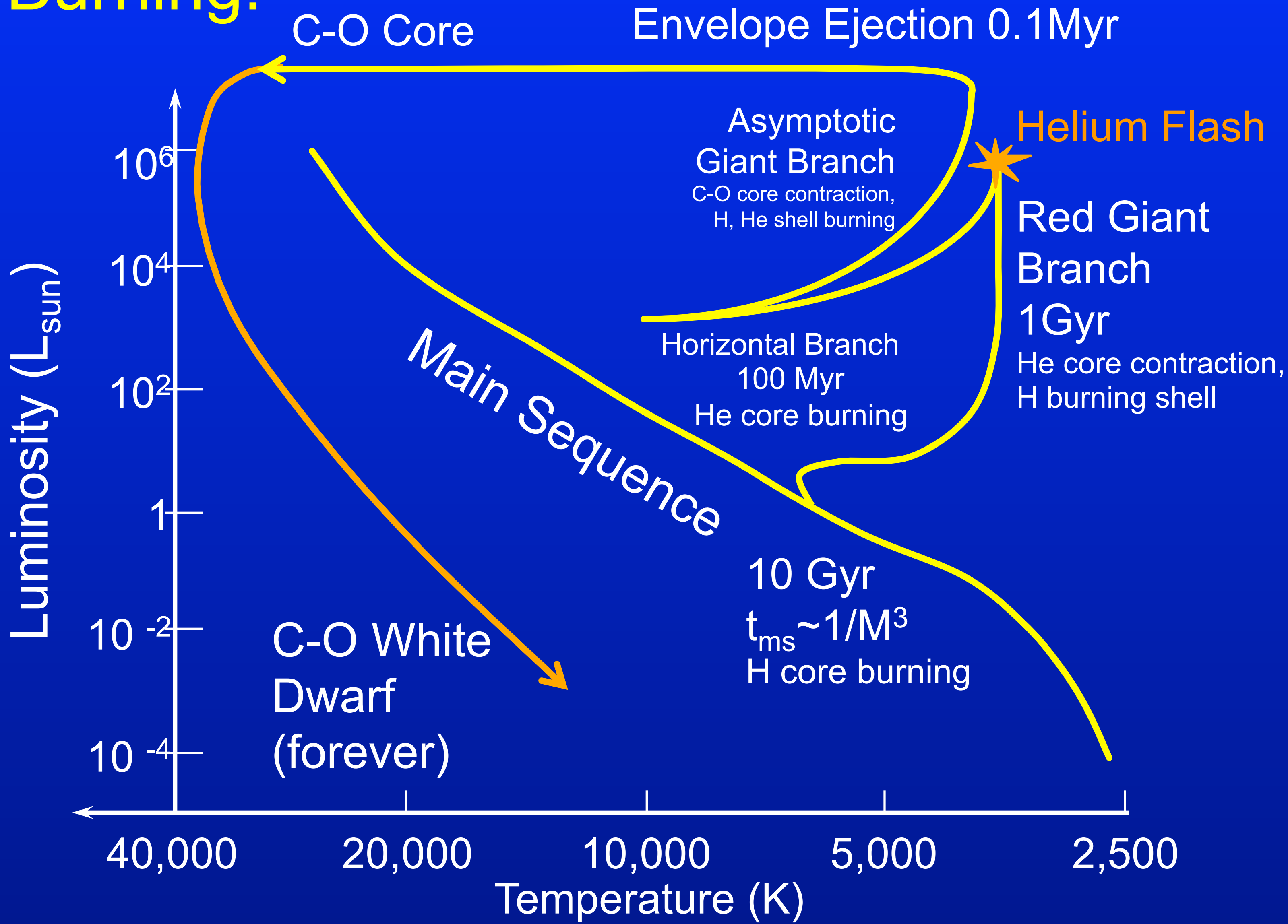
# Evolution of Low-Mass stars $M < 4\ M_{sun}$

## No C Burning!



# Supernovae

Astronomy 1101

# Key Ideas:

End of the Life of a Massive Star:

- Burn H through Si in successive cores
- Finally build a massive Iron core.

Iron core collapse & core “bounce”

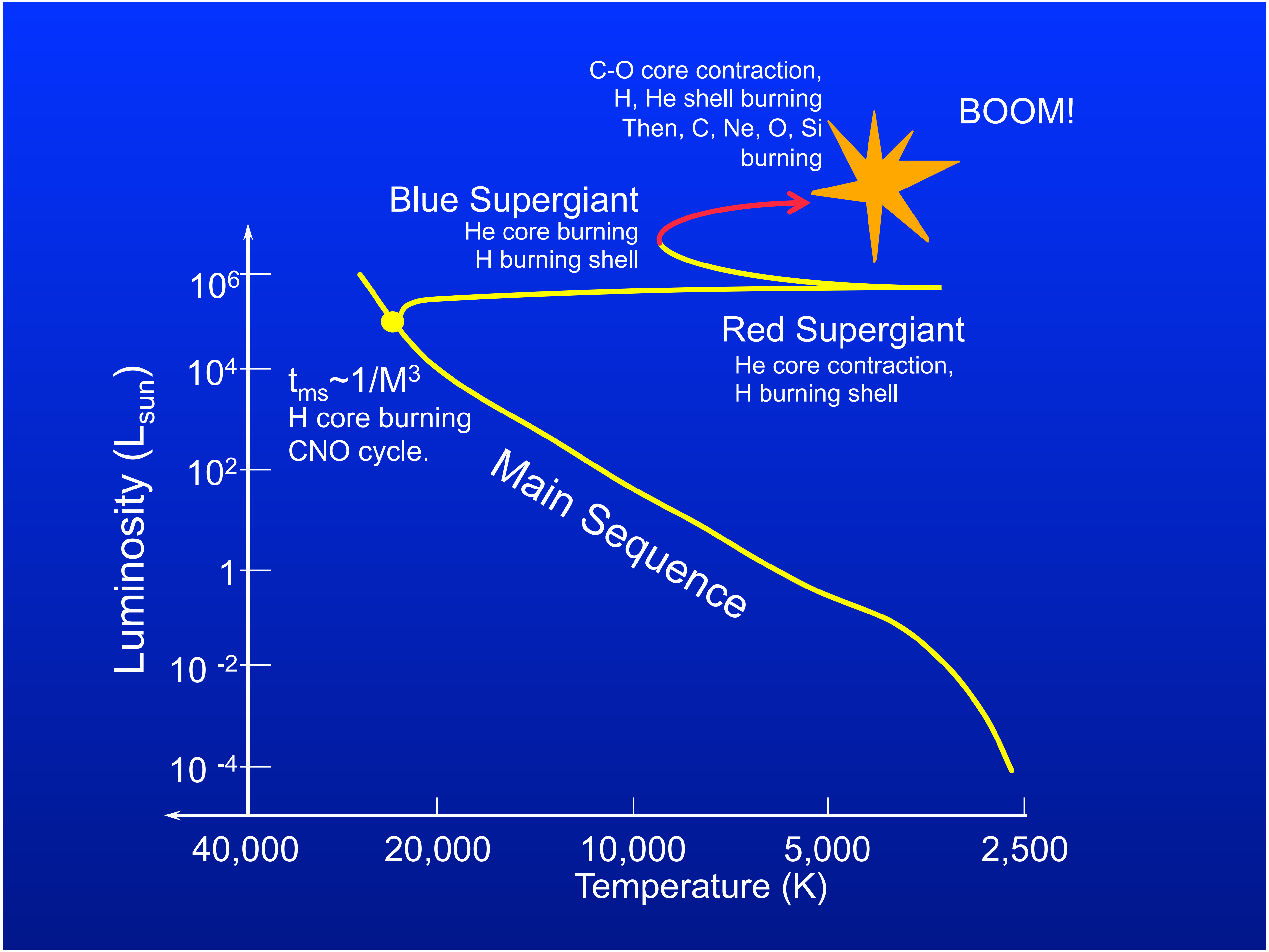
Neutron star formation.

Supernova Explosion:

- How? We don’t really know. Then, envelope ejection

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
$t_{ms} \sim 1/M^3$
H core burning
CNO cycle.
Main Sequence
Luminosity ($L_{sun}$)
$10^6$
$10^4$
$10^2$
1
$10^{-2}$
$10^{-4}$
40,000
20,000
10,000
5,000
2,500
Temperature (K)

