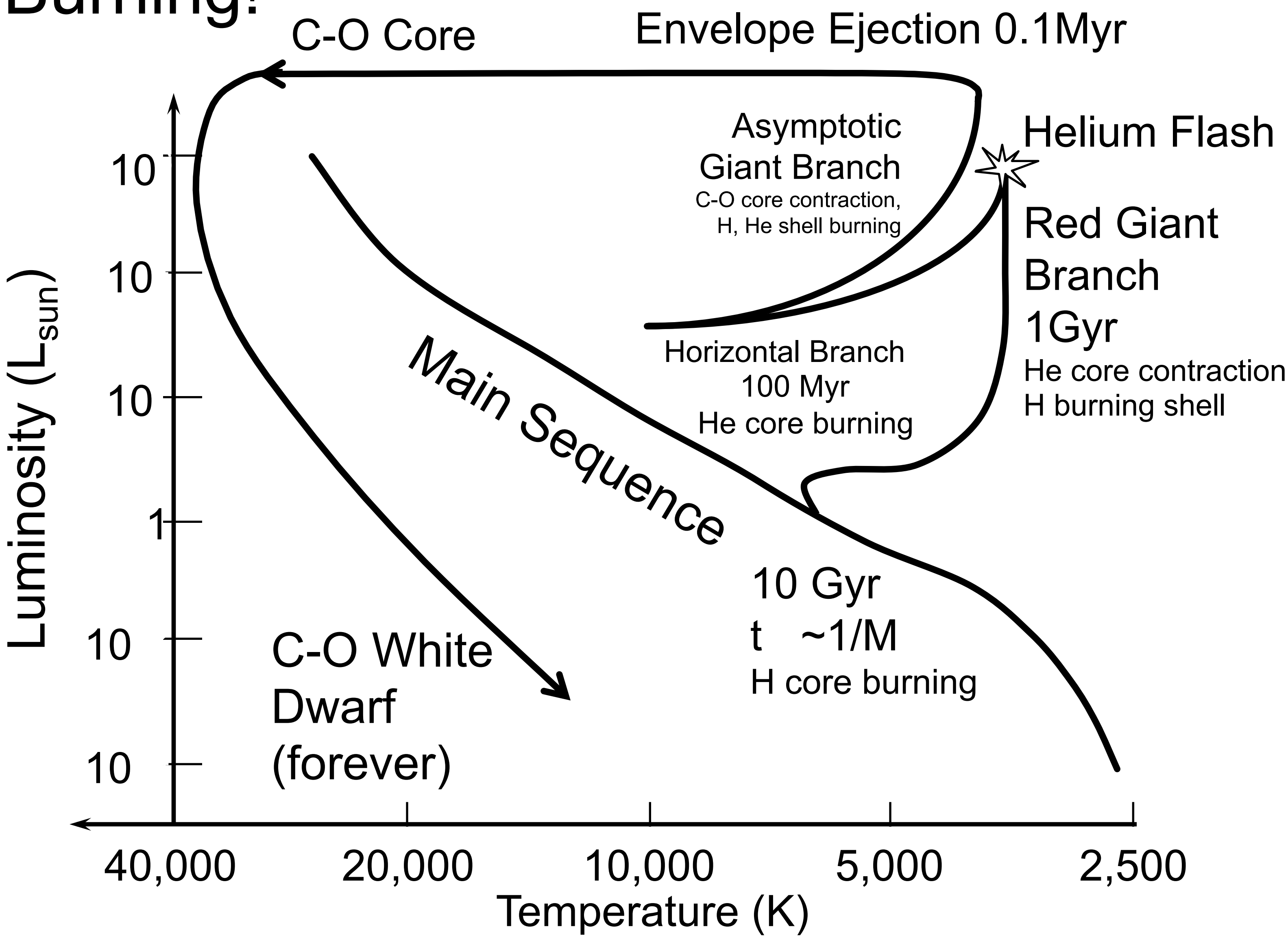
Evolution of Low-Mass stars M < 4 M_{sun}
No C Burning!



Supernovae

Astronomy 1101

Key Ideas:

End of the Life of a Massive Star:

-
-

Iron core collapse & core “bounce”

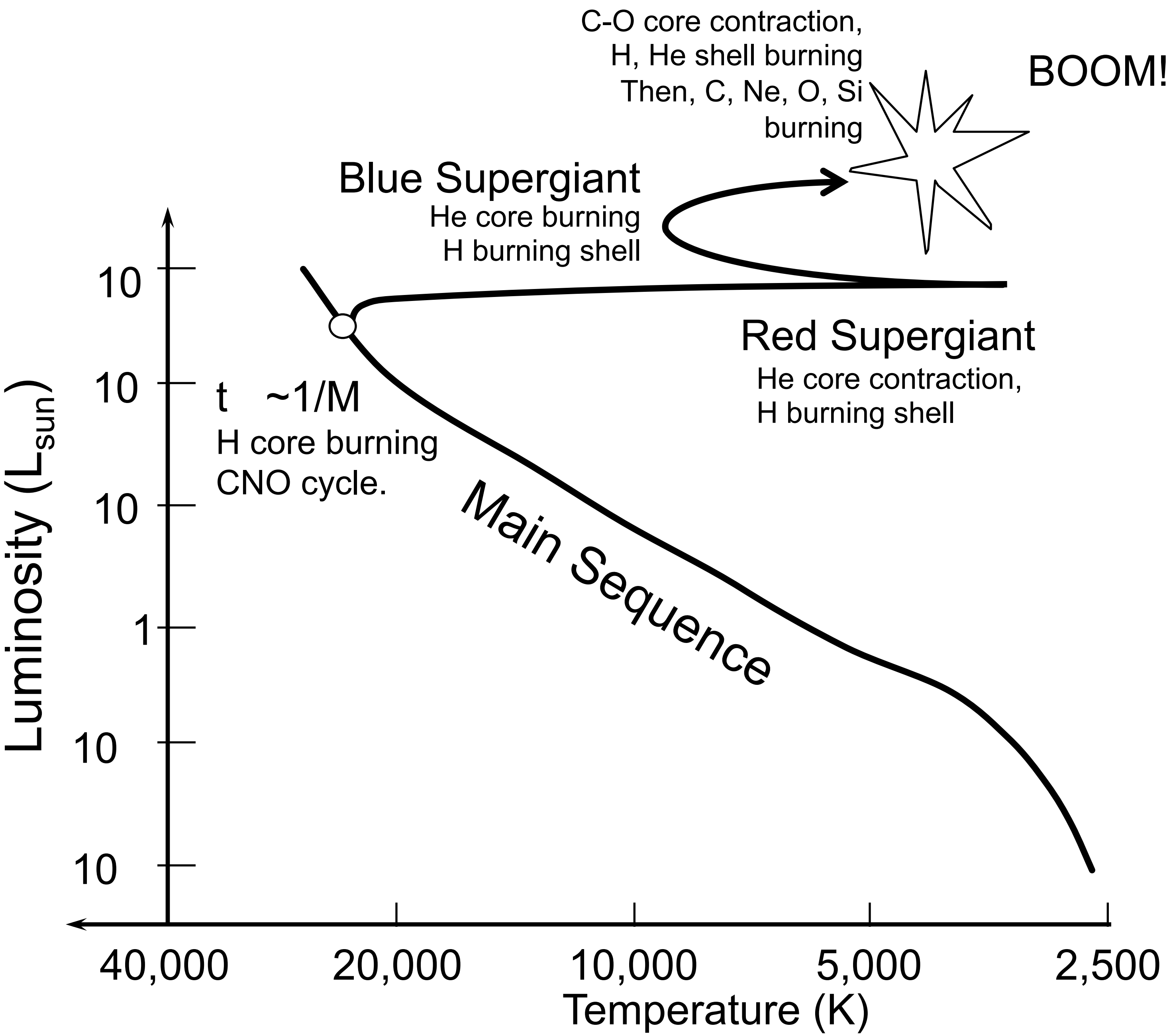
Neutron star formation.

Supernova Explosion:

-

Neutron stars and pulsars.

The other Supernovae: the explosion of White Dwarfs (Type – Ia supernovae)


C-O core contraction,
H, He shell burning
Then, C, Ne, O, Si
burning
BOOM!
Blue Supergiant
He core burning
H burning shell
Red Supergiant
He core contraction,
H burning shell
t ~1/M
H core burning
CNO cycle.
Main Sequence
Luminosity (L_{sun})
10
10
10
1
10
10
40,000
20,000
10,000
5,000
2,500
Temperature (K)

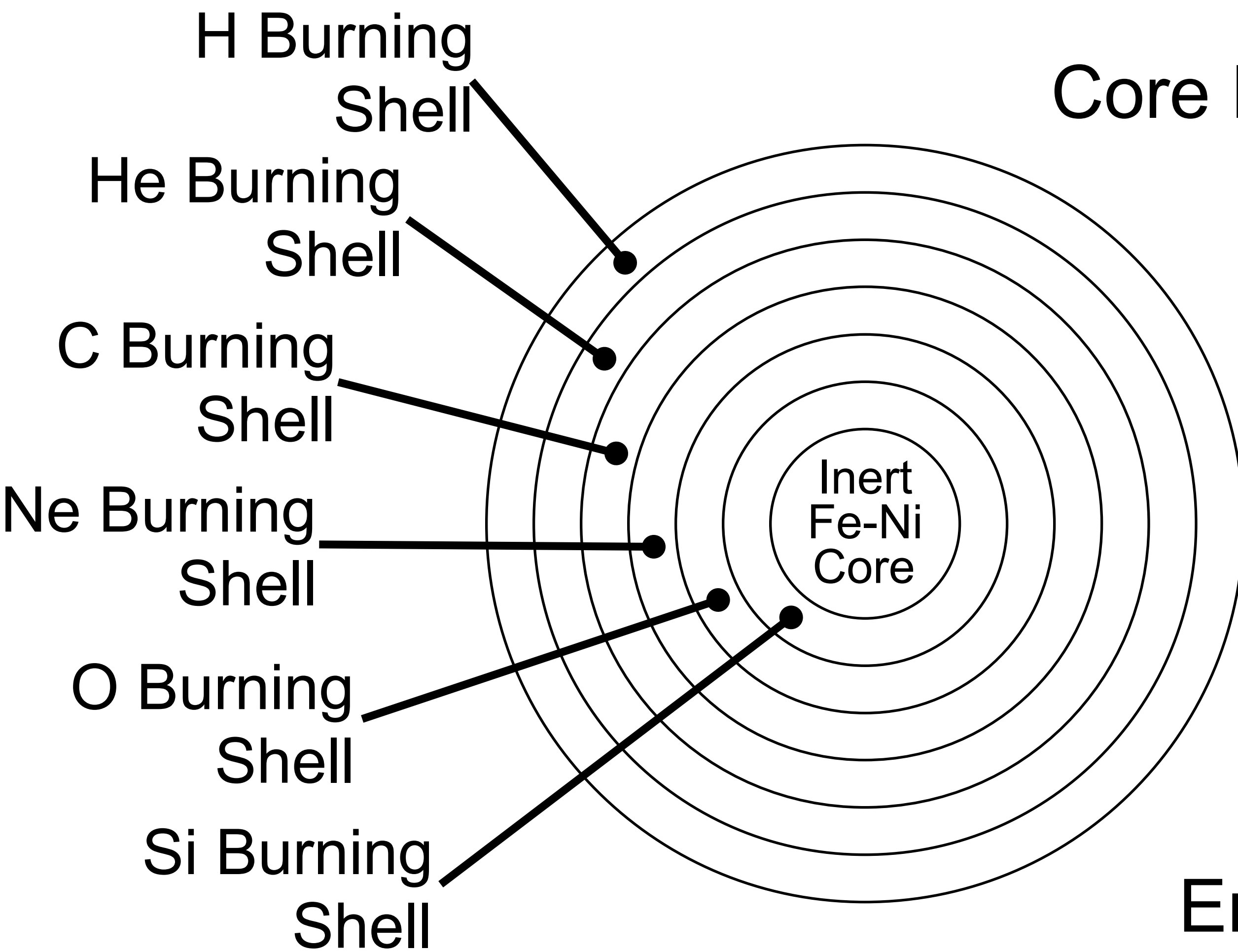
Last Days of a Massive Star

Burns a succession of nuclear fuels:

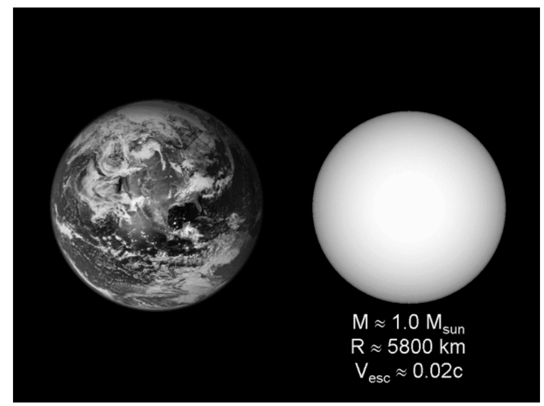
- Myr
- Helium burning : 1 Myr
- Carbon burning : 1000 years
- Neon burning : ~10 years
- Oxygen burning : ~1 year
- Silicon burning : ~1 day

Builds up an inert Iron core in the center…

End of Silicon Burning Phase:



Core Radius: ~1 R_{earth}



Envelope: ~ 5 AU

The Nuclear **Impasse**

Fusion works by releasing *nuclear binding energy*.

But, Iron (Fe) is the most bound nucleus:

- Fusion of nuclei lighter than Fe *releases* energy (exothermic).
- Fusion of nuclei heavier than Fe *absorbs* energy (endothermic)

Once an Fe core forms, there are no fusion fuels left for the star to tap.

Iron Core Collapse

Iron core grows to a mass of ~1.4 M_{sun}

-

10

Two energy ***consuming*** processes kick in:

- Photodisintegration: high-energy photons melt Fe/Ni nuclei into He, p & n
- Neutronization: protons & electrons combine into neutrons & neutrinos: (this produces a 'neutron' star)

- Neutrinos escape & carry away energy

So, no source of energy, and energy leaking out rapidly! Collapse accelerates as it accelerates.

Catastrophic Collapse

Start of Iron Core collapse:

- Radius ~ 6000 km (~R_{earth})
- Density ~ 10^{10} - 10^{8} g/cm^3

0.1 second later...

- Radius ~20 km
- Density ~3 x 10^{14} g/cm^3
- Collapse Speed ~ 0.1 c ~ 20,000 miles/sec.

Bounce!

Core collapses until its density is ~2-3x10^{14} g/cc, the density of a single nucleus.

