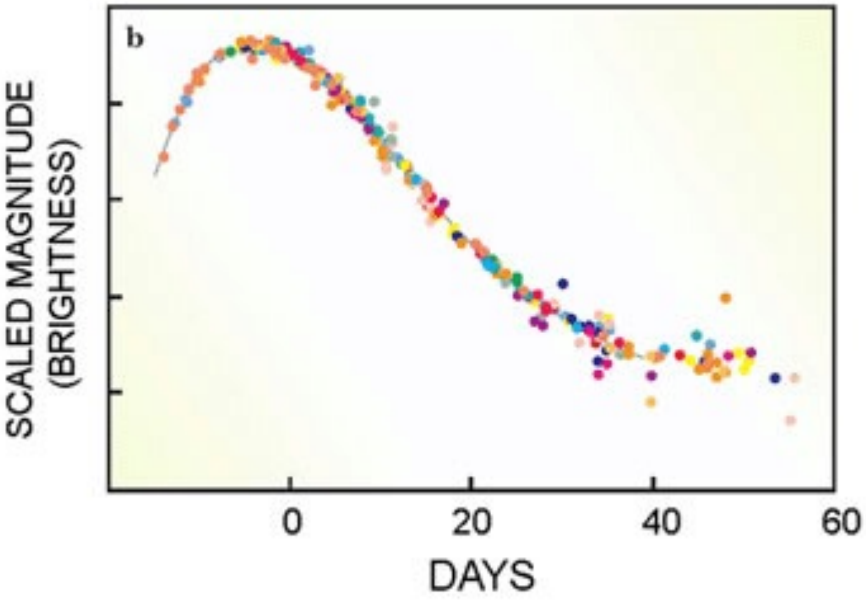
TYPE IA SUPERNOVAE

- In a binary system in which there is a WD, when it accretes from the companion star or merge with a second WD, it could reach the Chandrasakhar limit of M ~ 1.4 M_{sun} and explode as a supernova



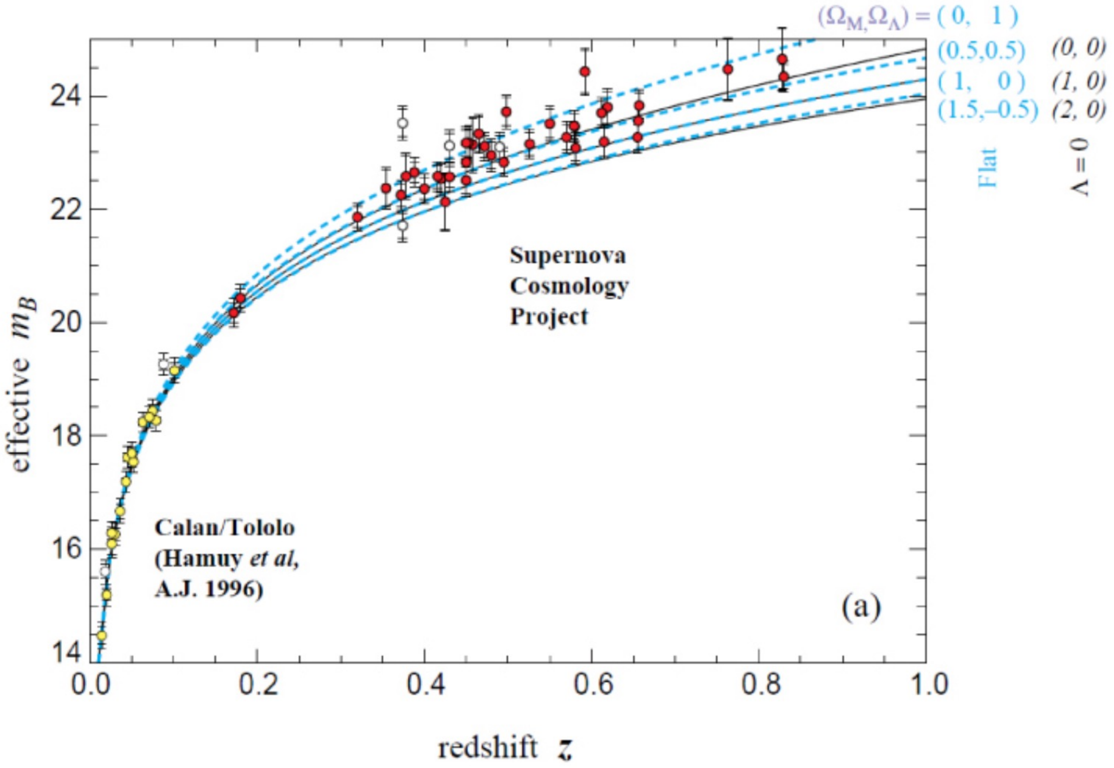
TYPE IA SUPERNOVAE ARE STANDARD CANDLES

- These Type Ia supernovae produce a consistent peak luminosity, which allows them to be used as standard candles to measure the distance in the universe



ACCELERATING EXPANSION OF UNIVERSE!

- Observations of Type Ia SNe led to the discovery of the accelerating expansion of the universe (blue lines)
- The observed relationship is inconsistent with a non-accelerating universe with $\Lambda = 0$ (black lines)
- Nobel Prize in Physics 2011



SUMMARY

- Evolution of a star is largely determined by its ***mass***
  - All stars go through the ***main sequence*** phase of H burning
  - If $M < 8\ M_{sun}$, $M_{core} < 1.4\ M_{sun}$
    star -> red giant -> planetary nebula -> WD
  - If $8\ M_{sun} < M < 20\ M_{sun}$, $1.4\ M_{sun} < M_{core} < 2\text{-}3\ M_{sun}$
    star -> supergiant -> core-collapse (Type II) supernova -> NS
  - If $20\ M_{sun} < M$, $3\ M_{sun} < M_{core}$
    star -> supergiant -> core-collapse (Type II) supernova -> BH
- Neutron stars
  - Properties & extreme conditions
  - Different types -- pulsars, magnetars
  - Internal structure & the unknown EOS of matter in the core – can be probed by the NICER X-ray mission by observing pulsars

SUMMARY

- Formation of stellar-mass BHs
  - Mass distributions of smbhs are determined by (1) initial mass function of star formation, and (2) core mass after supernova explosions
  - Supernova models predict a ***mass gap*** of smbhs in the range of ***~50-150 M_{sun}***
  - Some smbhs found by GWs are within this gap, challenging current theoretical models
- Evolution of binary stars
  - ***Mass transfer*** is an important process for (1) solving the binary paradox (ex: Agol), (2) explaining the emission of X-ray binaries by accretion (ex: Cygnus X-1)
  - A binary system with a WD can explode as ***Type Ia SN*** when the WD exceeds the Chandrasakhar limit
  - Understanding the evolution of binary systems is crucial for predicting the numbers of BH-BH, NS-NS, or BH-NS merger events that generate GWs