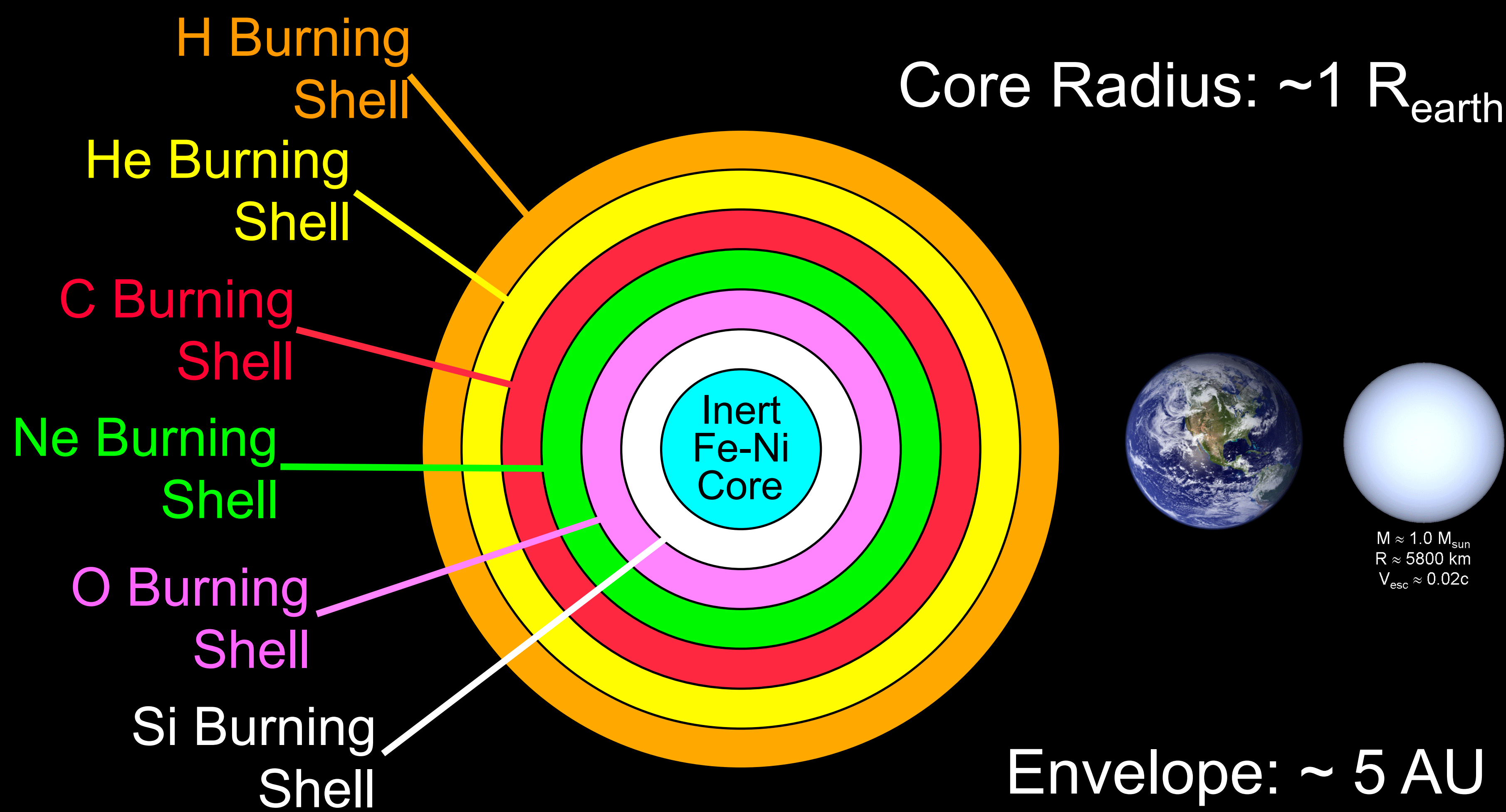
# Last Days of a Massive Star

Burns a succession of nuclear fuels:

- Hydrogen burning : 10 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:



# 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 $M_{sun}$

- T > 10 Billion K & density ~$10^{10}$ g/cc

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)

$$e^- + p \rightarrow n + \nu_e$$

- 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 ~2-3x$10^{14}$ 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! (more than Sun radiates in its lifetime)

After about 50 milliseconds:

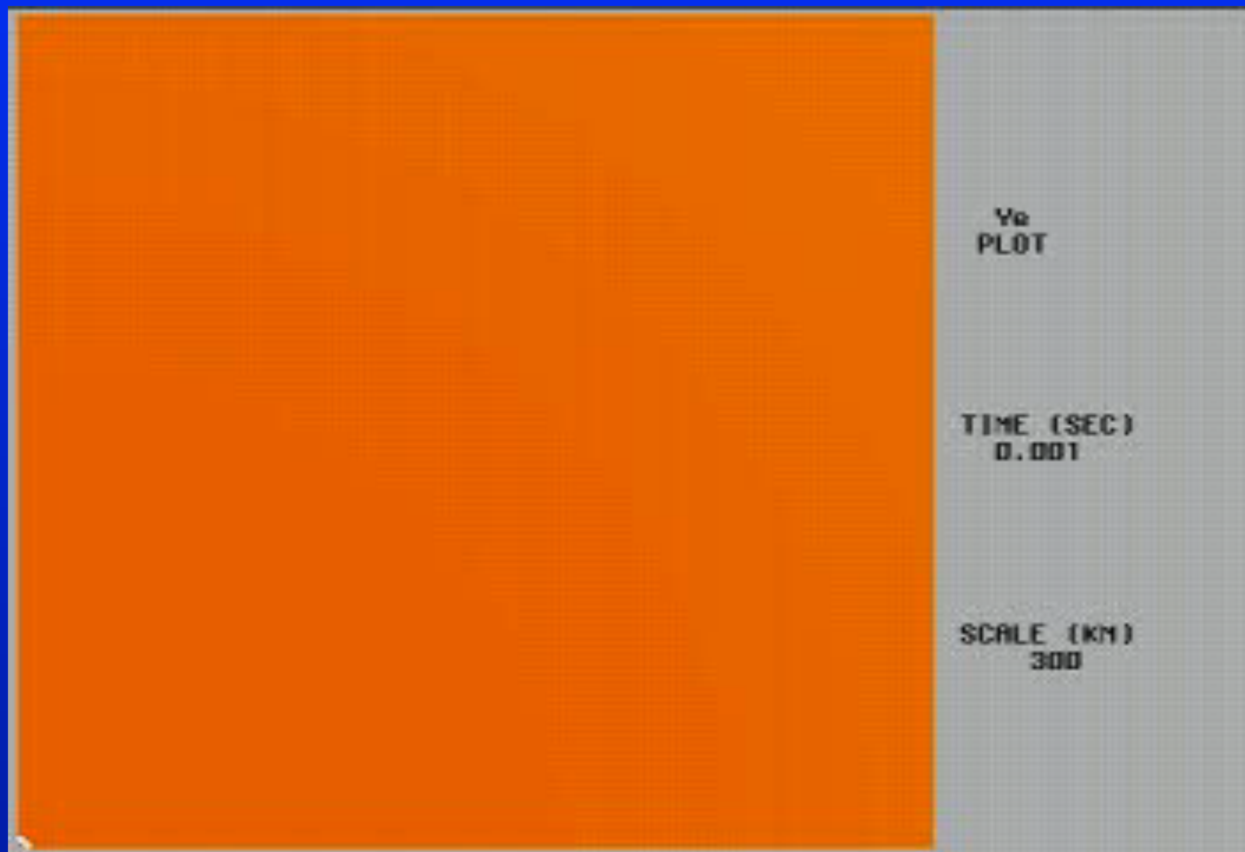
- Shockwave *stalls*

Meanwhile, <u>neutrinos</u> pour out of the core:

- Some heating the gas, leads to violent convection

$$e^{-} + p \rightarrow n + \nu_e \qquad e^{-} + p \leftarrow n + \nu_e$$

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!).

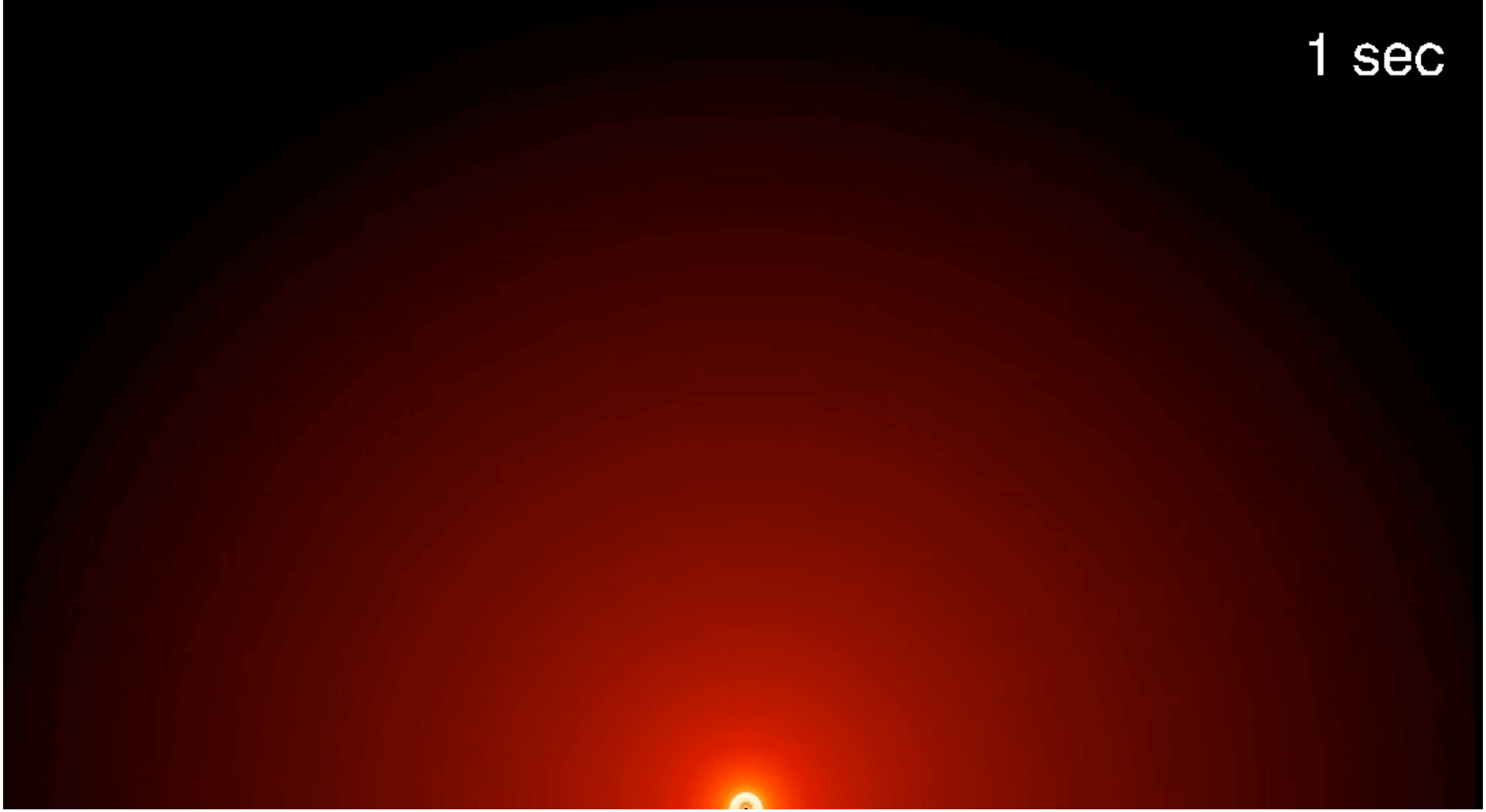
Blastwave smashes out through the star:

- 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:

- Brightens by 10 Billion $L_{sun}$ 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°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:

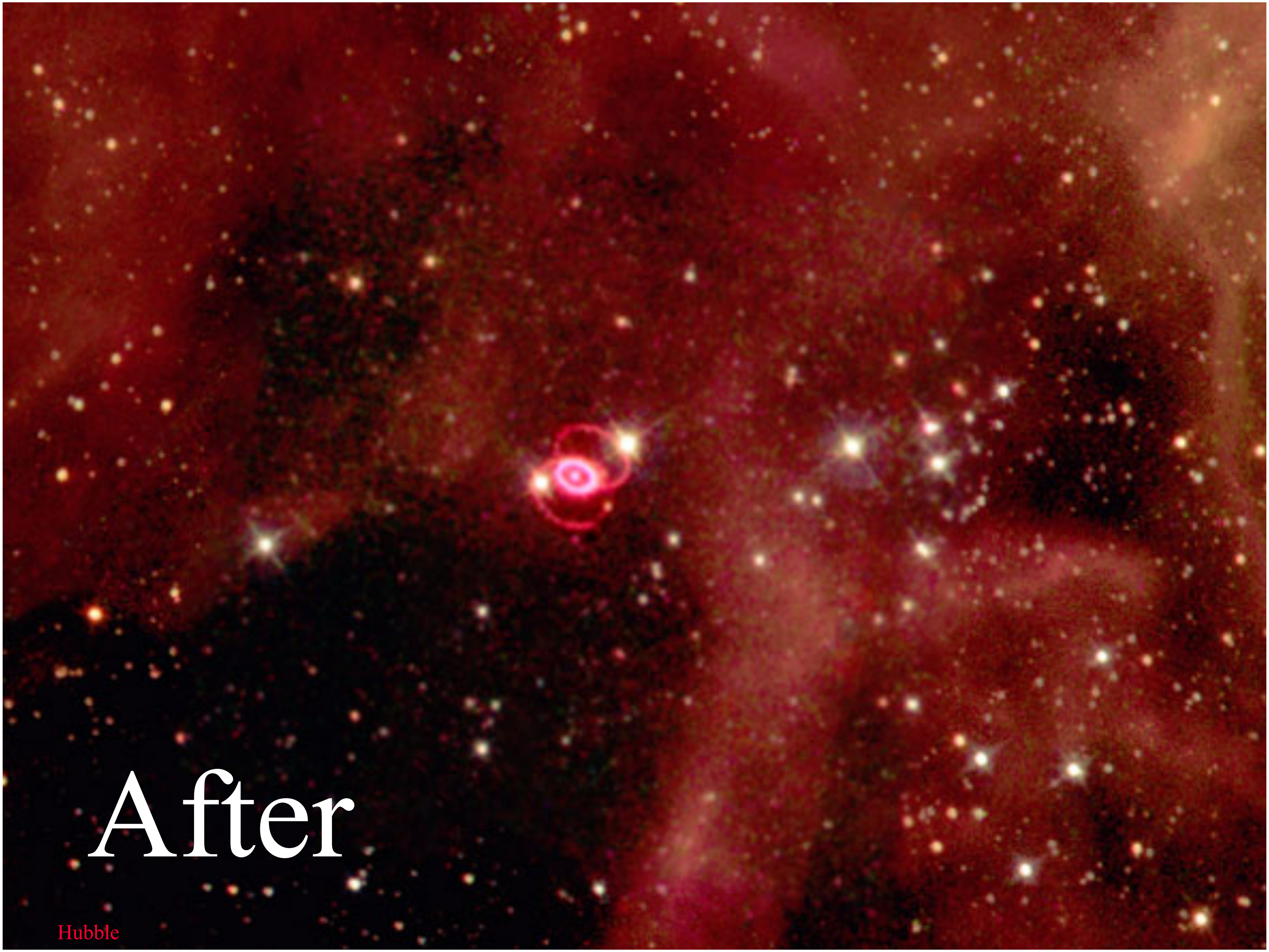
Sanduleak -69$^o$ 202a

Supergiant

CTIO

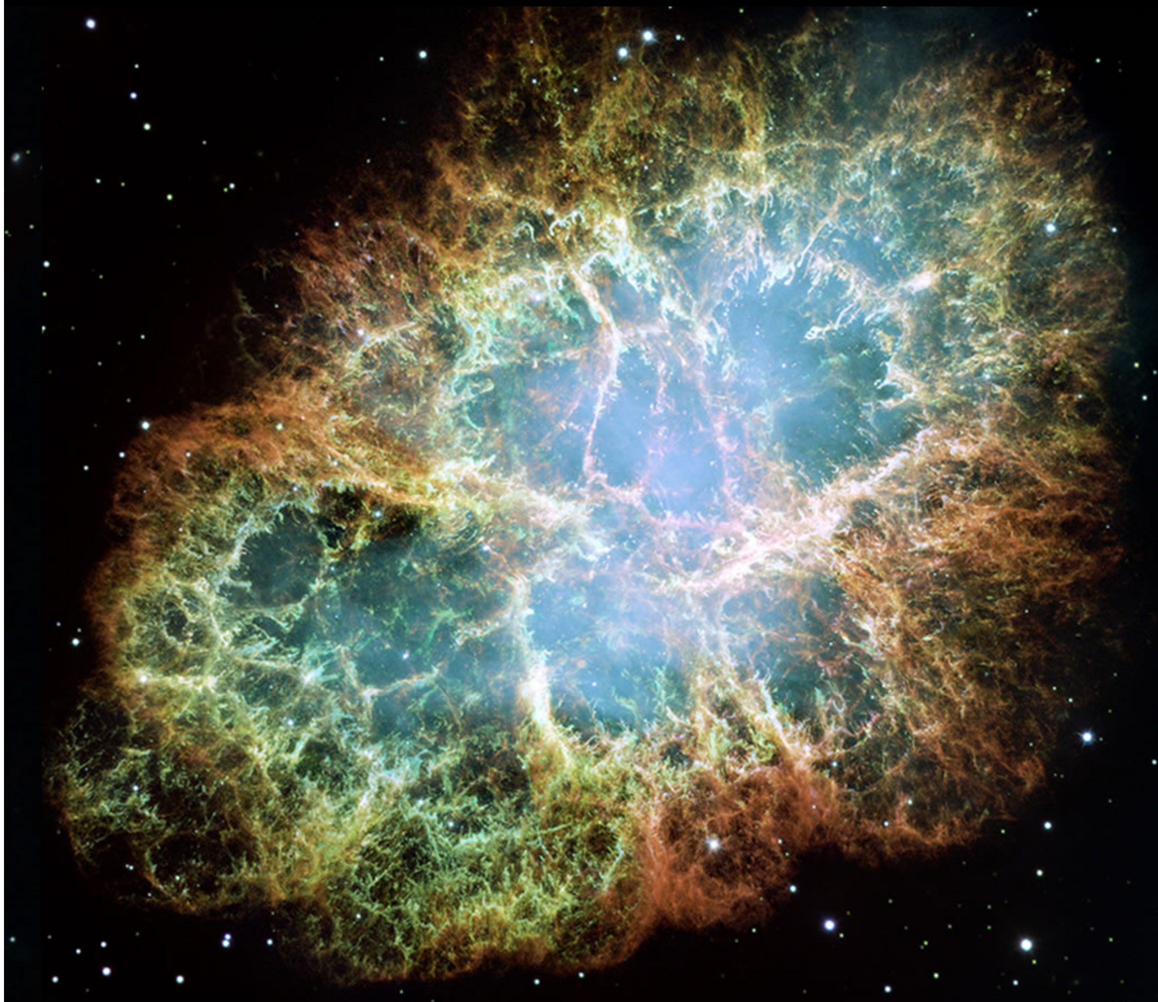
Before

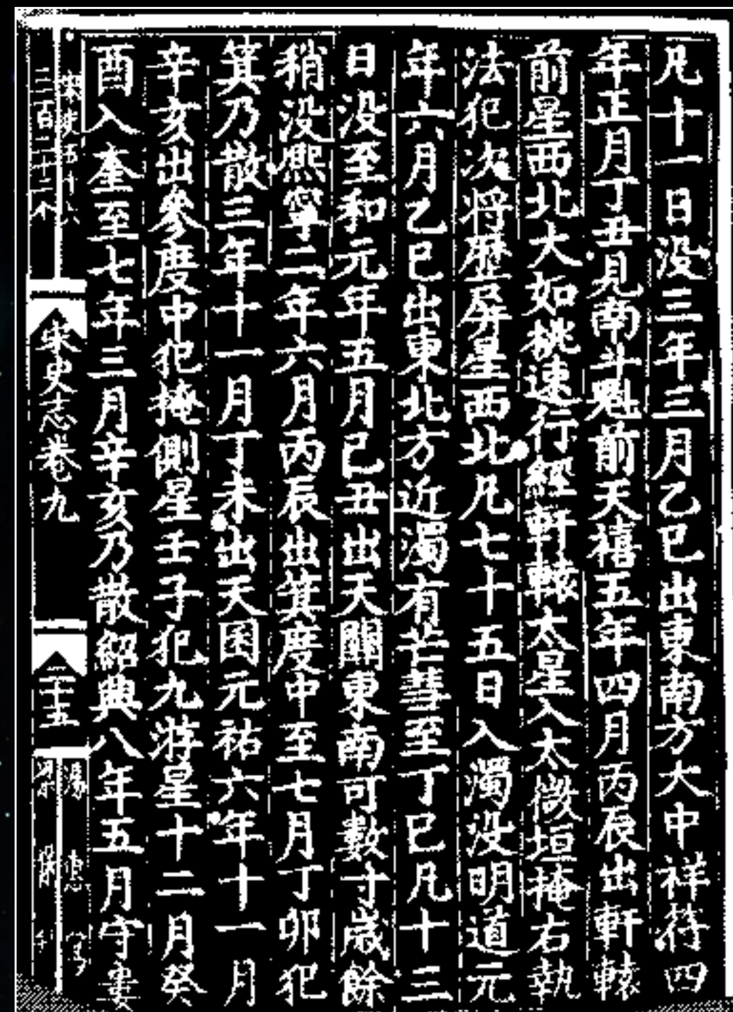
During


After
Hubble

# Crab Nebula

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