Then, the *Strong Nuclear Force* comes into play.

It binds nuclei together.

But, if you compress to much, it repels.

Complex equation of state.

Inner part of the core comes to a screeching halt & springs back a bit (*bounces*)

Infalling gas hits the bouncing core head-on at 0.1*c*!

Post-Bounce Shockwave

Shockwave blasts out into the infalling star:

- Kinetic Energy is >10^{51} ergs!
  its lifetime)

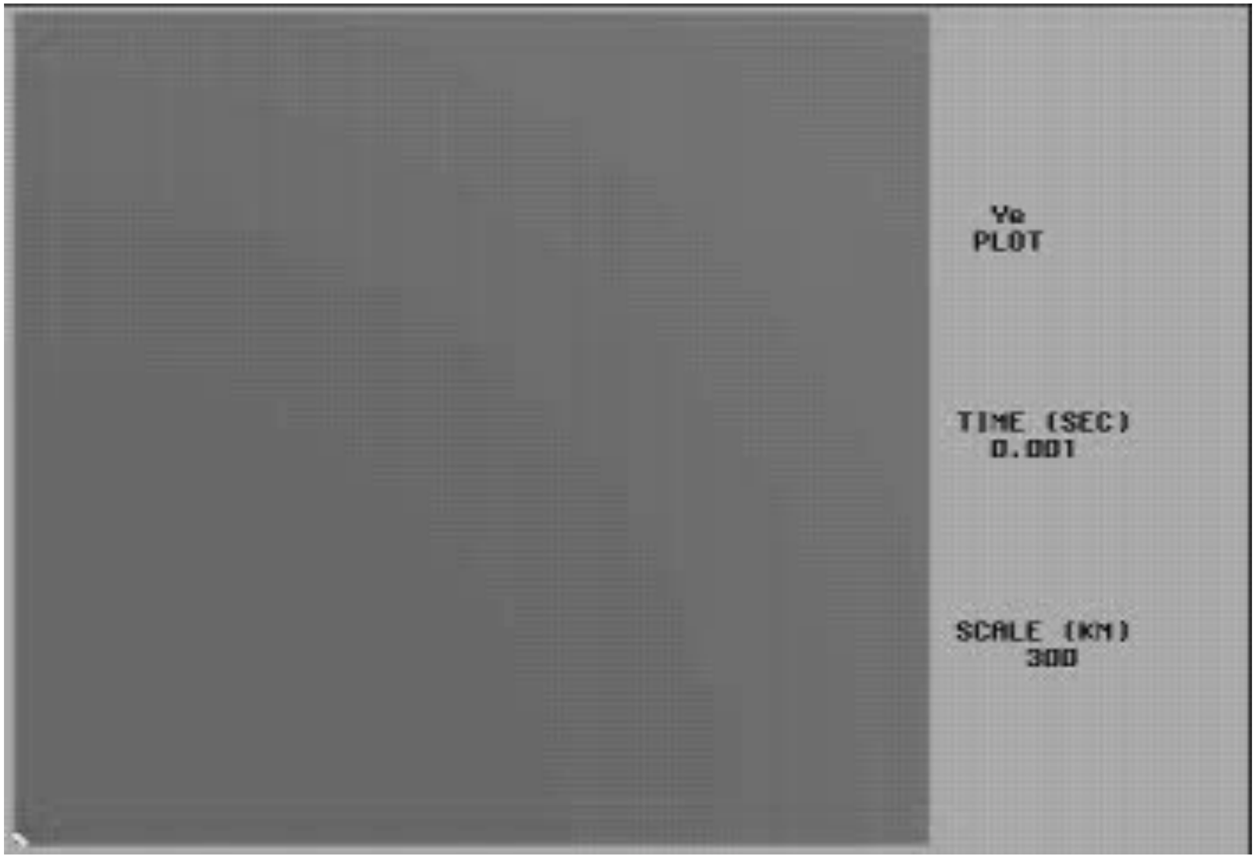
After about 50 milliseconds:

- Shockwave *stalls*

Meanwhile, neutrinos pour out of the core:

- Some heating the gas, leads to violent convection

Collapse – Bounce – Stall - Explosion(?) – Wind - Cooling



300 km

Burrows, Hayes, & Fryxell (1995)

Shockwave evolution:

Somehow shockwave revives and explodes (maybe!) after ~1 second. Otherwise, black hole formation (about 5-30% of the time!).

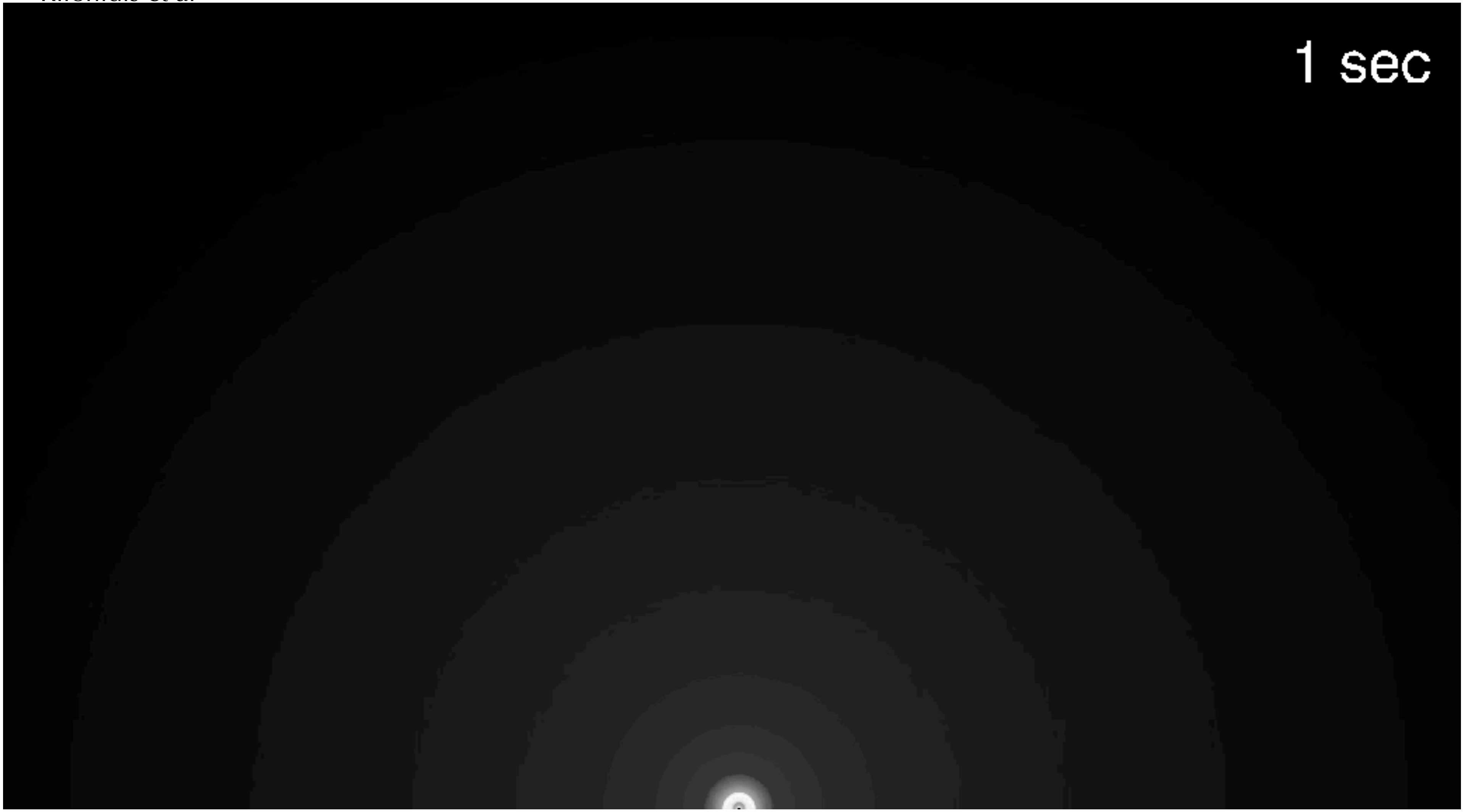
Blastwave smashes out through the star:

- Explosive nuclear fusion in its wake produces more heavy elements, like Ni, Co, Fe
- Heats up and accelerates the envelope

Shock breakout from the star’s surface a few hours later.

Supernova Shocks its Host Star

Kifonidis et al



Supernova!

At shock breakout:

-
  L_{sun} in minutes
- Outshines an entire galaxy of billions of stars!

Outer envelope is blasted off:

- accelerated to a few x 10,000 km/sec
- gas expands & cools off

Only the neutron star core remains behind…

Supernova 1987a

Nearest visible supernova since 1600’s.

February 23, 1987:

- 15 M_{sun} Supergiant Star SK 69^{o}202 Exploded in the Large Magellanic Cloud.
- Saw a pulse of neutrinos, then the explosion.
- Confirmed the basic picture of collapse.
- Continued to follow it for the last 25 years.

Wealth of information on supernova physics

SN 1987A

1987 A.D.

February 23

Type-II

Progenitor:

Sanduleak -69^{o} 202a

Supergiant

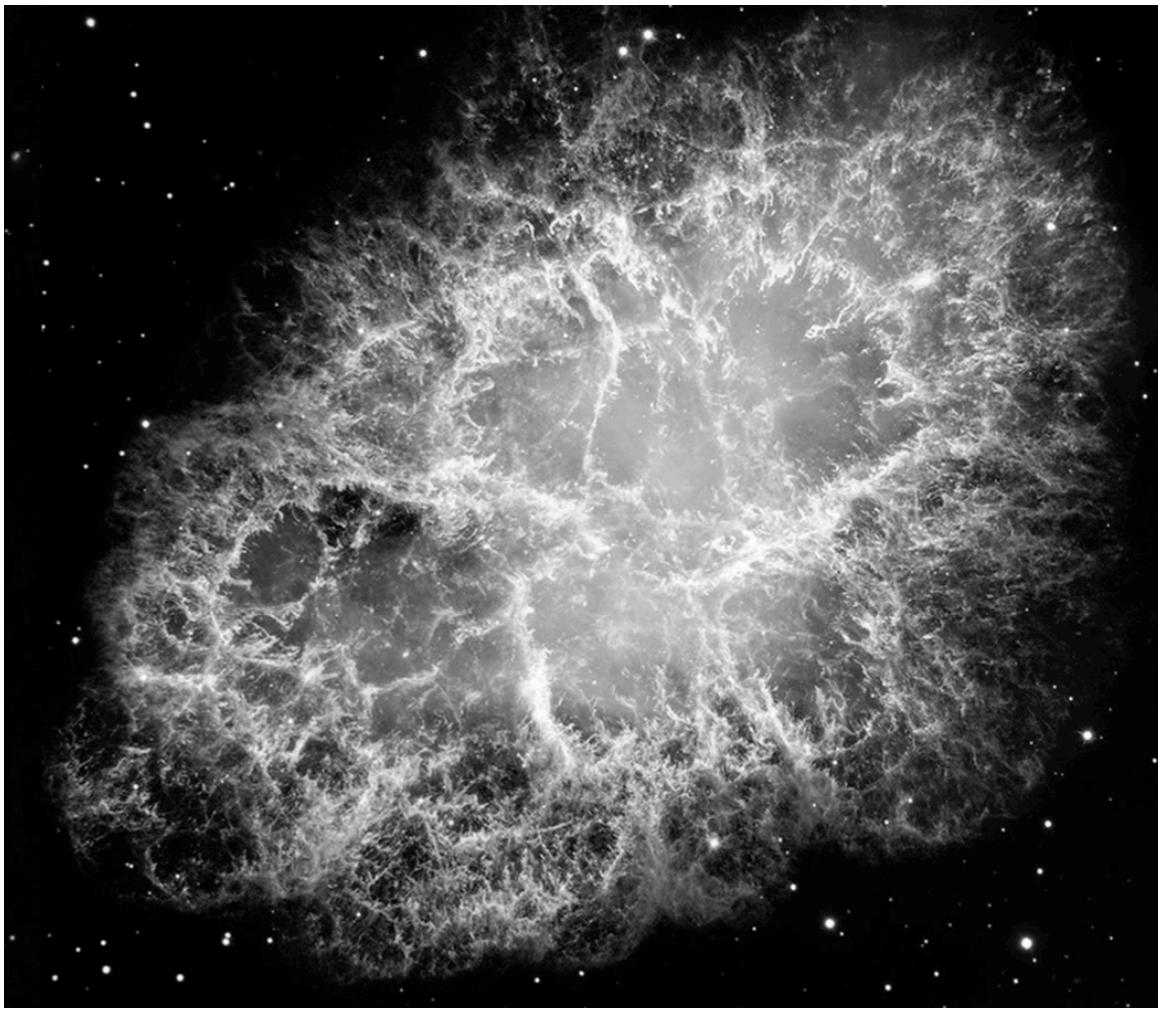
CTIO

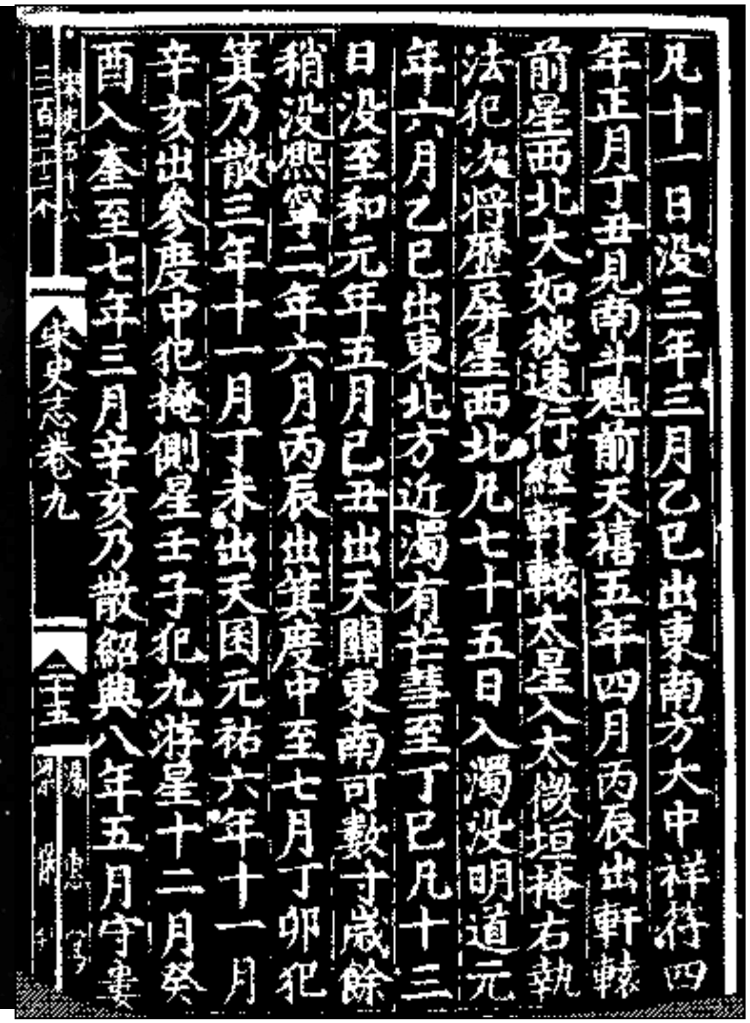
Before

During

Crab Nebula

Remnant of Supernova in 1054, Song dynasty discovery, visible in daylight for 23 days.

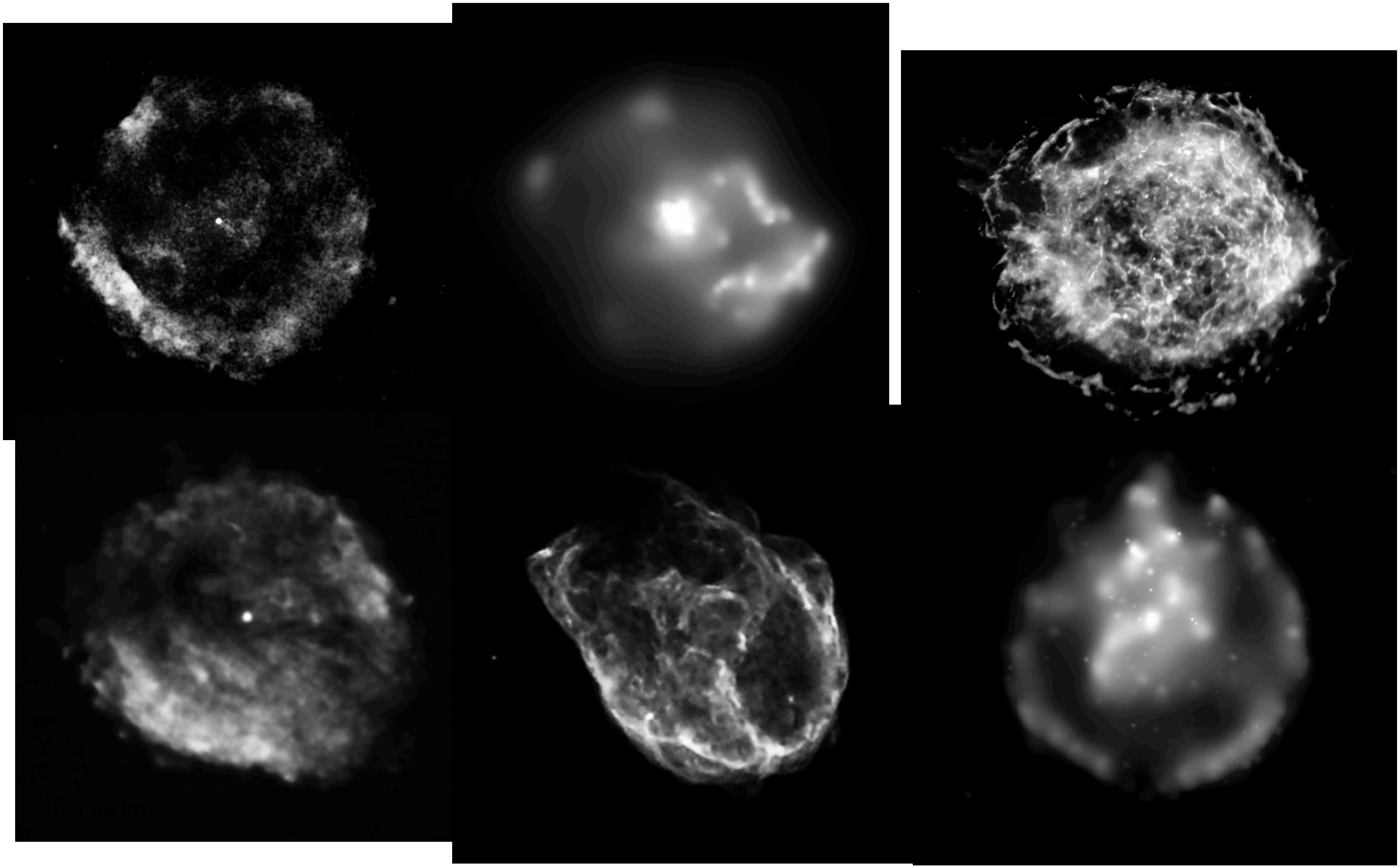




凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅大星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

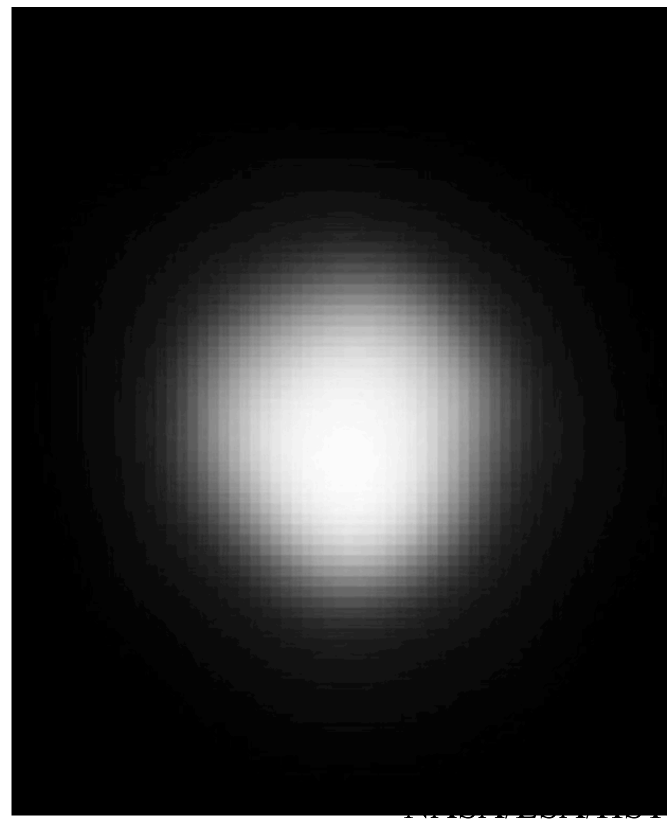
X-Ray Supernova Remnants



$D \sim 200$ pc (600 lyr)
$L \sim 100{,}000\ L_{sun}$
$R \sim 1000\ R_{sun}$
$T \sim 3500$ K
$M \sim 20\ M_{sun}$

Betelgeuse

It's supernova might be nearly as bright as the full moon.
For weeks.



NASA/ESA/HST

~ 1 Sun-like star born per year.
~ 1 massive star >8 Msun every 100 years.
~1 supernova every 100 years.

A galaxy

In 10 billion years:

~ 100 million supernovae.

~ 1 billion M_{sun} of elements ejected.

~ 100 million neutron stars.

What left behind? Neutron Stars

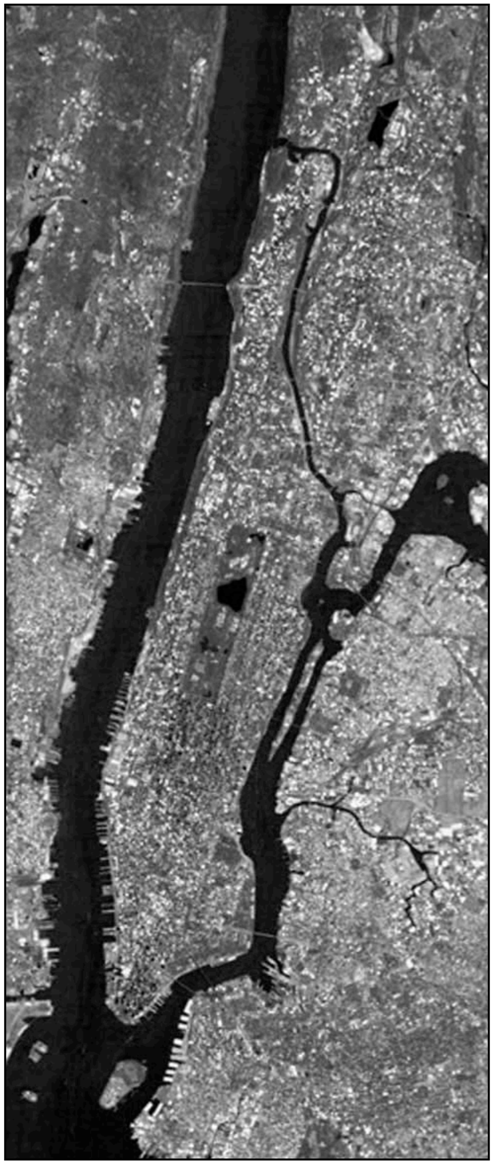
Remnant cores of massive stars:

- 8 < M < 100 M_{sun} (??)
- Leftover core of a core-collapse supernova
- Produced by

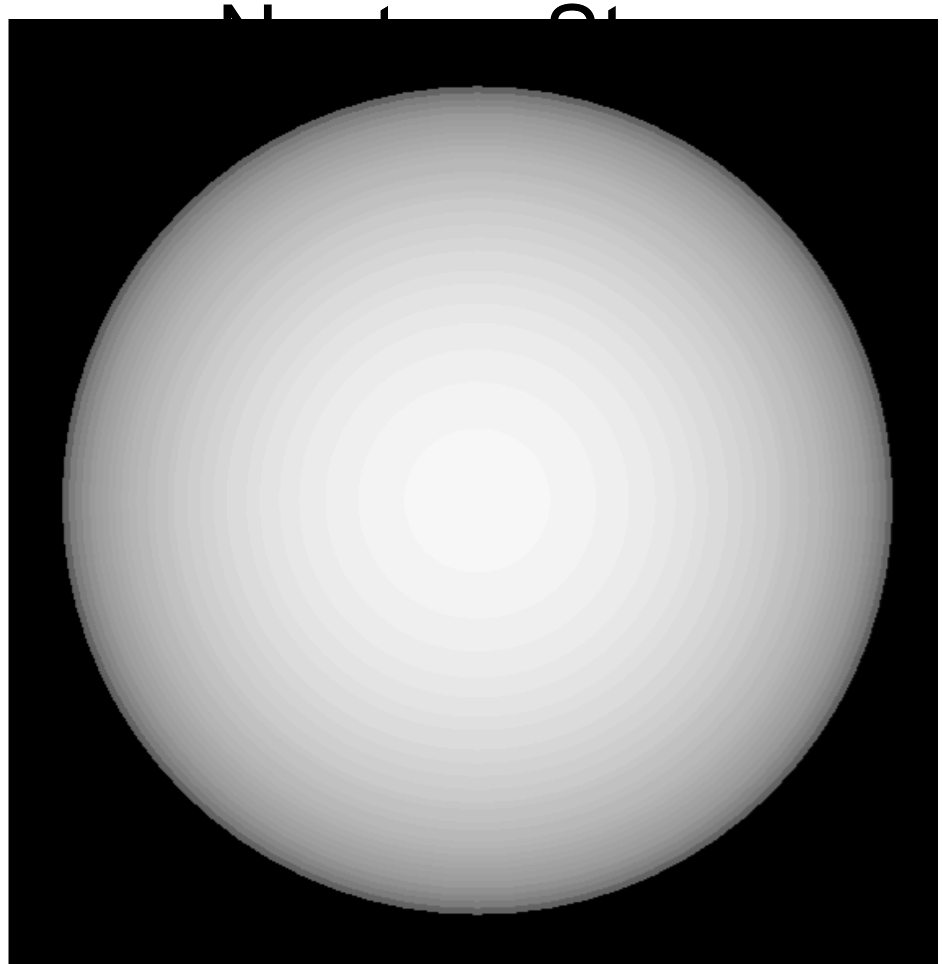
Held up by Neutron Degeneracy Pressure:

- Mass: ~1.2 2 M_{sun}, Radius: ~10 km (born 20-30km)
- Density: ~ few x 10^{14} g/cc
- Escape Speed: ~0.7c (70% speed of light)

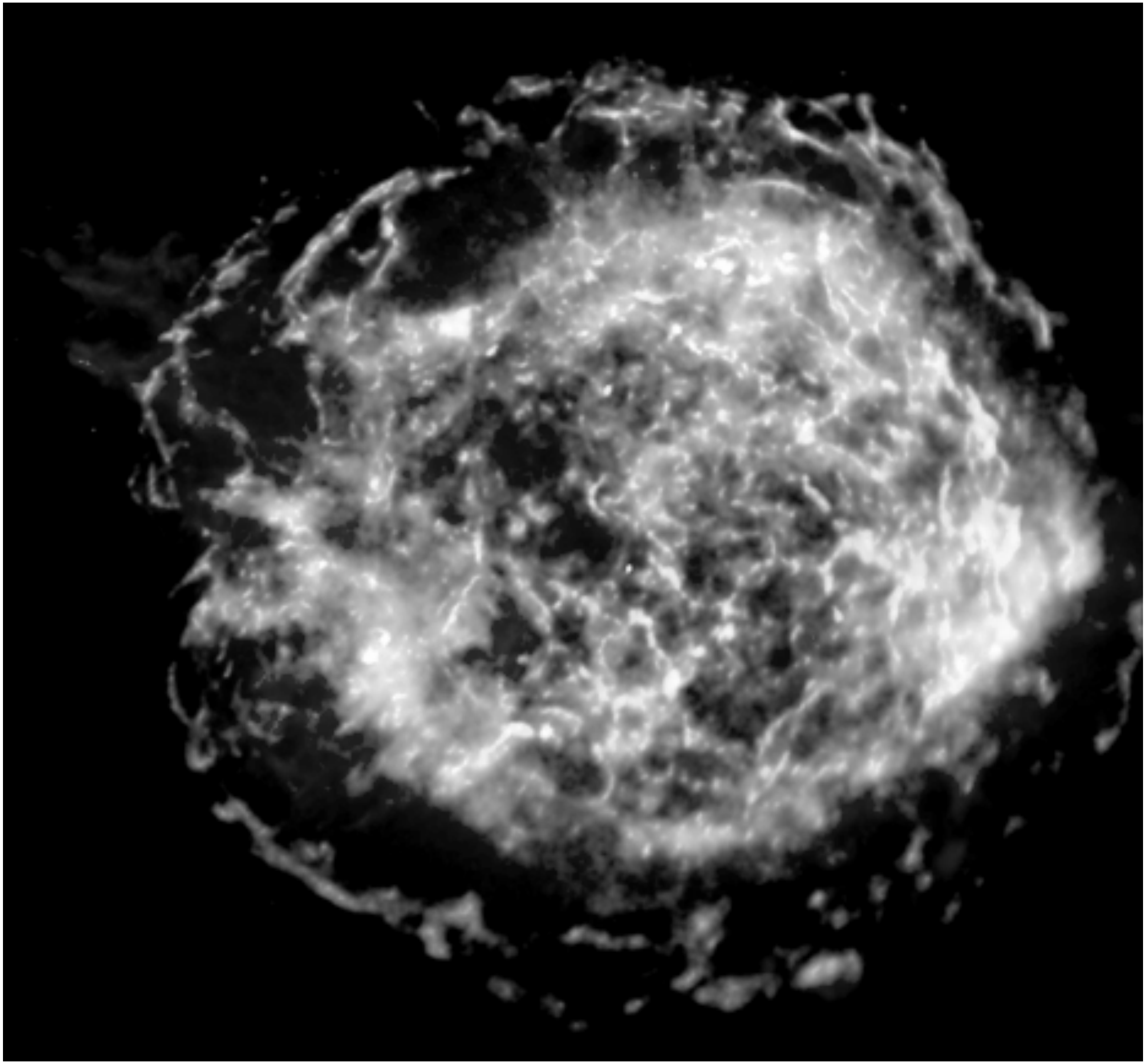
Shine by residual heat: no fusion or contraction