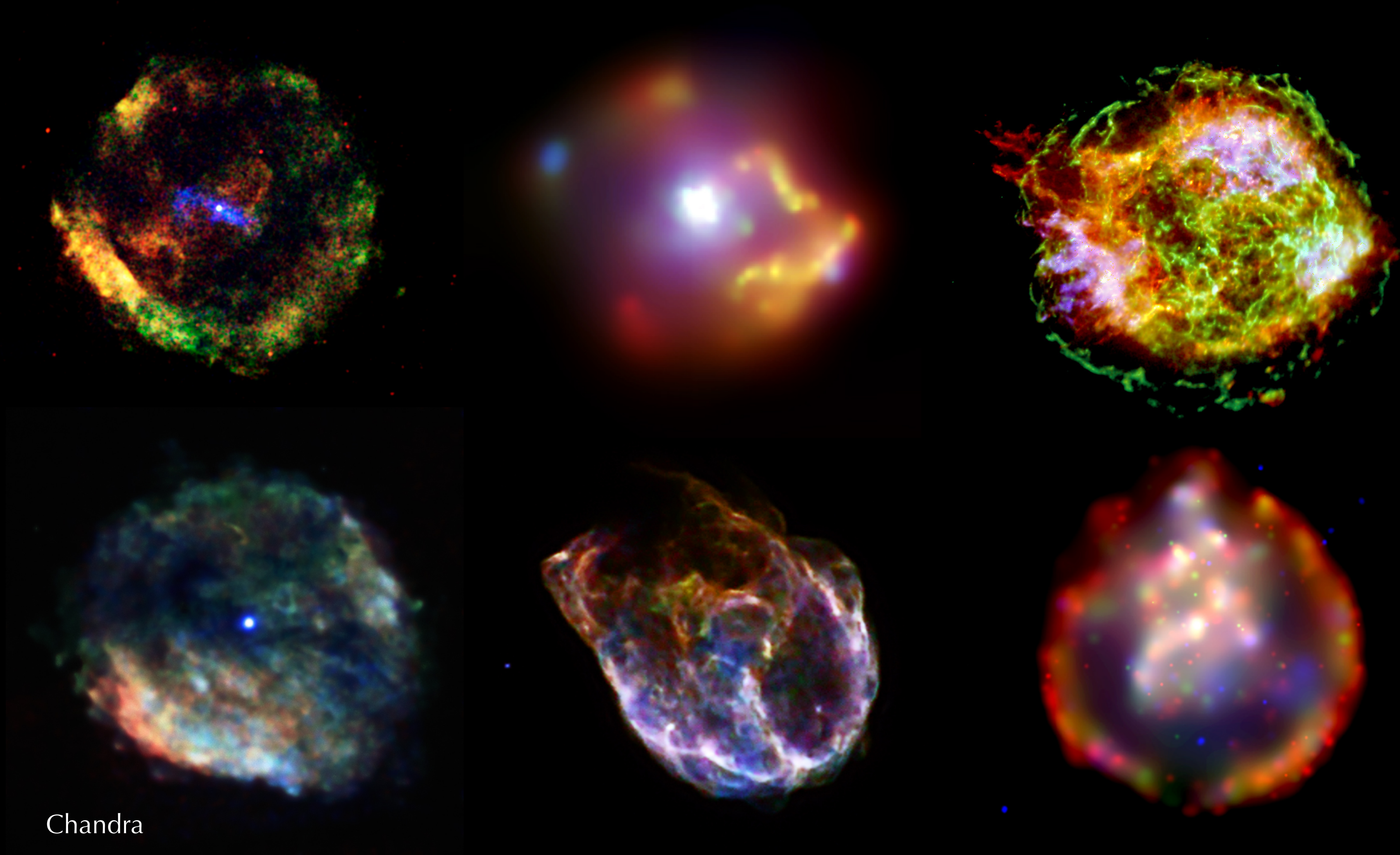




凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅大星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

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

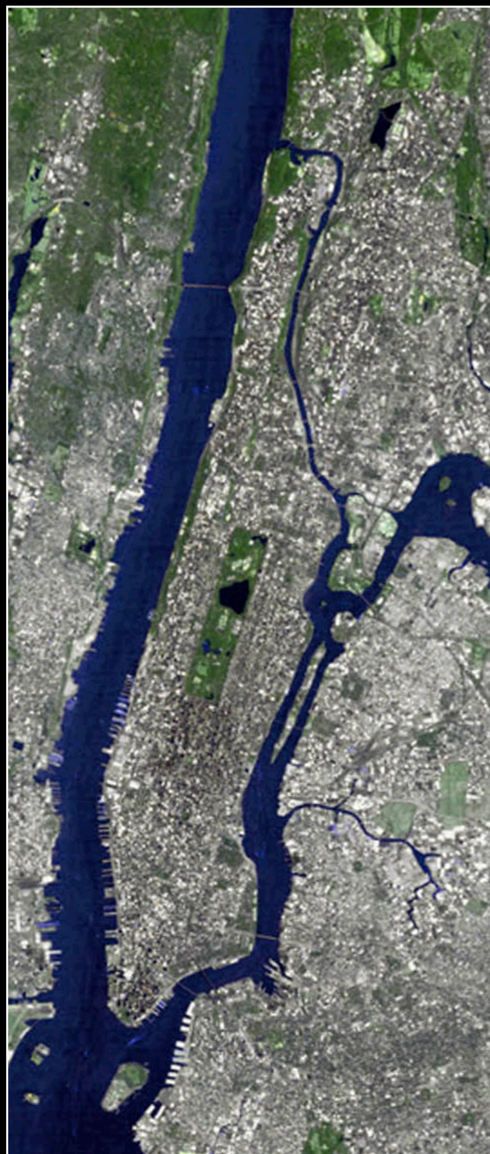
Remnant cores of massive stars:

- $8 < M < 100\ M_{sun}$ (??)
- Leftover core of a core-collapse supernova
- Produced by $e^- + p \rightarrow n + \nu_e$

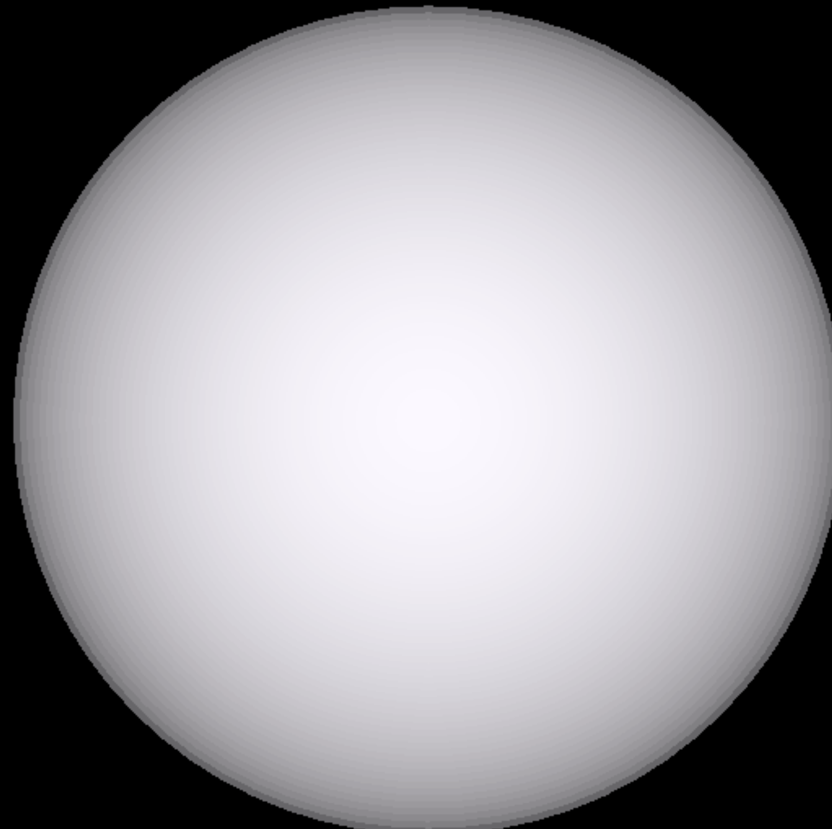
Held up by Neutron Degeneracy Pressure:

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

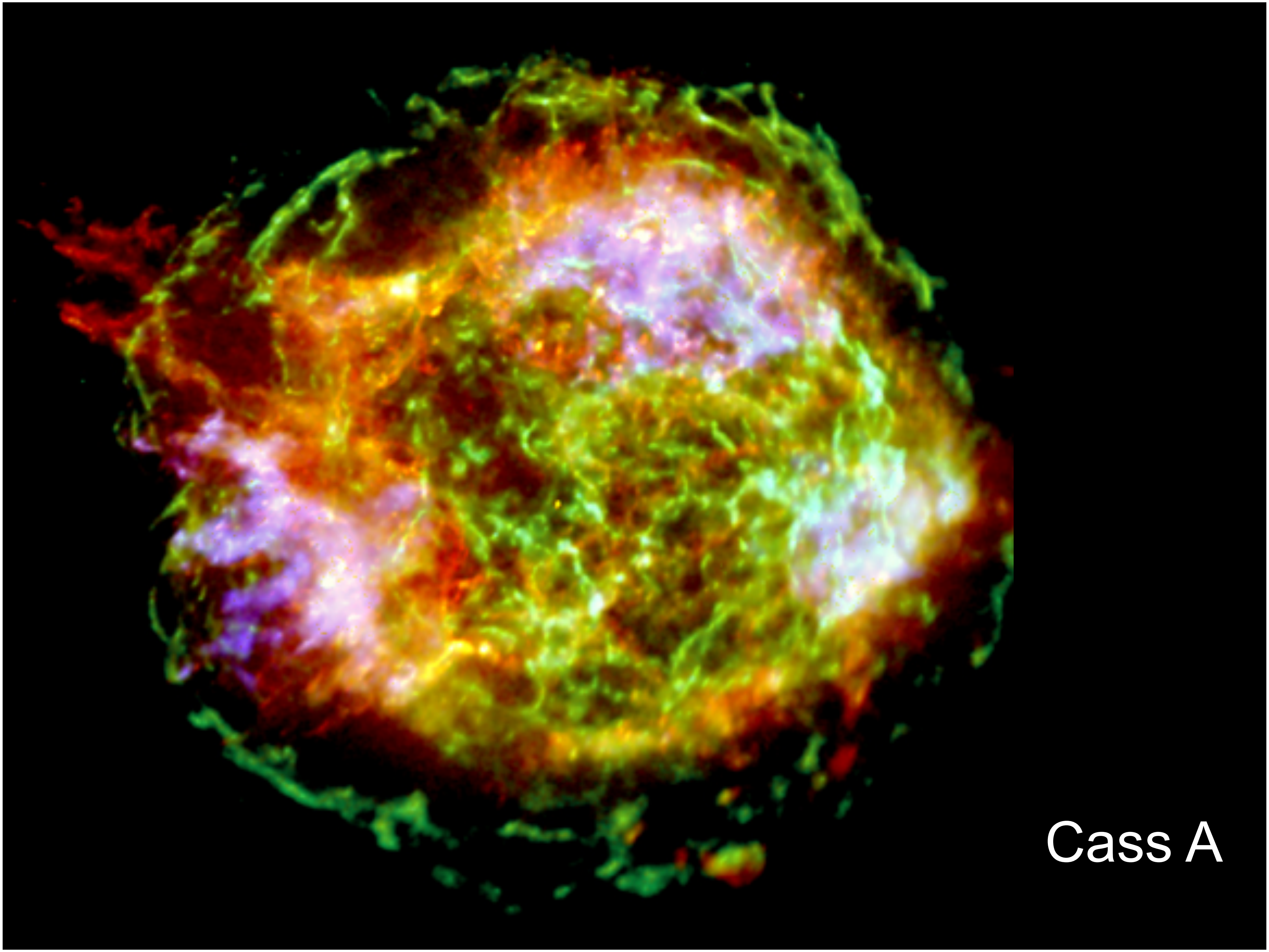
Shine by residual heat: no fusion or contraction


Manhattan
(spaceimaging.com)

Neutron Star



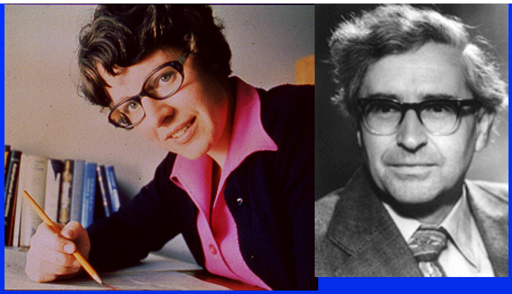
$M = 1.5\ M_{sun}$
$R \sim 10$ km
$V_{esc} \sim 0.7c$


Cass A

Ended here, Weds Oct 15


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

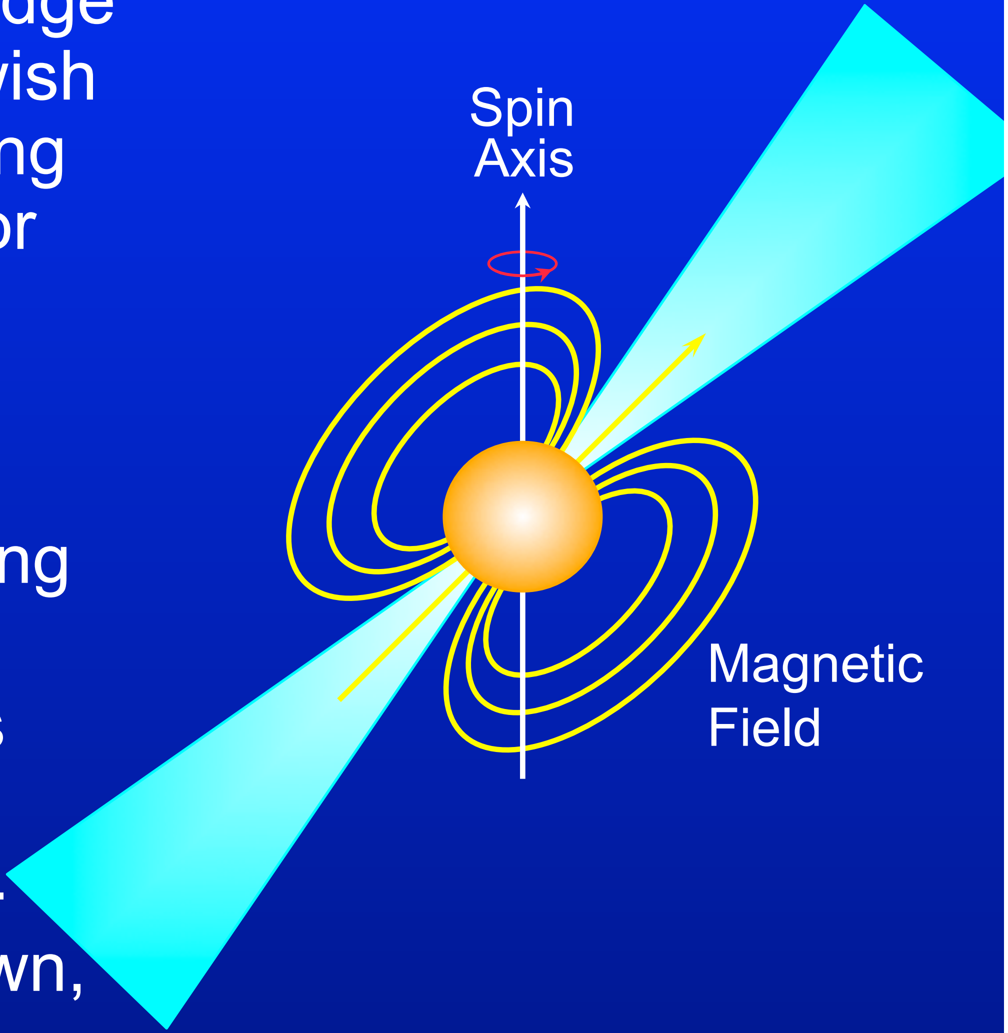
# What about old neutron stars? Accidental Discovery of Pulsars