Manhattan
(spaceimaging.com)

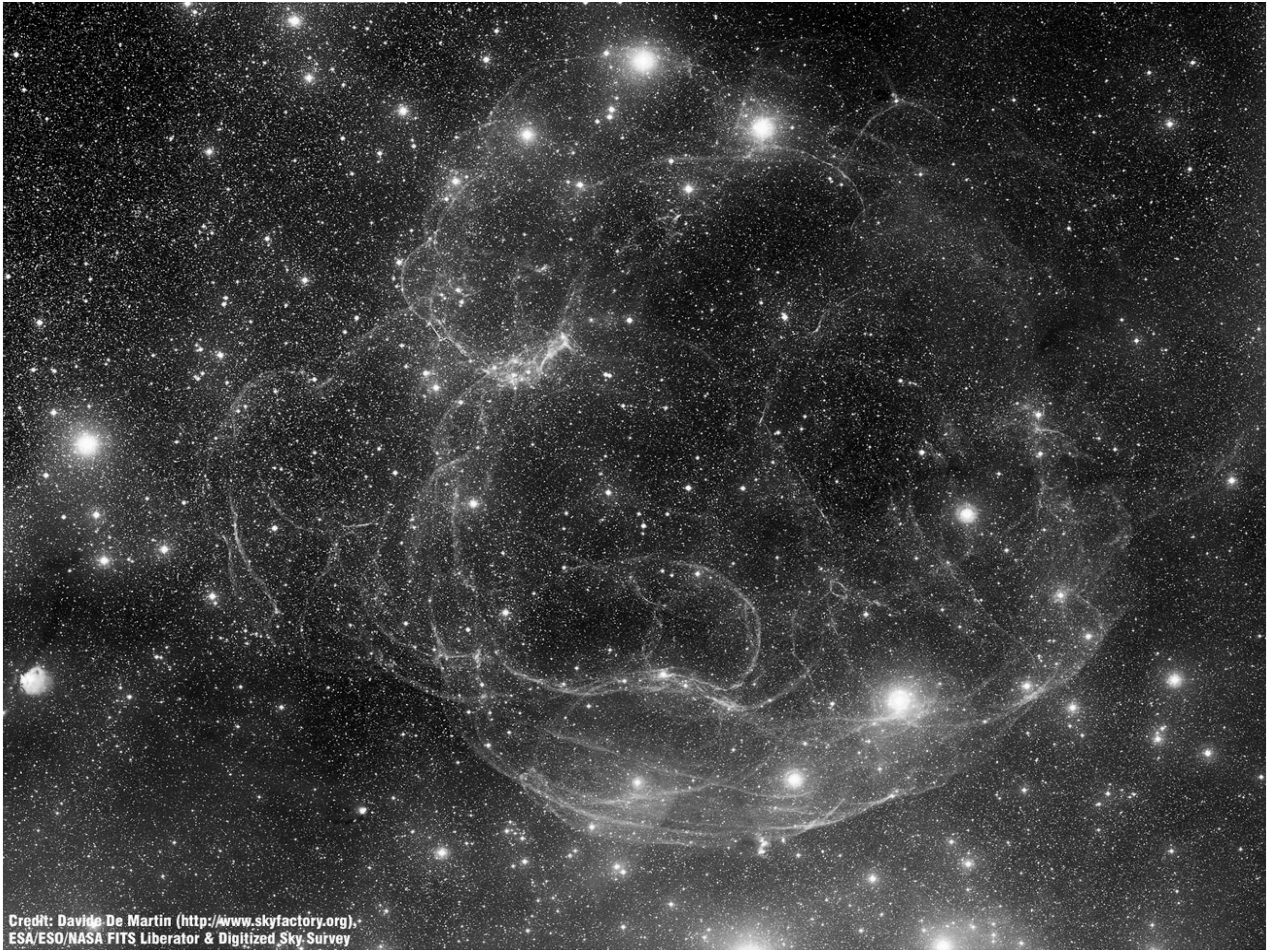


$M = 1.5\ M_{sun}$
$R \sim 10$ km
$V_{esc} \sim 0.7c$

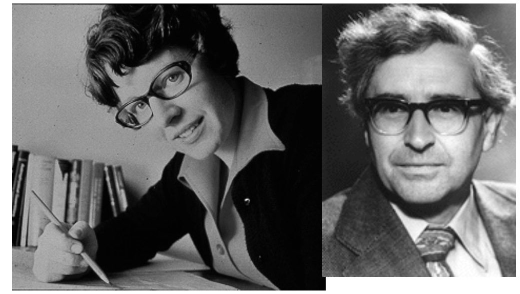


Cass A

Ended here, Weds Oct 15


Credit: Davide De Martin (http://www.skyfactory.org),
ESA/ESO/NASA FITS Liberator & Digitized Sky Survey

What about old neutron stars? Accidental Discovery of Pulsars

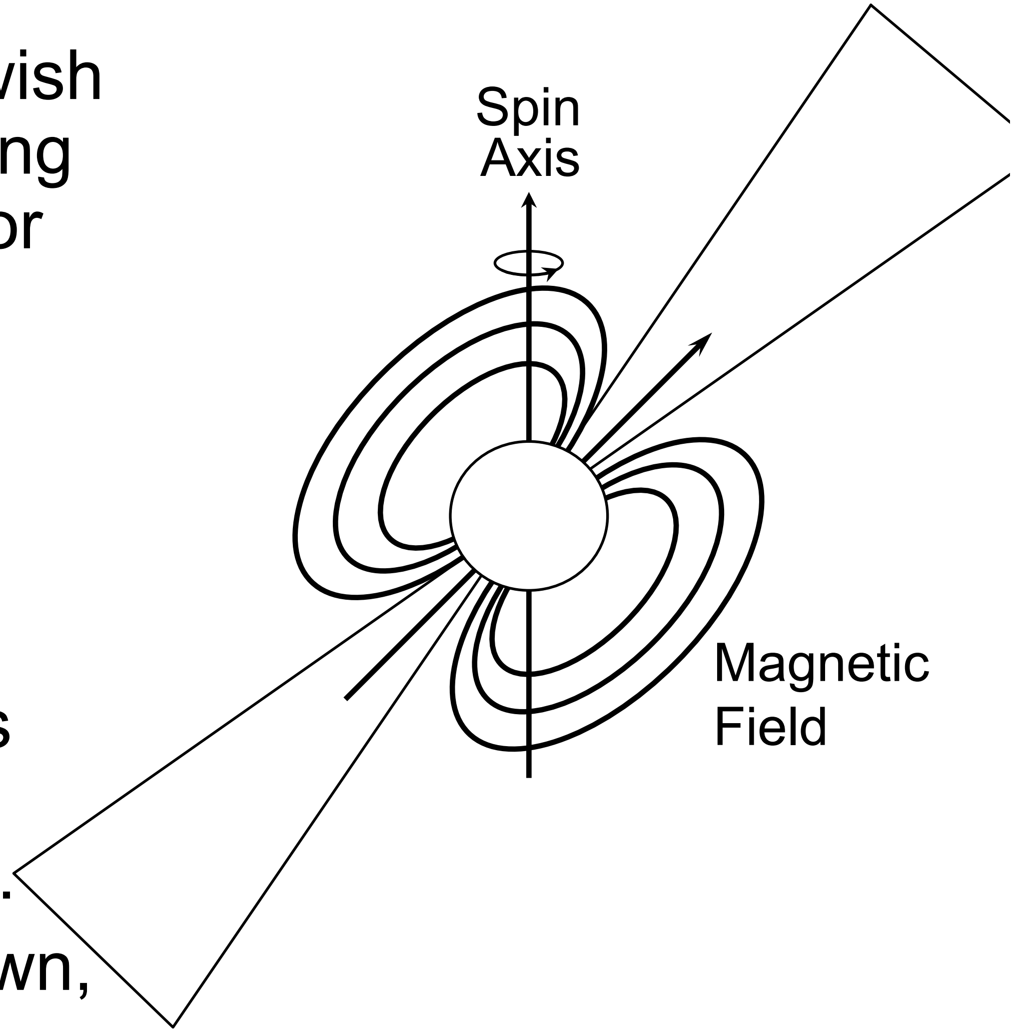


<u>1967</u>:
grad student) & Anthony Hewish (her adviser) discover pulsating radio sources while looking for something else.

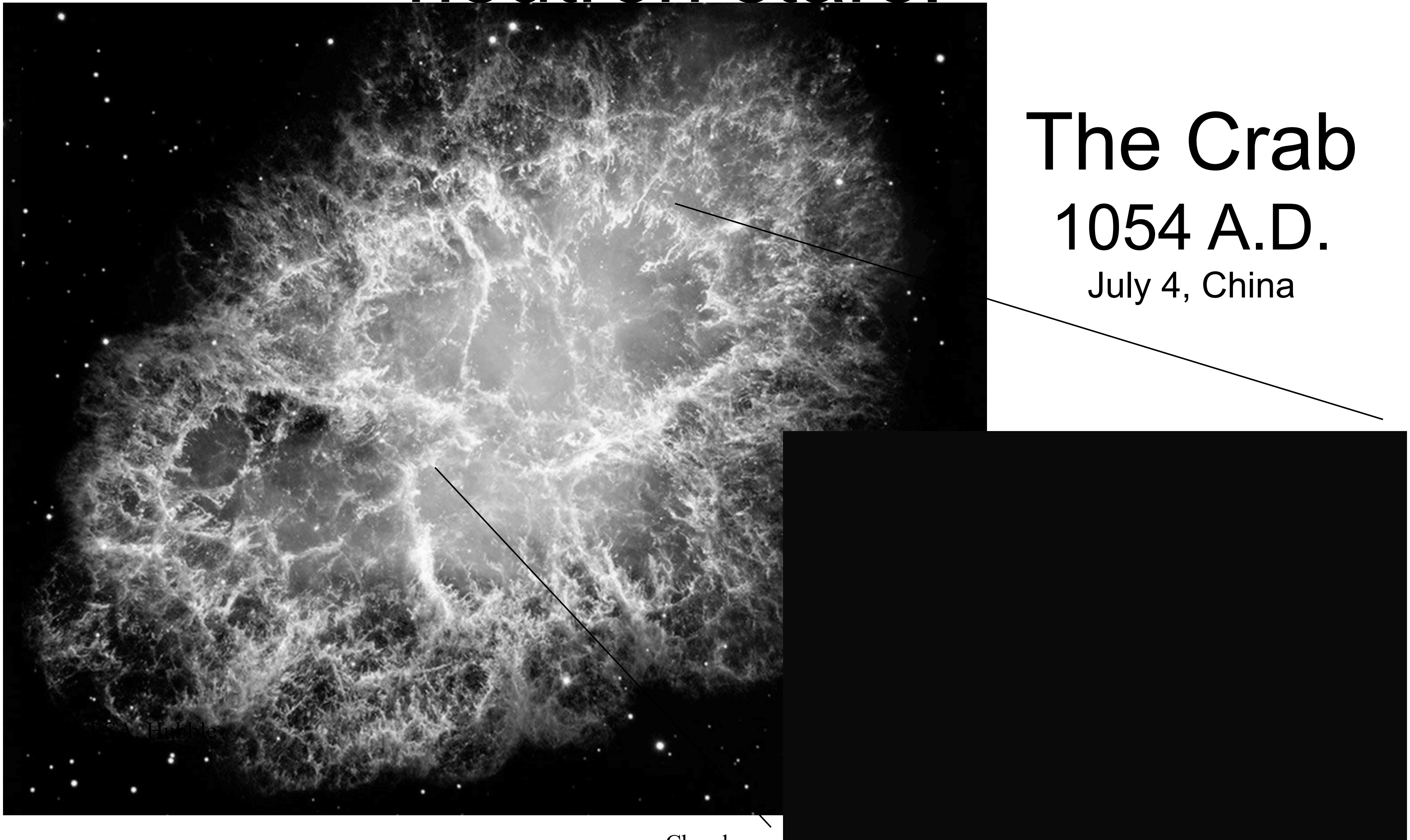
Pulsars = Pulsating Radio Sources

-

  pulses every spin period.
- Strong magnetic field rips electrons off the surface, beams radio waves to us.
- Many hundreds now known, Periods from 0.002 – 20s.



Massive stars explode, leave neutron stars.



Chandra

The Crab
1054 A.D.
July 4, China

Pulsar Evolution

Pulsars spin slower as they age.

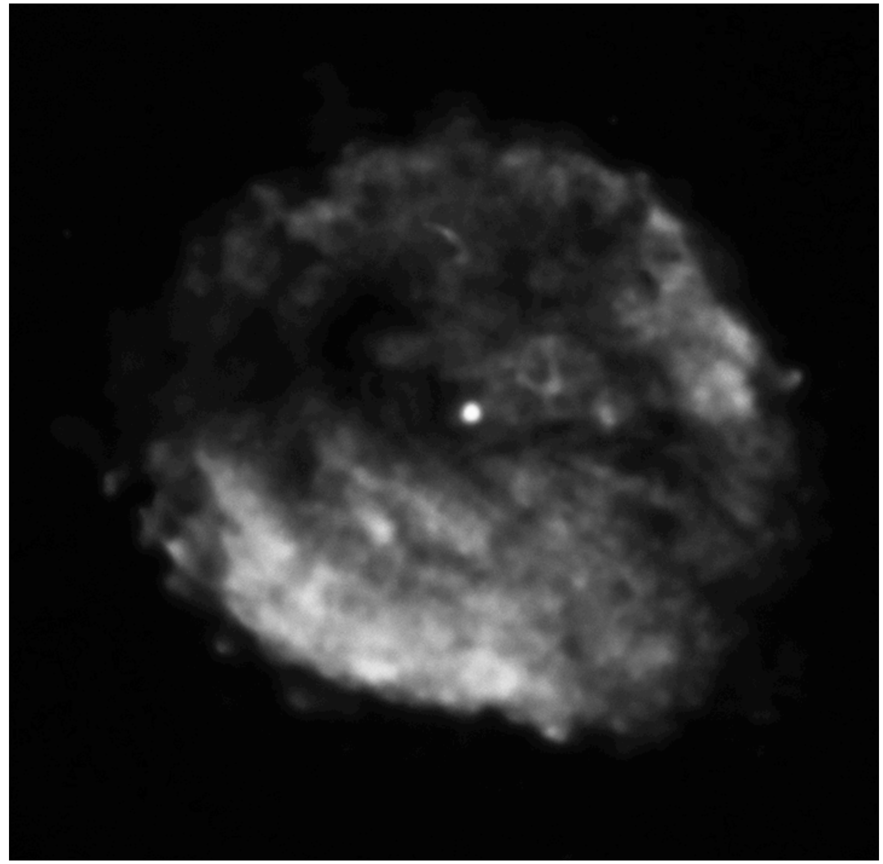
- Lose rotational energy

Young neutron stars:

- fast spinning pulsars.
- found in supernova remnants (e.g., Crab pulsar)

Old neutron stars:

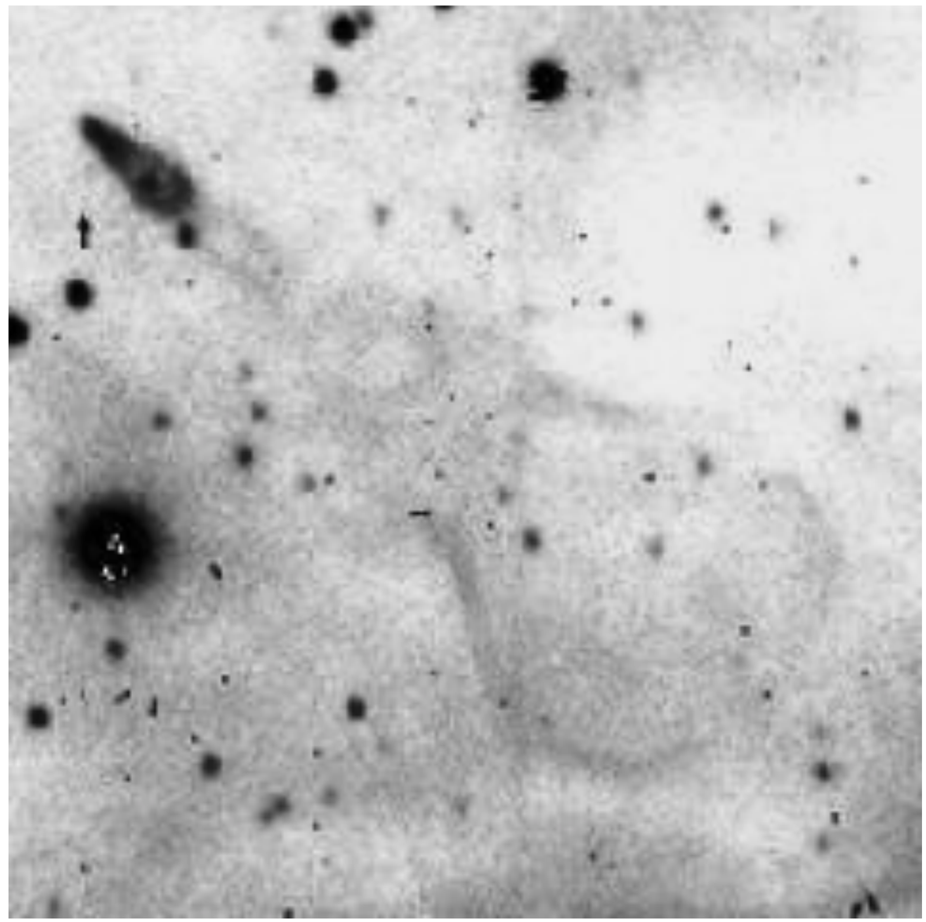
- cold and hard to find



Neutron Stars Move Fast: Kicks!

V ~ 1000 km/s

Much faster than normal stars (orbital velocity in galaxy uniform ~200 km/s)



Over the top?

What if the remnant core is massive?

$M_{core} > 2.2\ M_{sun}$ or so.

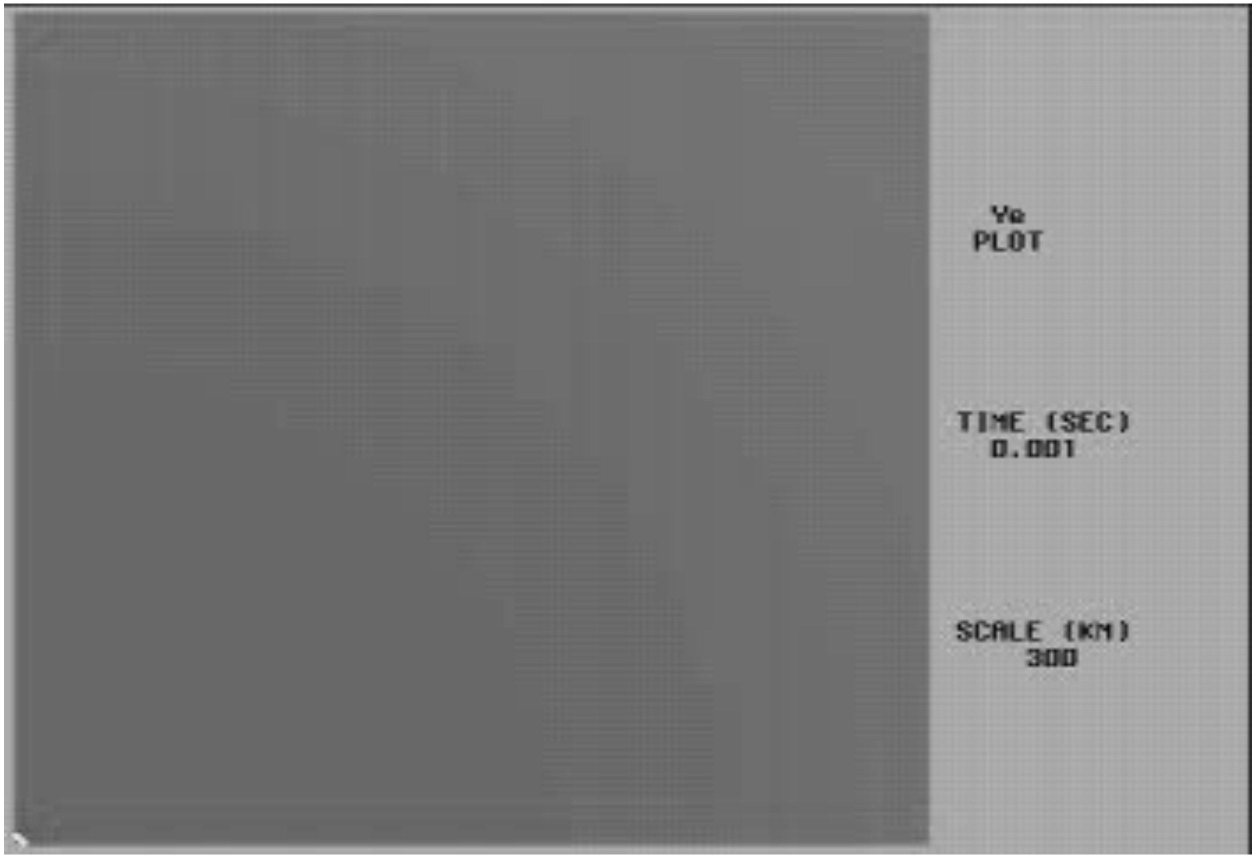
(original star had $M \sim 20\text{-}30\ M_{sun}$)

- Neutron degeneracy pressure fails.
- Strong force fails.
- Nothing can stop gravitational collapse.
- Collapses to zero radius and infinite density.

Becomes a Black Hole...

(This process has never been observed)

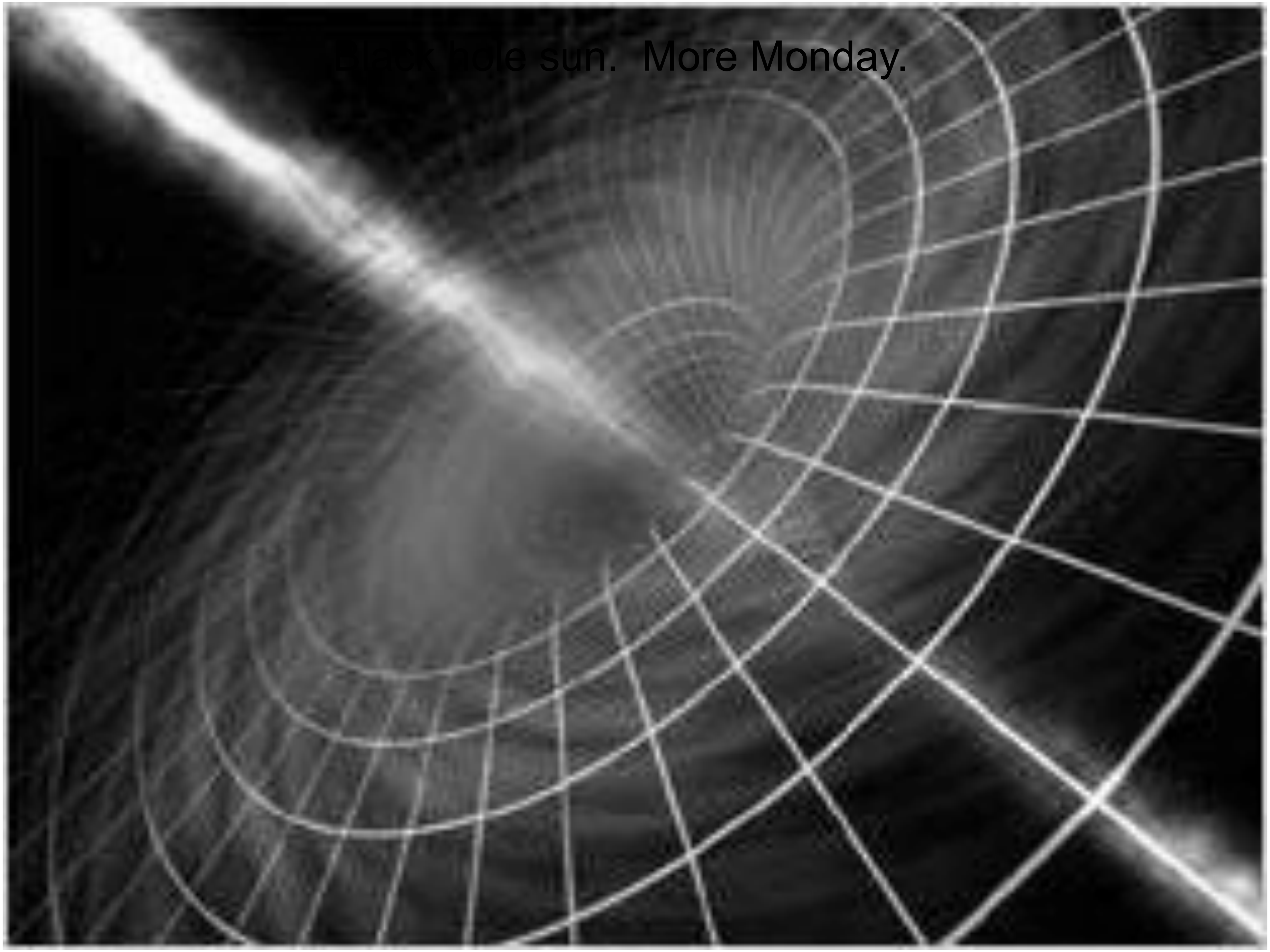
Collapse – Bounce – Stall - Explosion(?) – Wind - Cooling



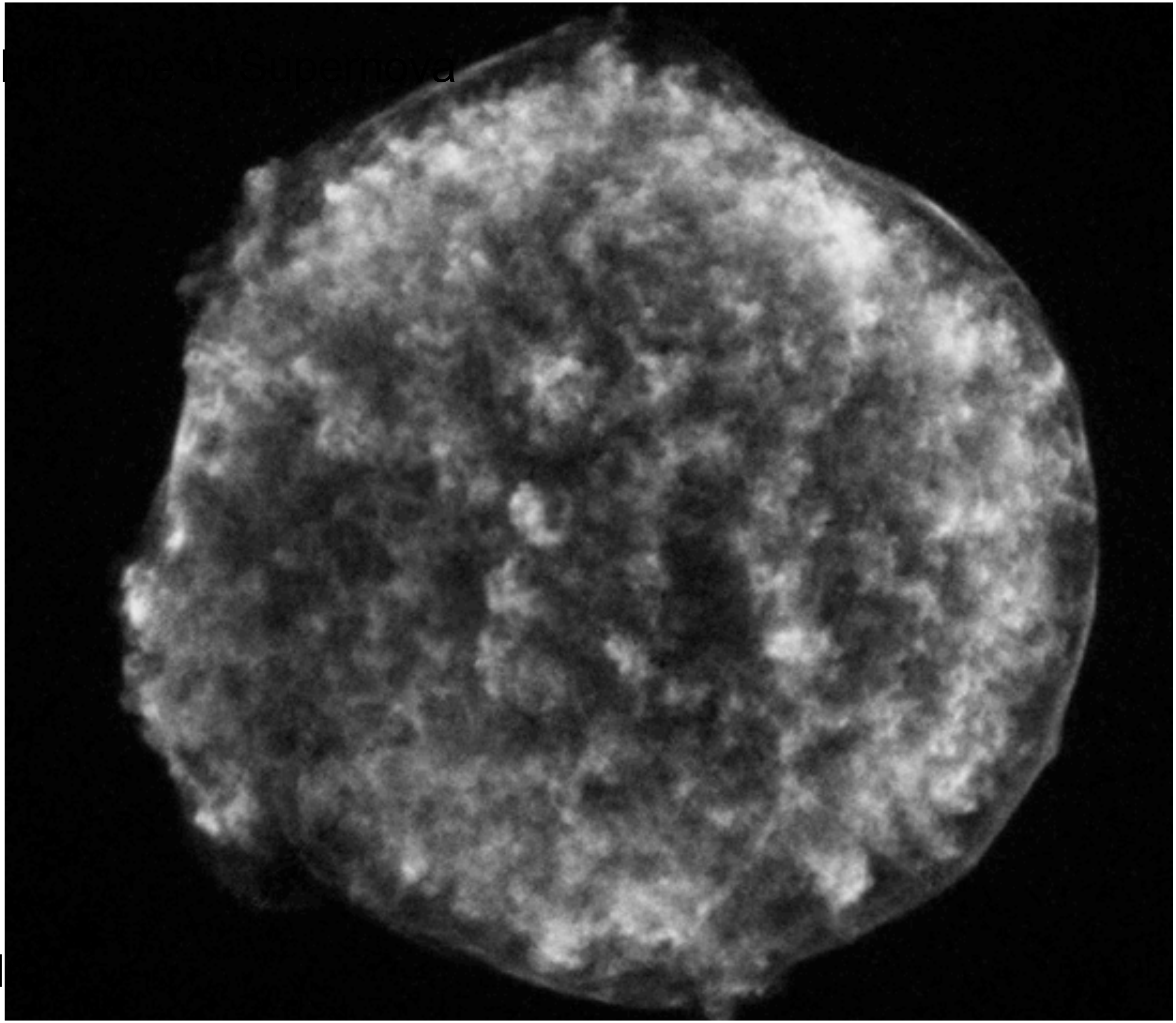
300 km

Burrows, Hayes, & Fryxell (1995)

Black hole sun. More Monday.