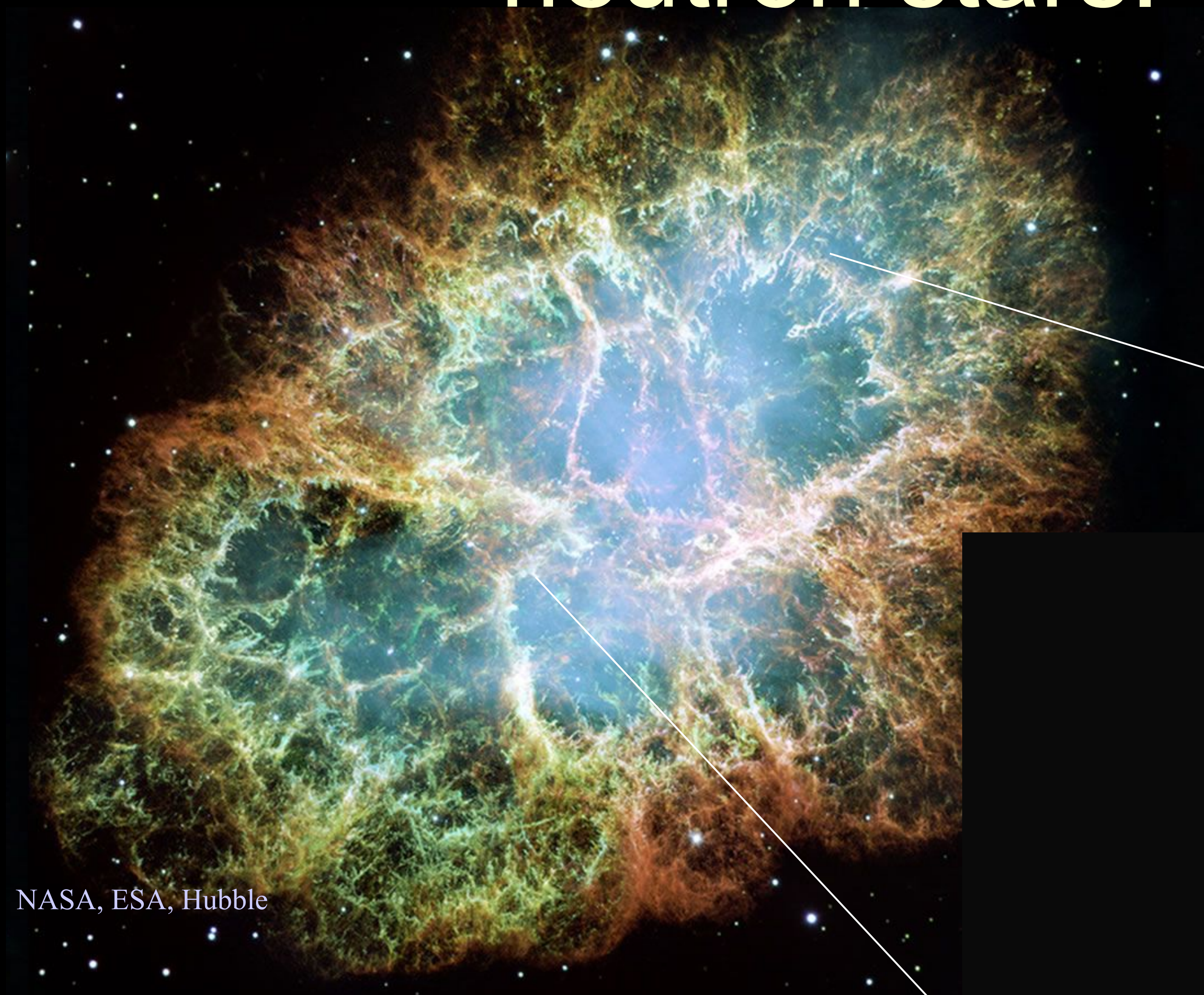
1967: Jocelyn Bell (Cambridge grad student) & Anthony Hewish (her adviser) discover pulsating radio sources while looking for something else.

Pulsars = Pulsating Radio Sources

- Emit sharp millisecond-long 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.




The Crab
1054 A.D.
July 4, China

Chandra

# Pulsar Evolution

Pulsars spin slower as they age.

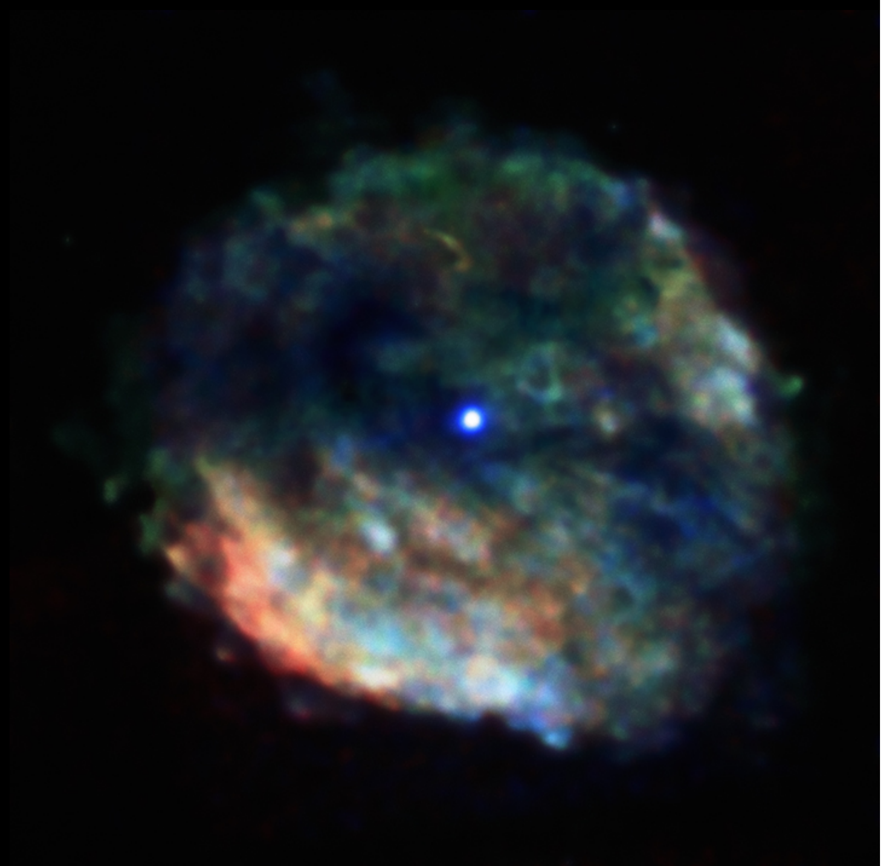
- Lose rotational energy

Young neutron stars:

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

Old neutron stars:

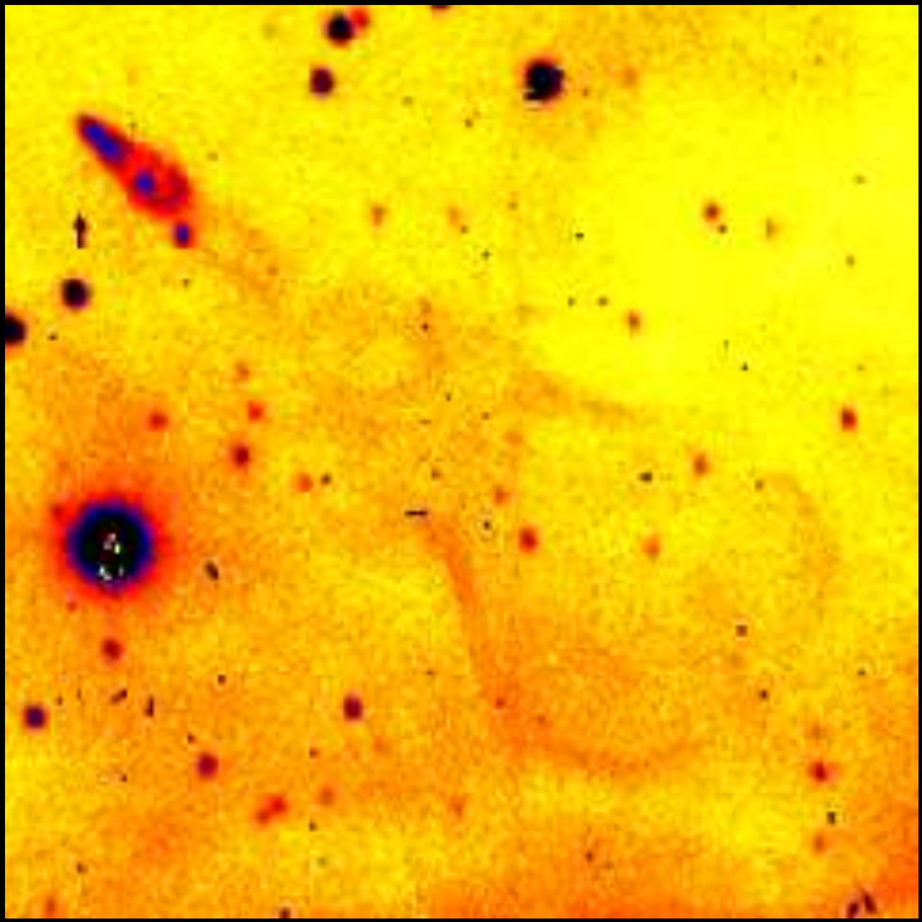
- cold and hard to find



# 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 *very* massive?

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

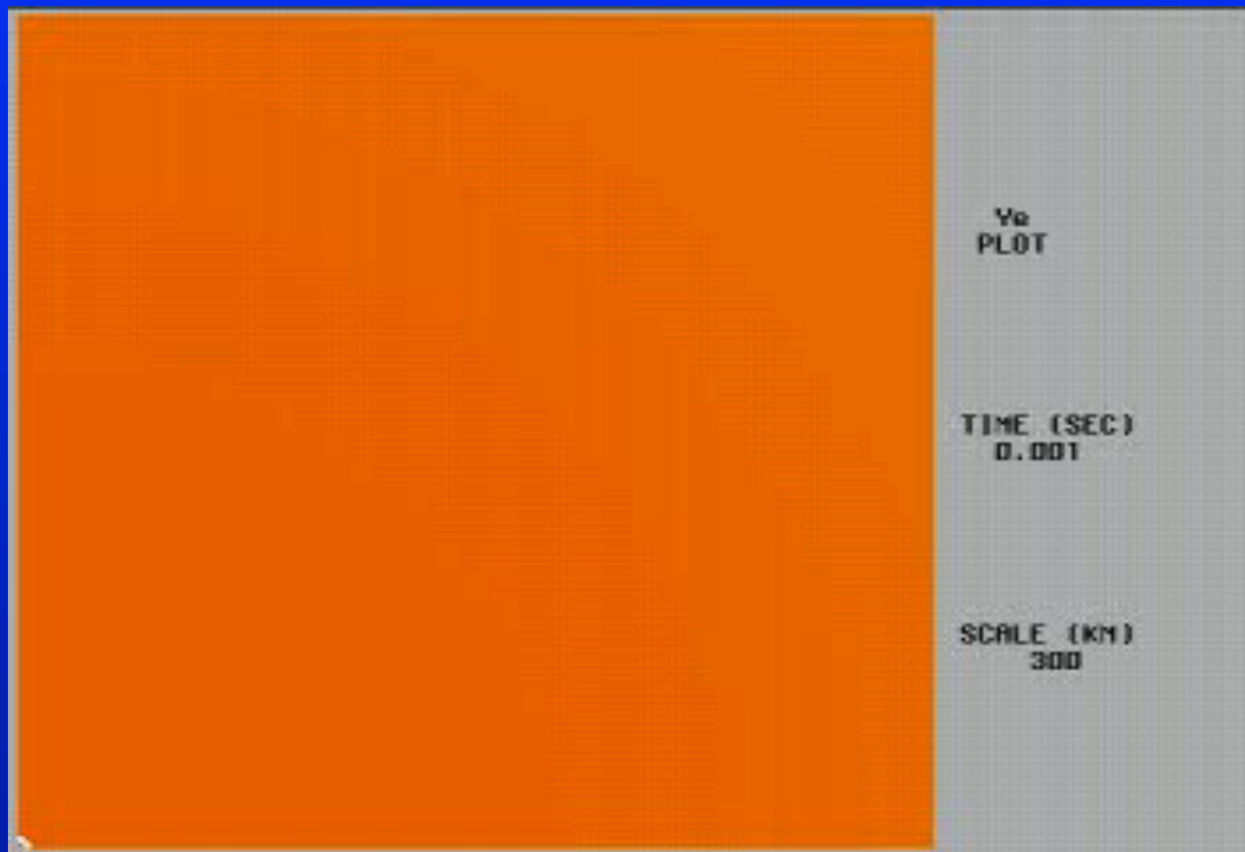
(original star had $M \sim 20\text{-}30\ M_{sun}$)

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

Becomes a Black Hole...

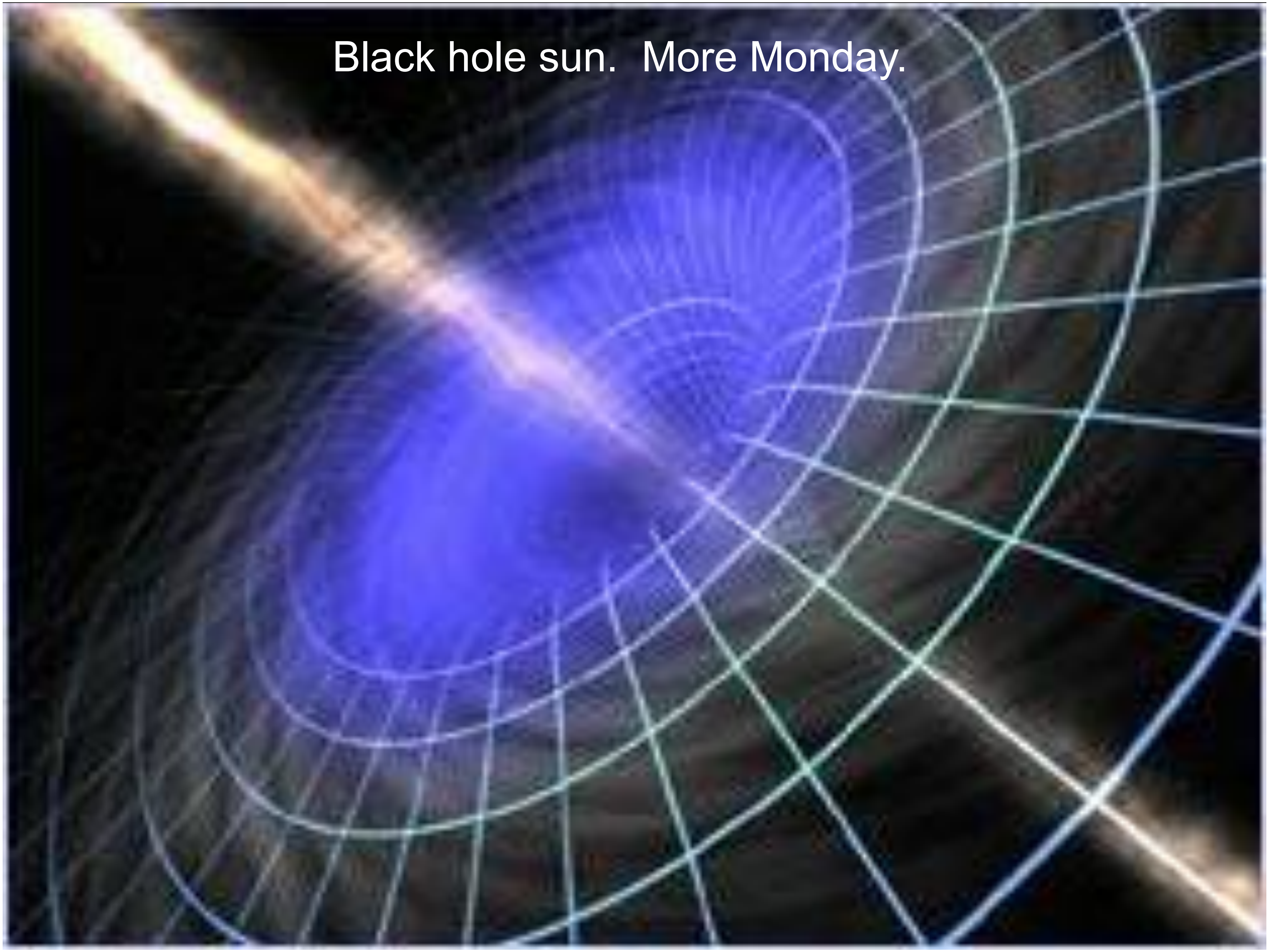
(This process has never been observed)

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

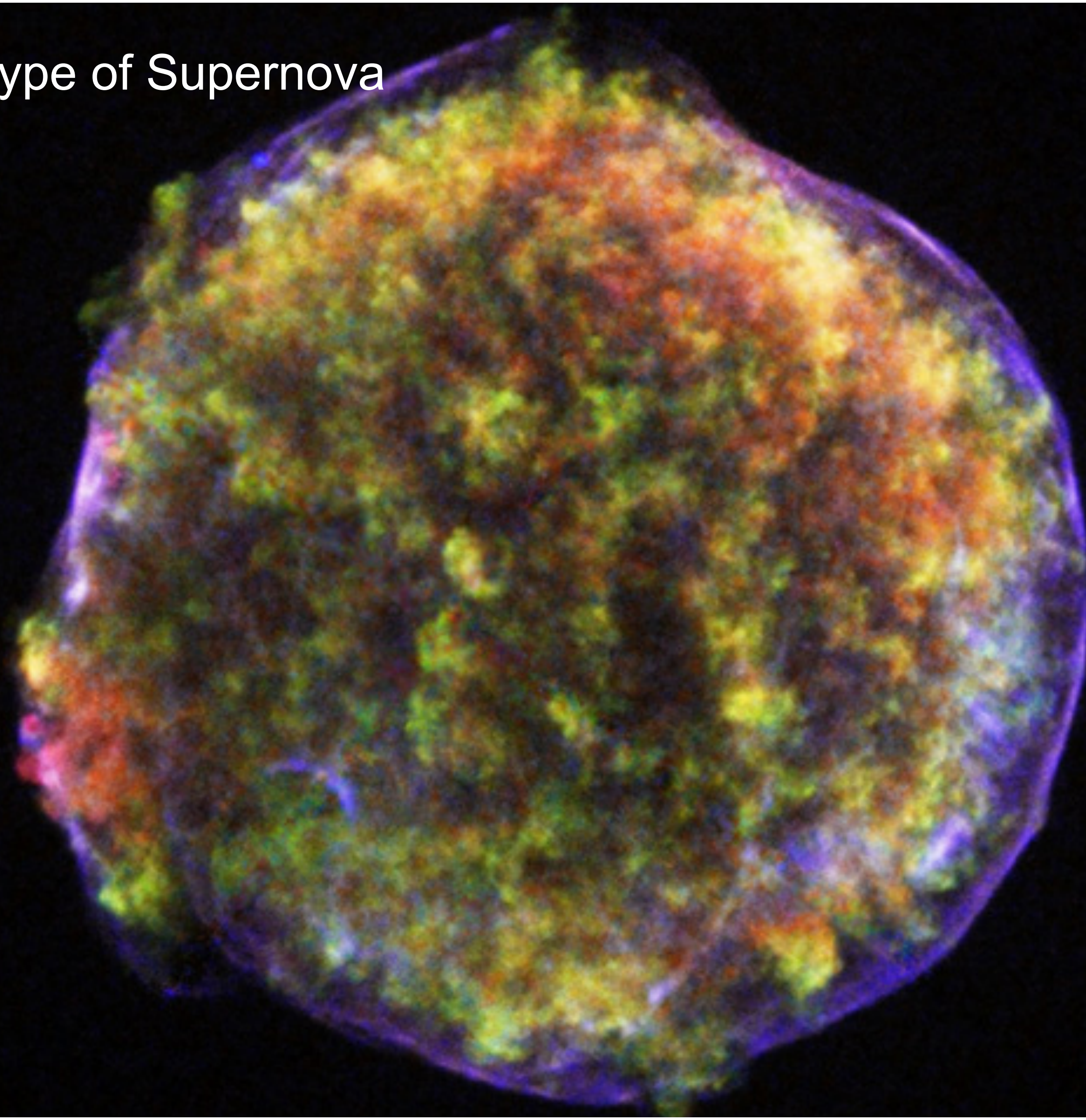



300 km

Burrows, Hayes, & Fryxell (1995)


Black hole sun.  More Monday.