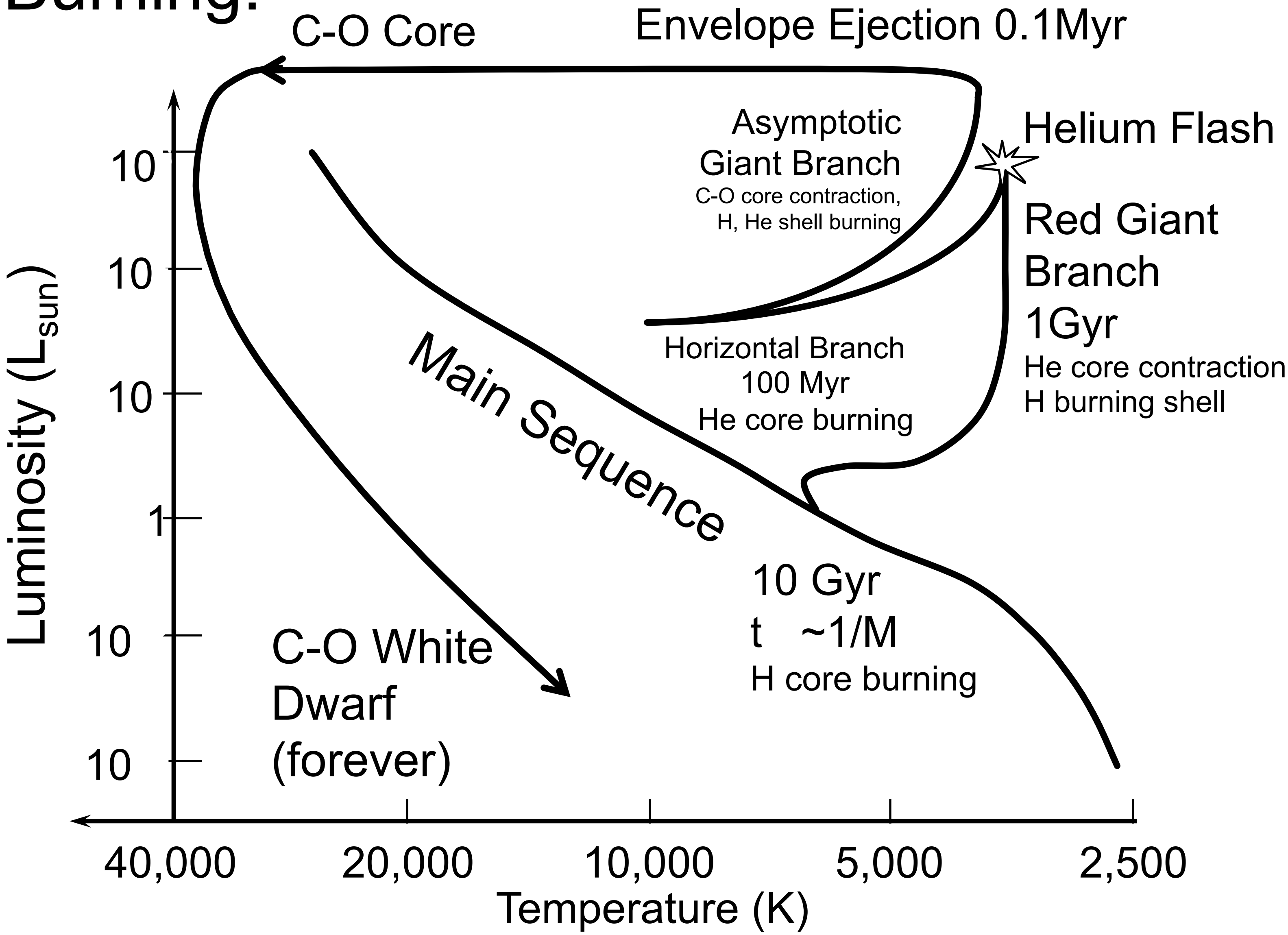


The Ot



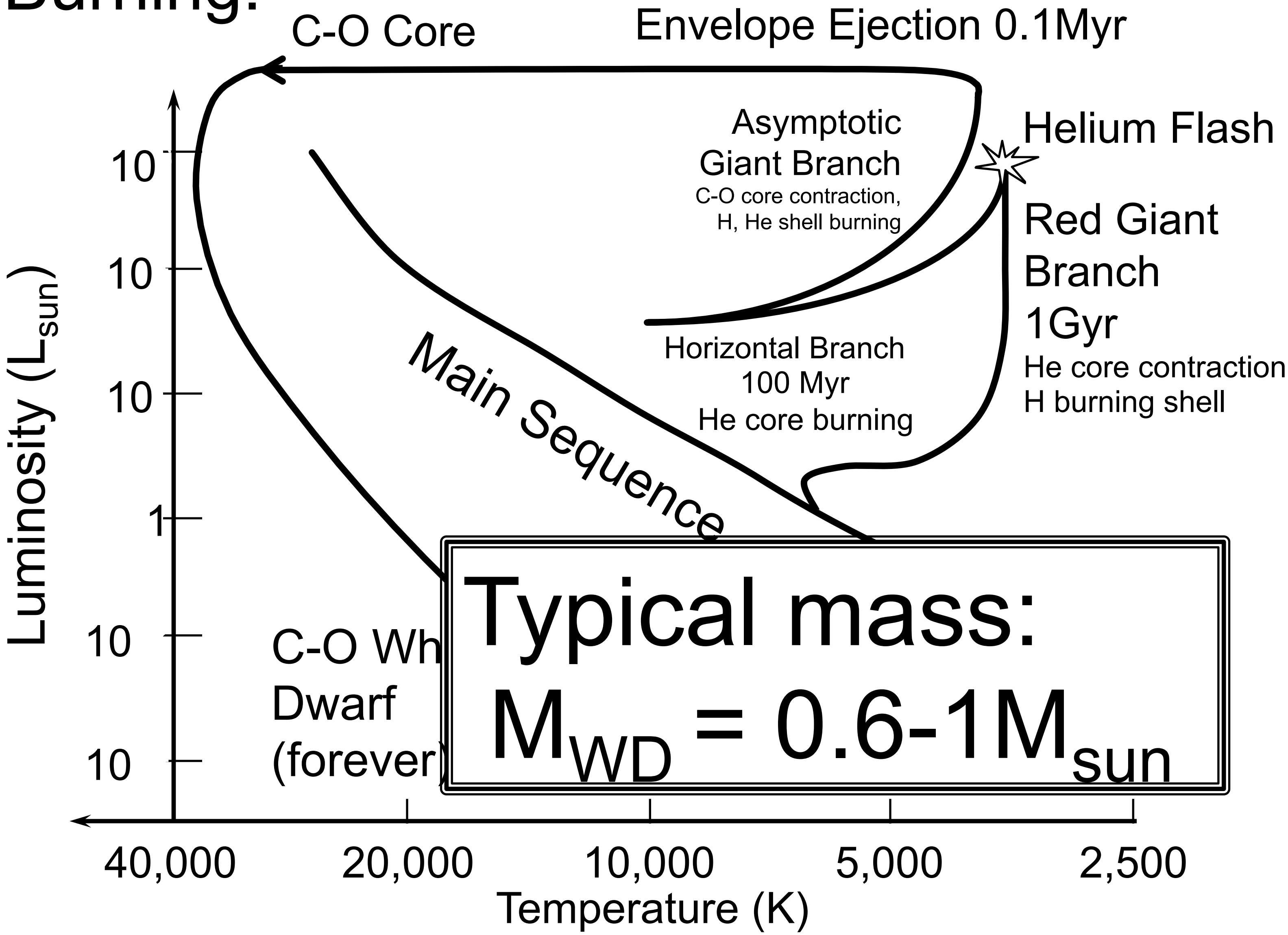
Chand

Evolution of Low-Mass stars $M < 4\ M_{sun}$
No C Burning!



Evolution of Low-Mass stars $M < 4\ M_{sun}$

No C Burning!



Typical mass:

$M_{WD} = 0.6\text{-}1M_{sun}$

Degenerate Gas Law

At high density, a new gas law takes over:

- Pack many electrons into a tiny volume
- These electrons "fill" all low-energy states
- Pauli exclusion principle: fermions (e.g., electrons, neutrons, protons) cannot occupy the same energy state.
- Only high-energy = high-pressure states left

Result is a "*Degenerate Gas*" equation of state:

- Pressure is ***independent*** of Temperature.

Allows for very cold objects to be in Hydrostatic Equilibrium.

(Related to how the cores of planets hold themselves up.)

White Dwarfs

Remnant cores of stars with $M < 8\ M_{sun}$.

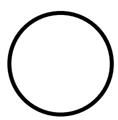
- Held up by Electron Degeneracy Pressure.
- $M < 4\ M_{sun}$: C-O White Dwarfs
- $M = 4 – 8\ M_{sun}$: O-Ne-Mg White Dwarfs

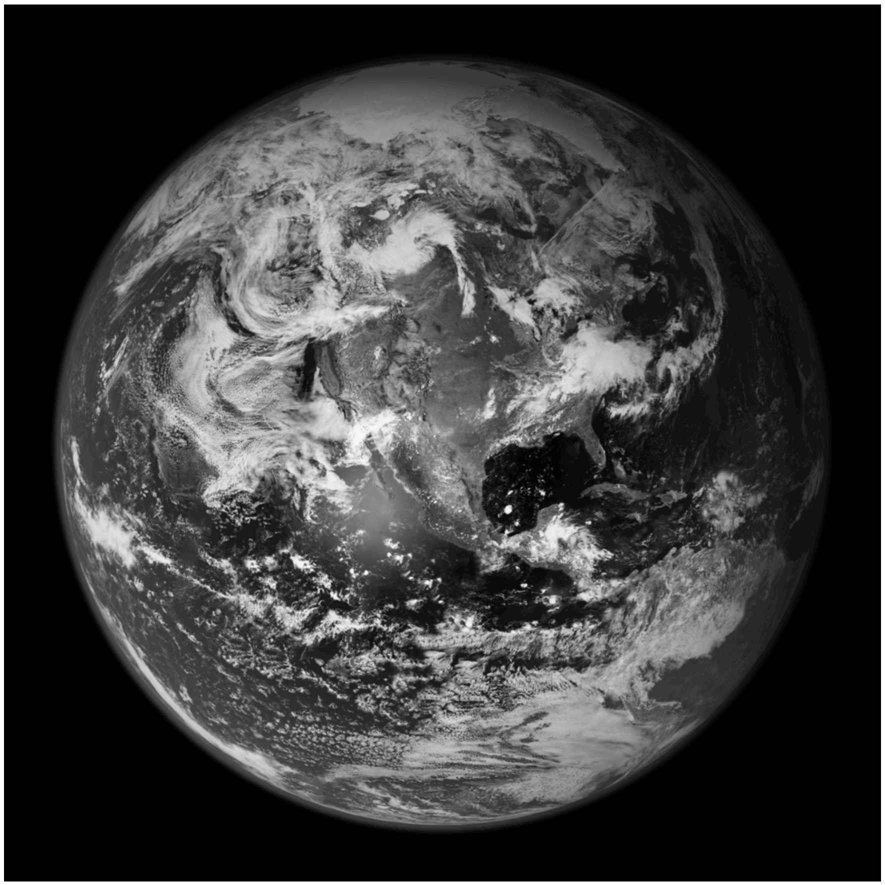
<u>Properties</u>:

- Mass: $< 1.2\ M_{sun}$, Radius: $\sim R_{earth}$ ($\sim 0.01\ R_{sun}$)
- Density: $\sim 10^6$ g/cc
- Escape Speed: few% speed of light (0.01-0.03c)

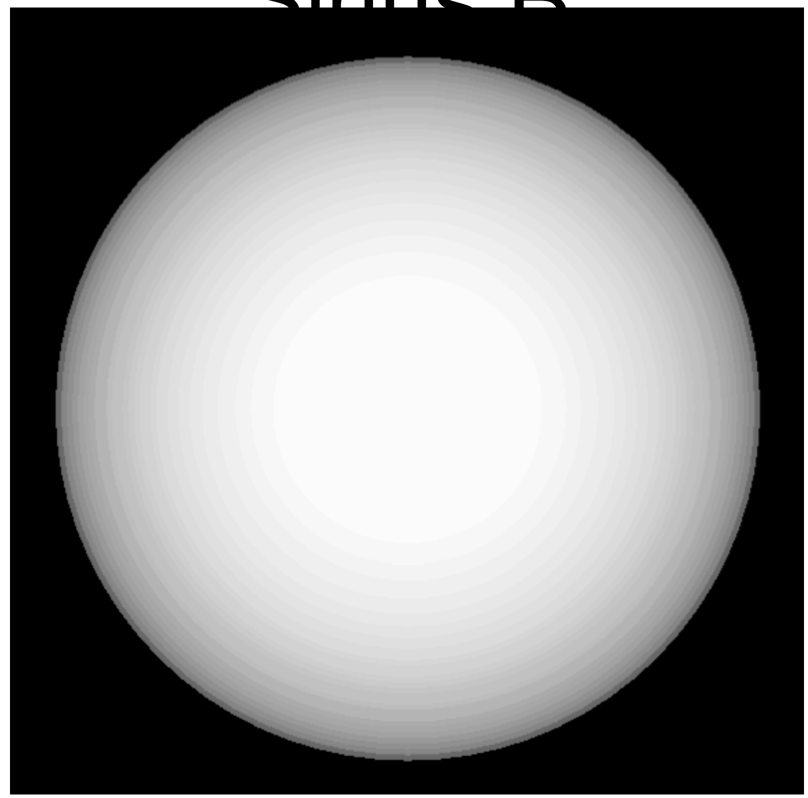
Shine by residual heat: no fusion or contraction

Binary of Sirius and Sirius B





Sirius B



M ~ 1.0 M_{sun}
R ~ 5800 km
V_{esc} ~ 0.02c

Evolution of White Dwarfs

White dwarfs shine by <u>leftover heat</u>:

- No sources of new energy (no fusion)
- Cool off and fade away slowly.

Ultimate State: A "Black" Dwarf:

- Old, cold White Dwarf
- Takes ~10 Tyr to cool off all the way…

Universe is not old enough for Black Dwarfs

Not to be confused with Black Holes

Chandrasekhar Mass

White dwarfs are supported by "electron degeneracy pressure". Temperature independent.

Maximum Mass for White Dwarf:

$$M_{Chandra} = 1.4\ M_{sun}$$

Calculated by S. Chandrasekhar in the 1930s. Above it, electron degeneracy fails to support the star in HE & the star collapses.

How could you make a WD greater than the Chandrasekhar mass? What would happen if you did?

White Dwarf in a Binary?

White dwarfs can “accrete” from a companion in a close binary system.

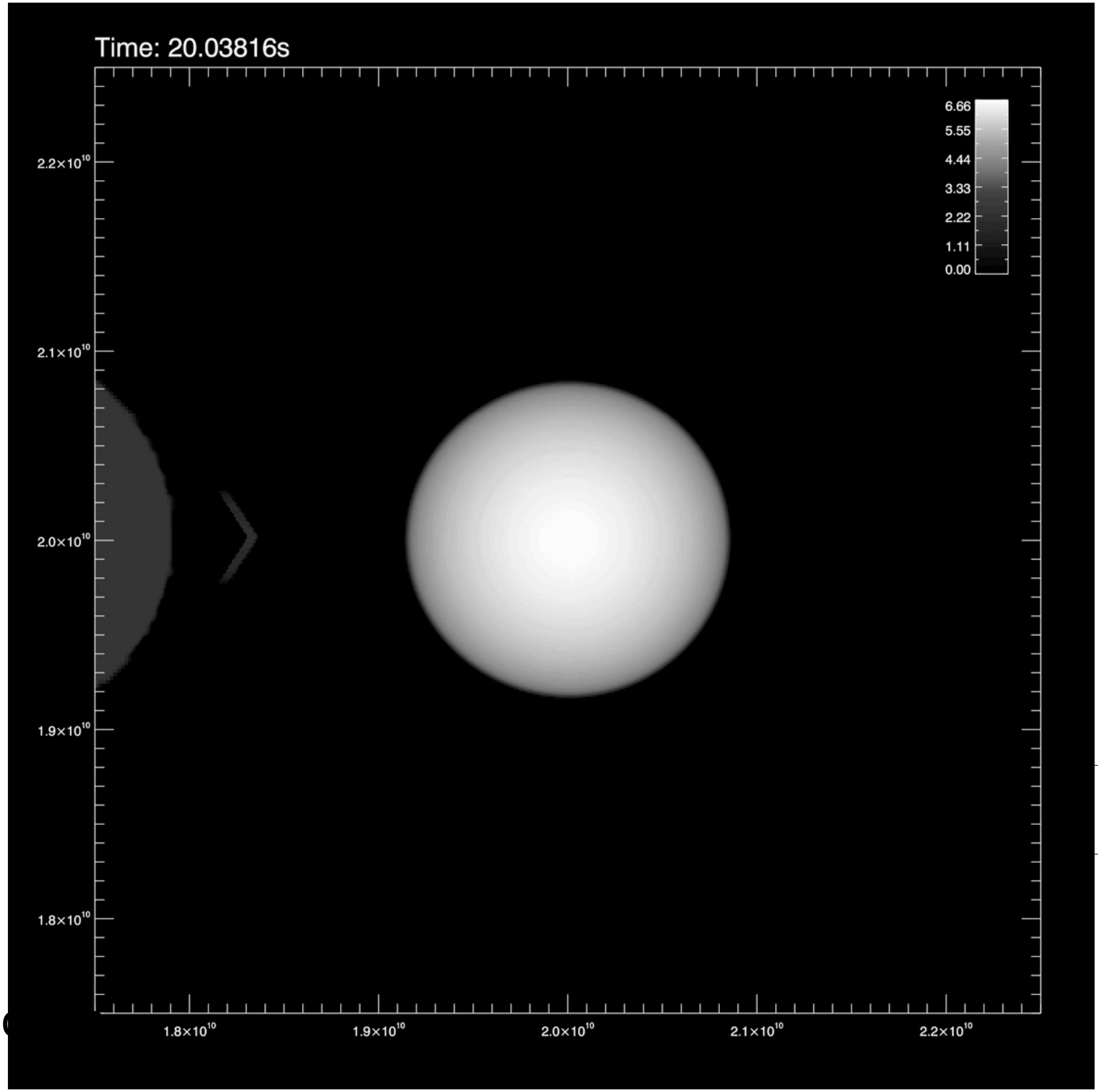
Artist’s impression of accretion onto a WD

But, then the mass grows, and grows, and grows …

What happens if M > 1.4 Msun?

Exceeds Chandrasekhar Mass

Guilloc



Time: 20.03816s
6.66
5.55
4.44
3.33
2.22
1.11
0.00
2.2×10^10
2.1×10^10
2.0×10^10
1.9×10^10
1.8×10^10
1.8×10^10
1.9×10^10
2.0×10^10
2.1×10^10
2.2×10^10

"Type-Ia" Supernovae

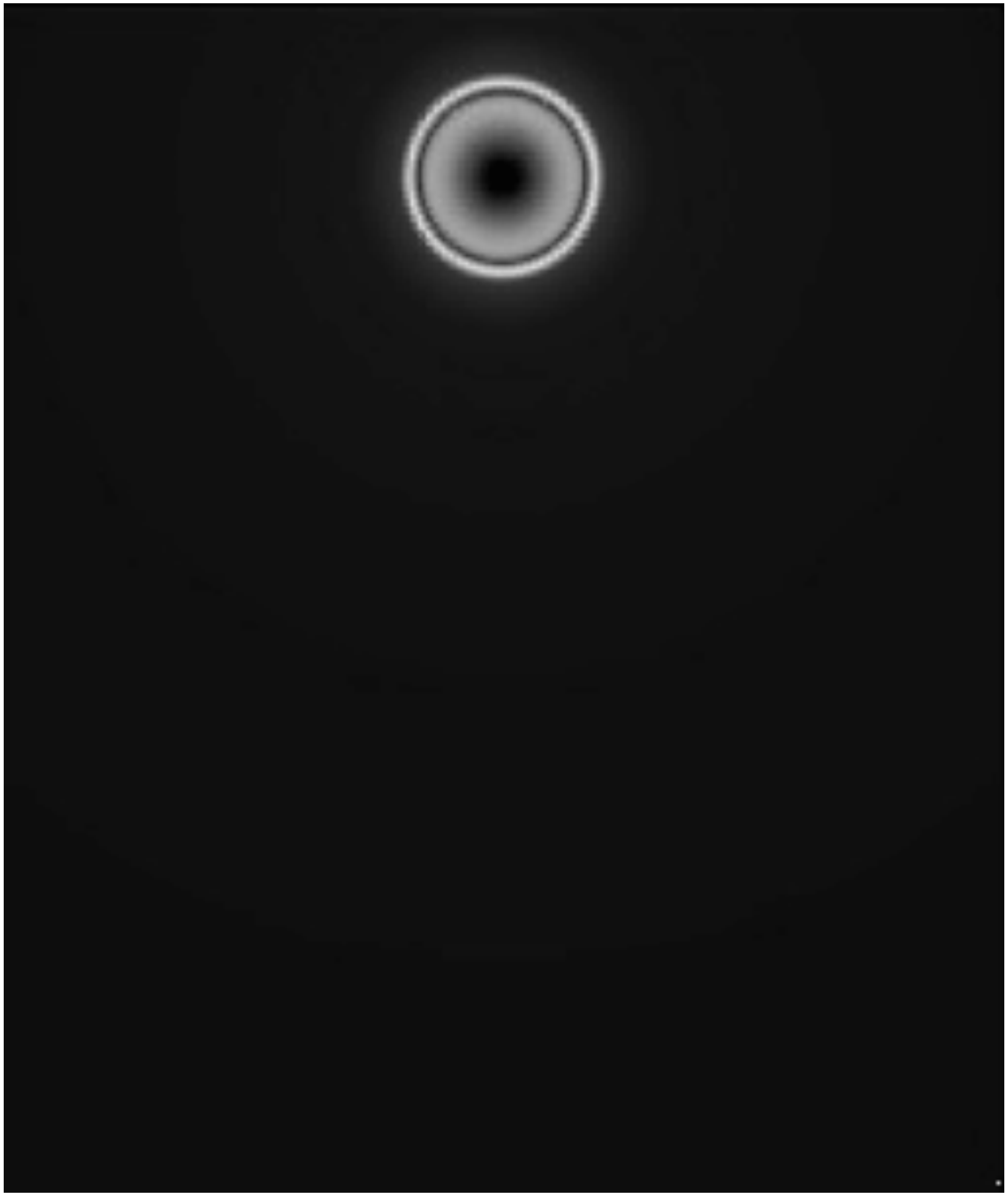
If M >1.4 M ? (Exceeds Chandrasekhar Mass)

- Electron degeneracy fails, no H.E., star collapses
- Ignites C-O (or O-Ne-Mg) fusion at high density
- Generates heat, but not enough to stave off gravity
- Greater heat = greater fusion = greater heat ...

Runaway nuclear explosion:

- Fusion of light elements into Iron & Nickel
- White Dwarf detonates as a **Type Ia Supernova**

Leaves behind nothing (total disruption). The brightest optical display in the universe. Litters the universe with Iron.



Marietta & Burrows

Another way

Strong evidence against accretion scenario (e.g., no such systems are seen; no blasted off material seen).

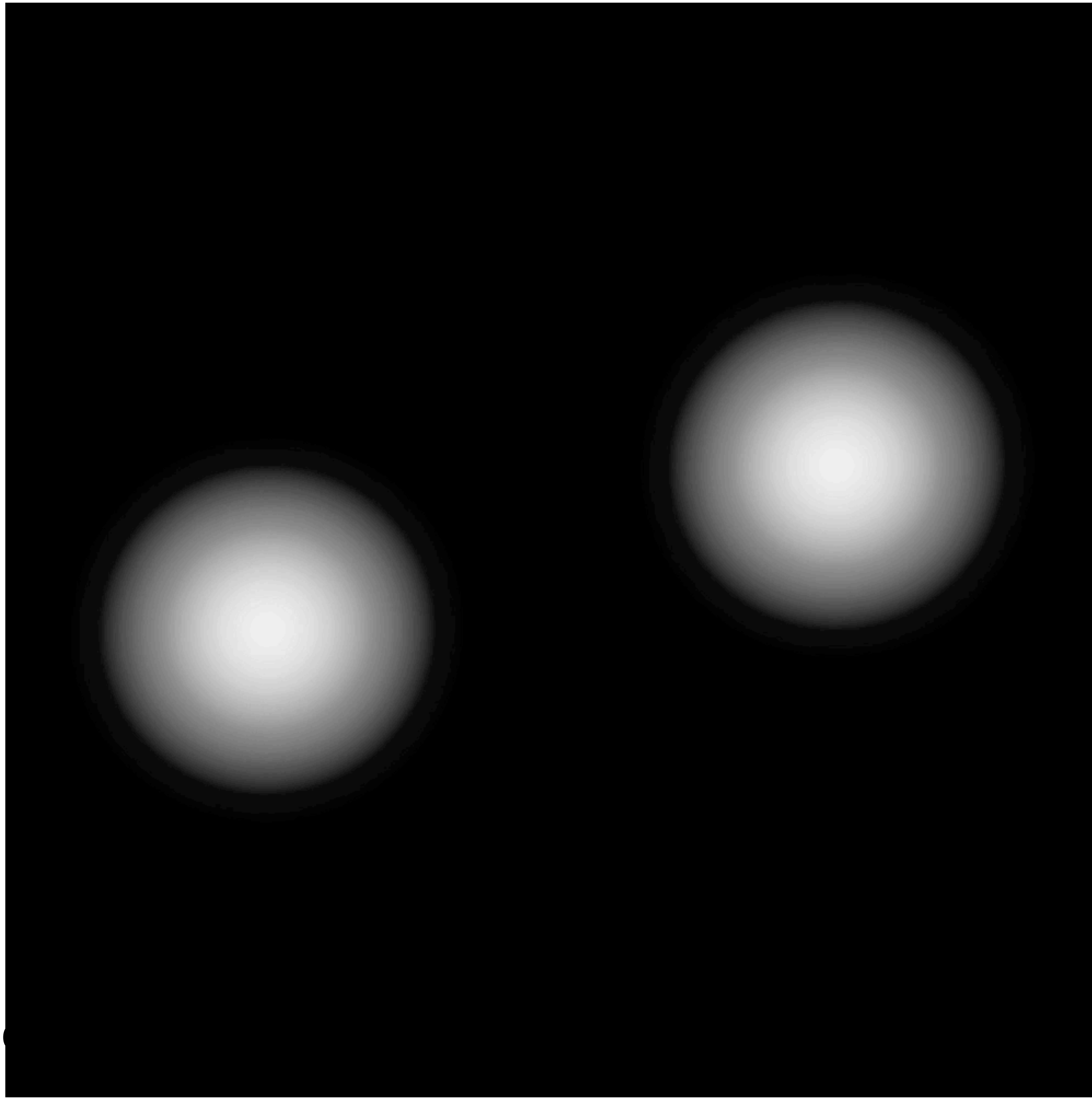
Another way: Slam two white dwarfs together.

Option 1: Binary WD+WD merge via gravitational wave emission. (>50% of all stars in binaries.)

Option 2: Binary WD+WD in a triple system. Exotic dynamics leads to a collision between the two WDs. (10% of systems on the sky are triple.)

Option 3: ?

Current active area of research.

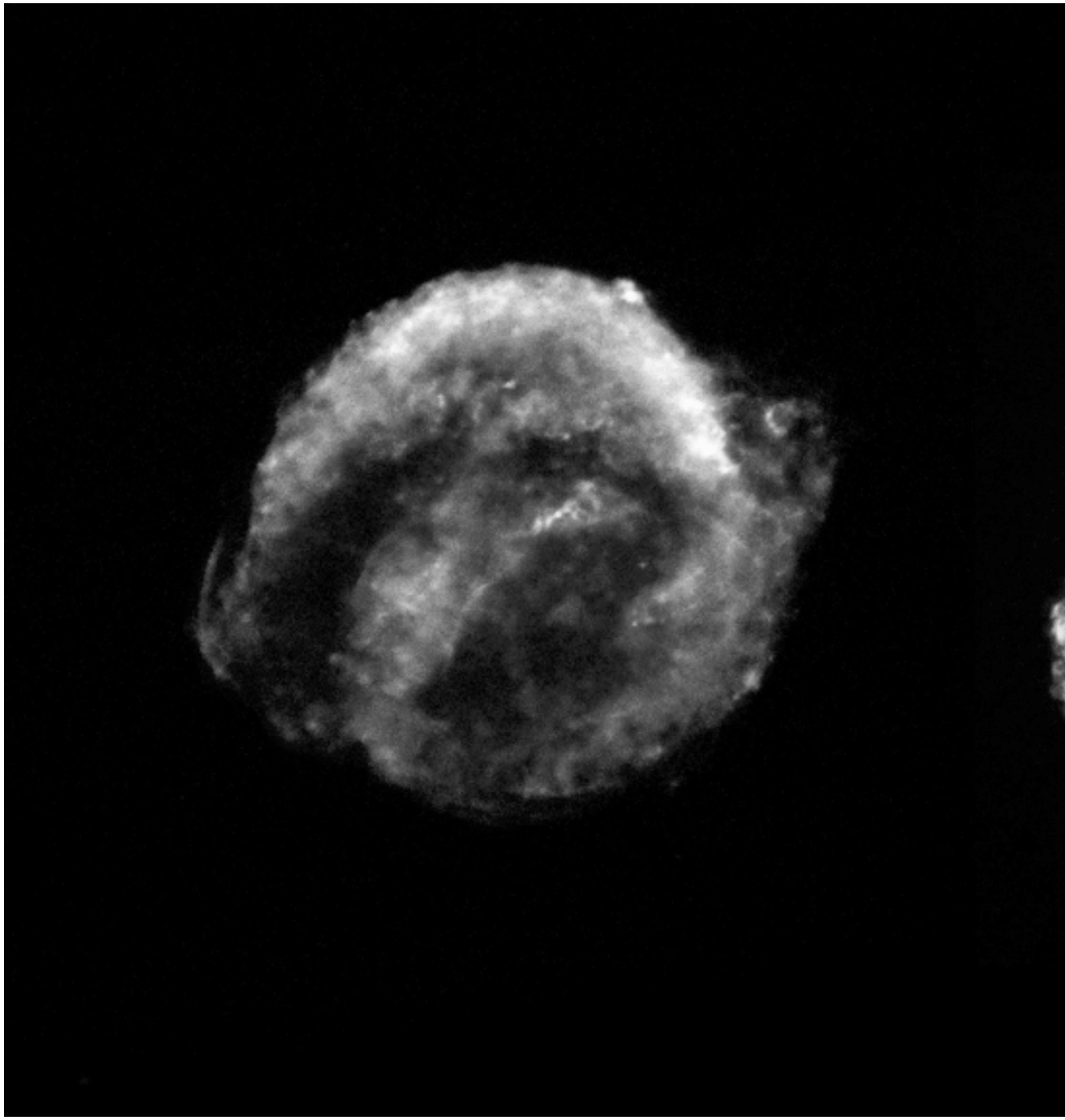


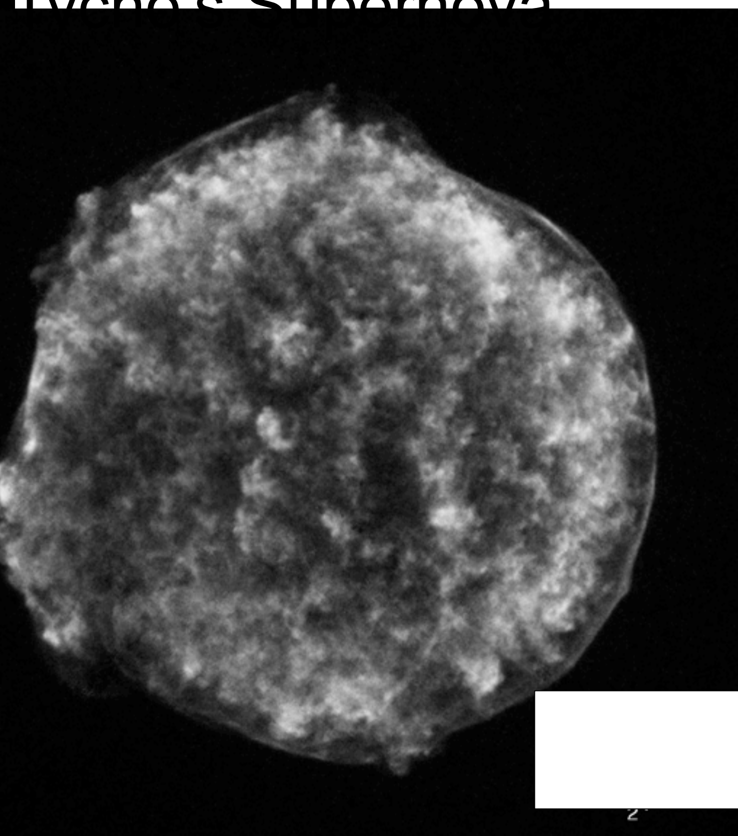
Guilloc

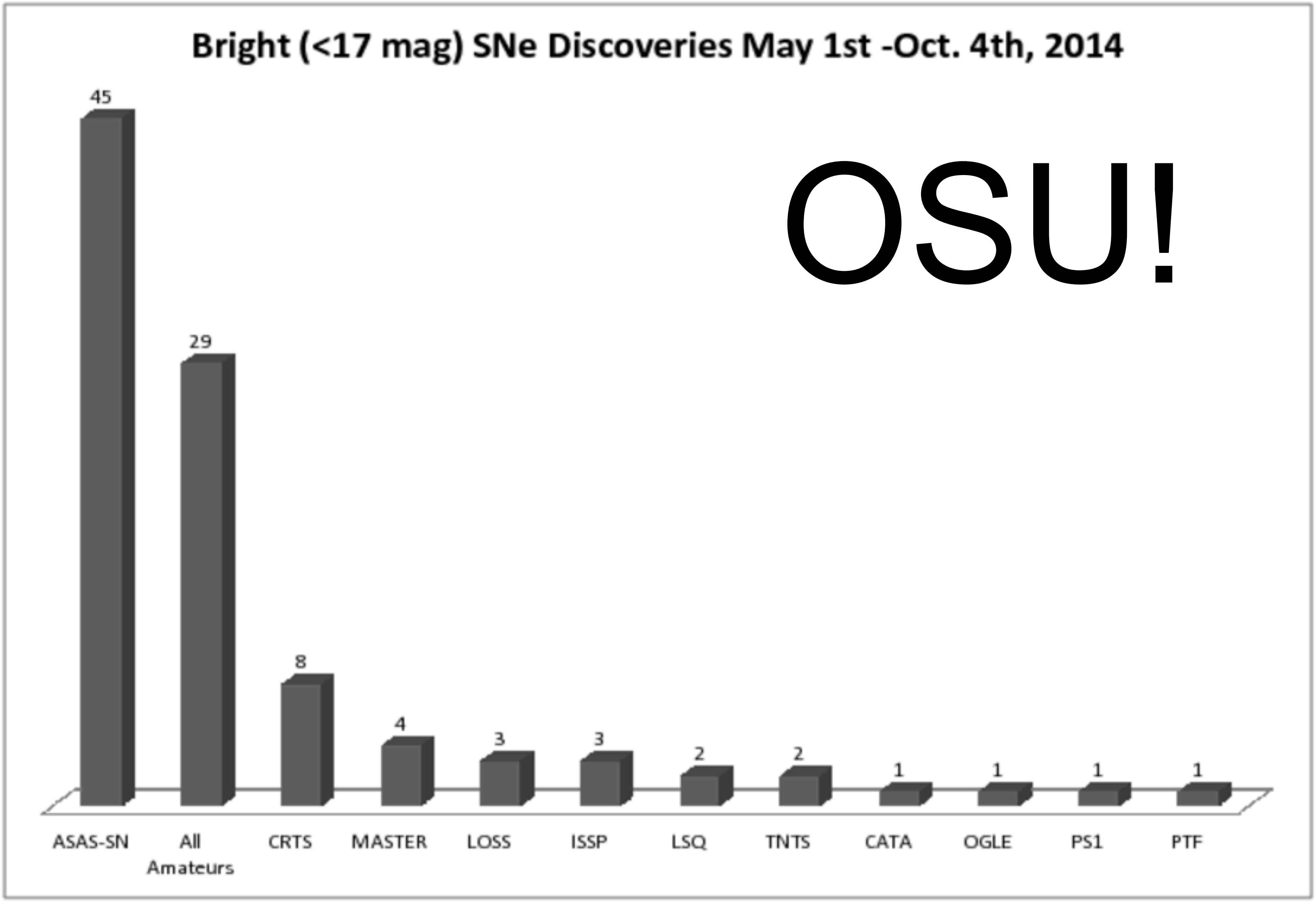
We see Type Ia Supernovae throughout the universe.

Ia supernova exploding in a galaxy by HST galaxy: 1 every 200yr.

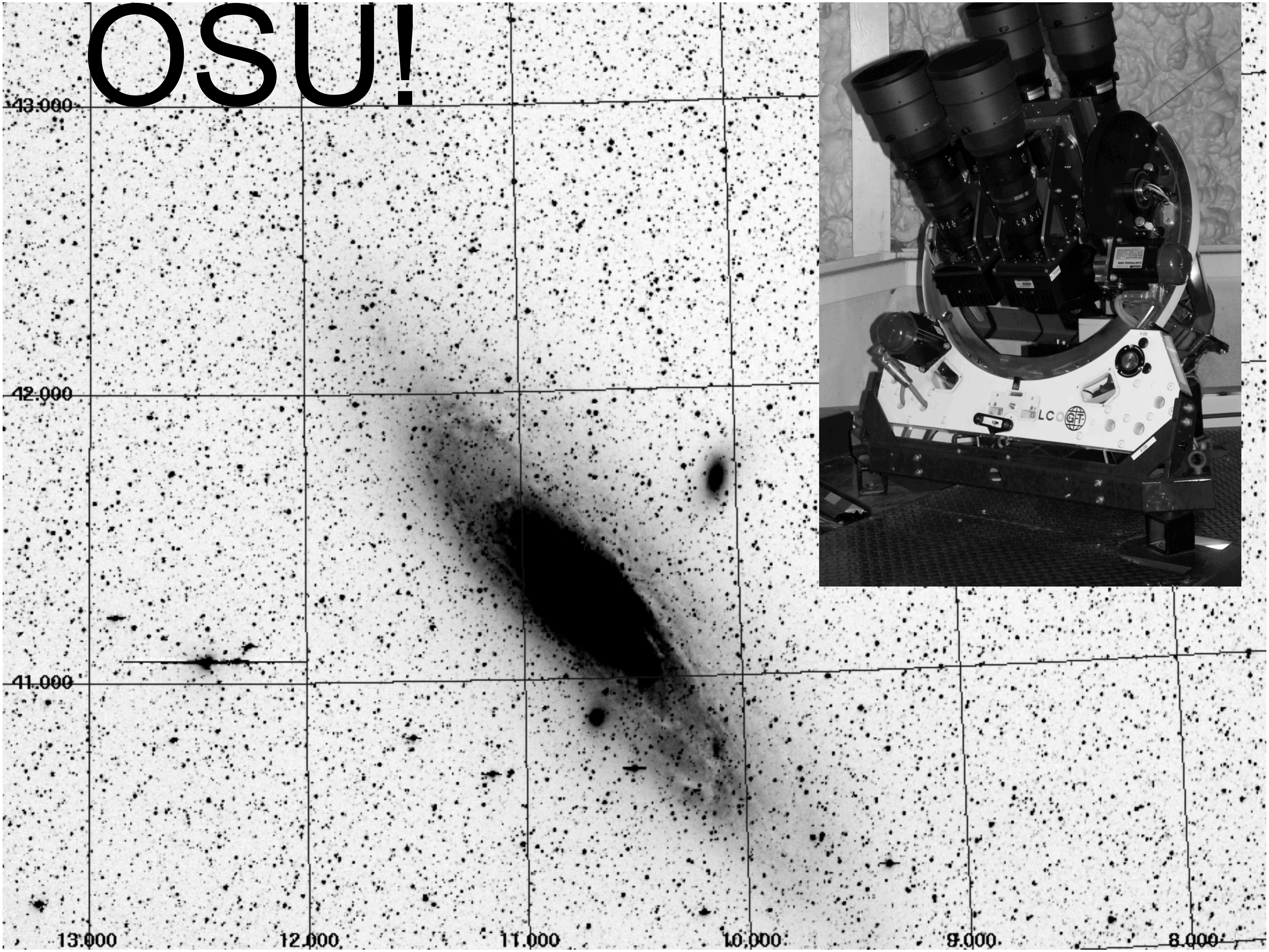
Tycho's Supernova






Bright (<17 mag) SNe Discoveries May 1st -Oct. 4th, 2014
45
29
8
4
3
3
2
2
1
1
1
1
ASAS-SN
All Amateurs
CRTS
MASTER
LOSS
ISSP
LSQ
TNTS
CATA
OGLE
PS1
PTF
OSU!

OSU!



End Oct 17