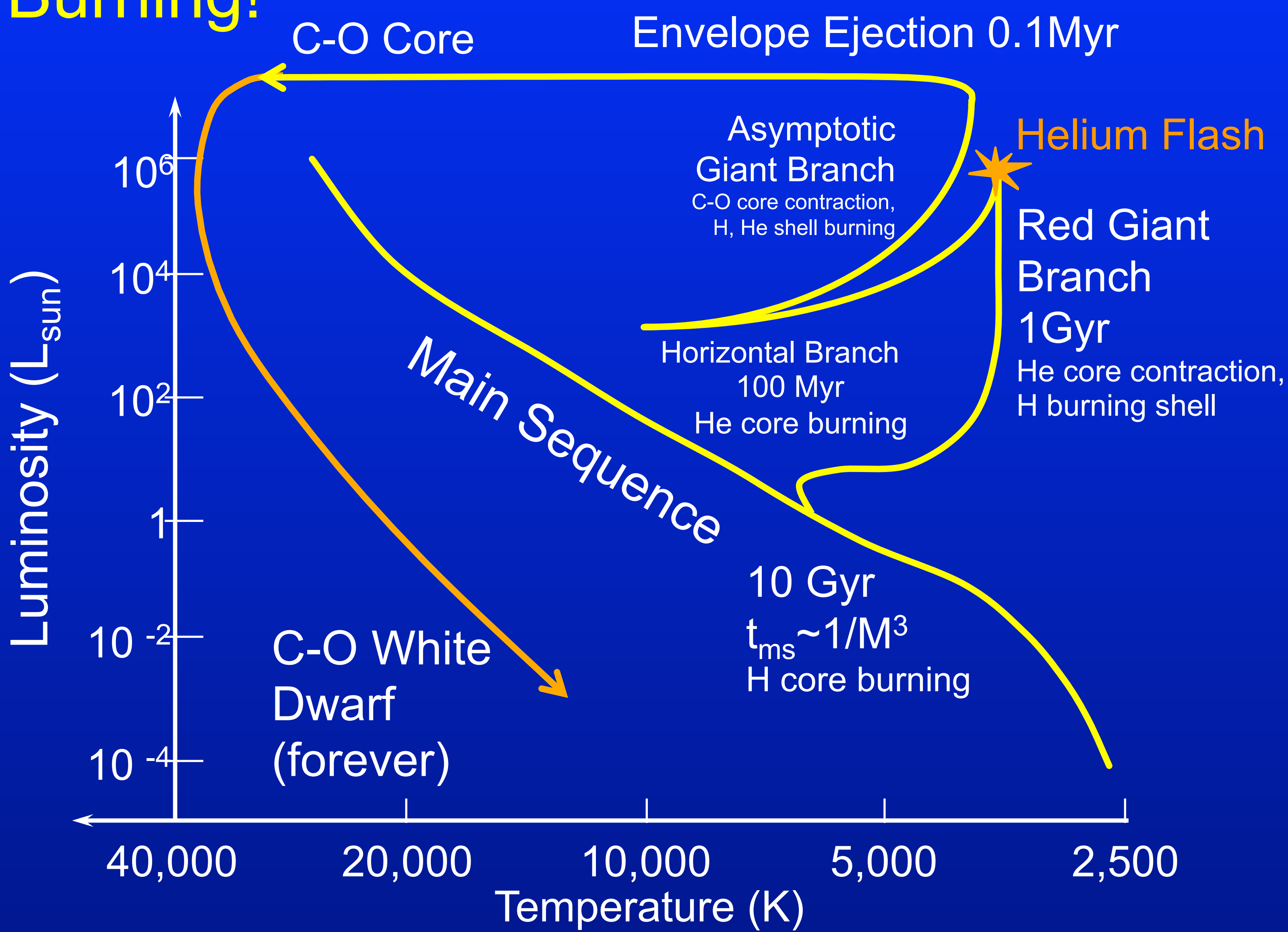
# The Other Type of Supernova



Chandra

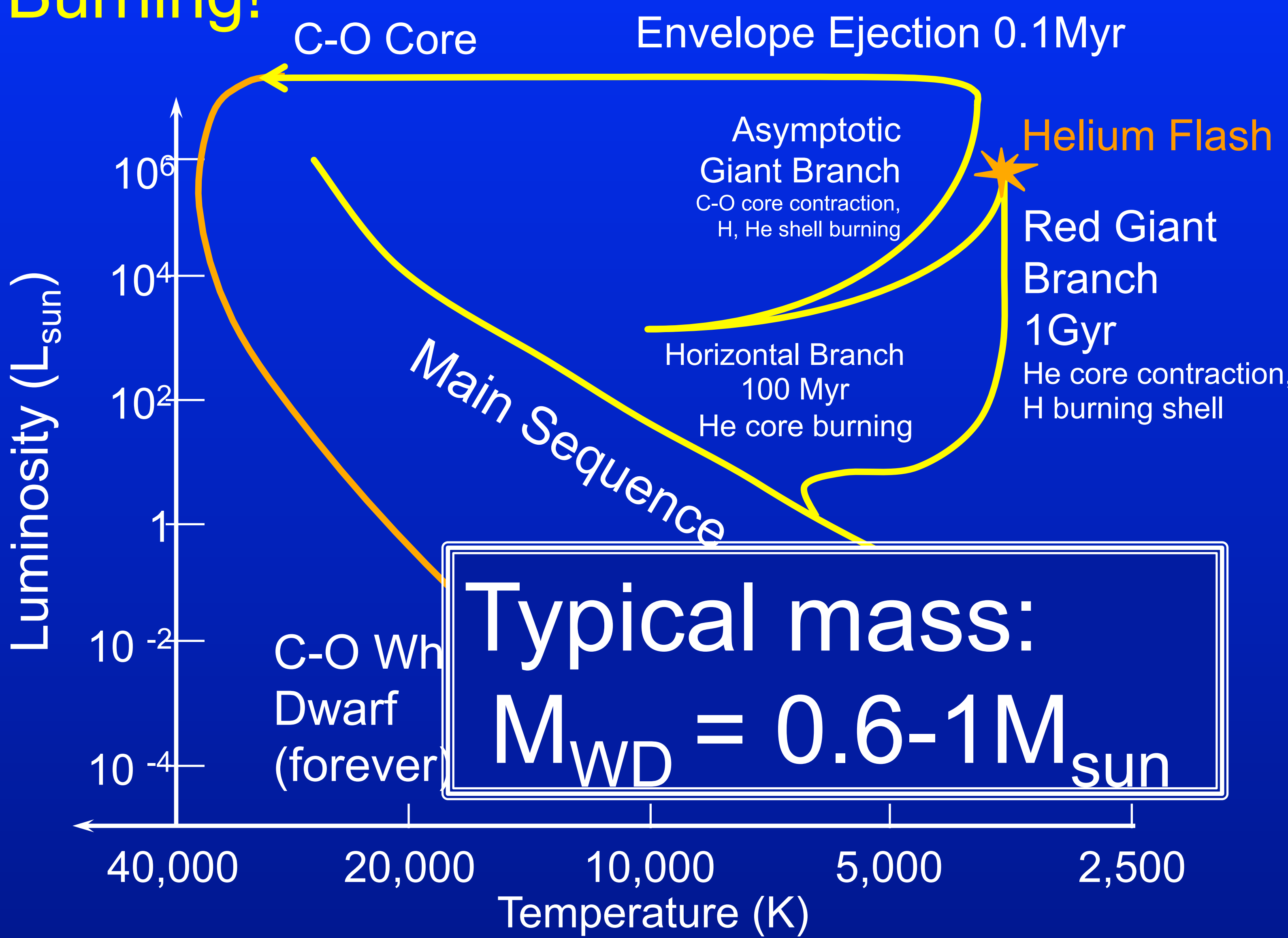
# Evolution of Low-Mass stars $M < 4 M_{sun}$

# No C Burning!



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

## No C Burning!



# 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 $M < 8\ M_{sun}$.

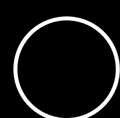
- Held up by Electron Degeneracy Pressure.
- $M < 4\ M_{sun}$: C-O White Dwarfs
- $M = 4 – 8\ M_{sun}$: O-Ne-Mg White Dwarfs

Properties:

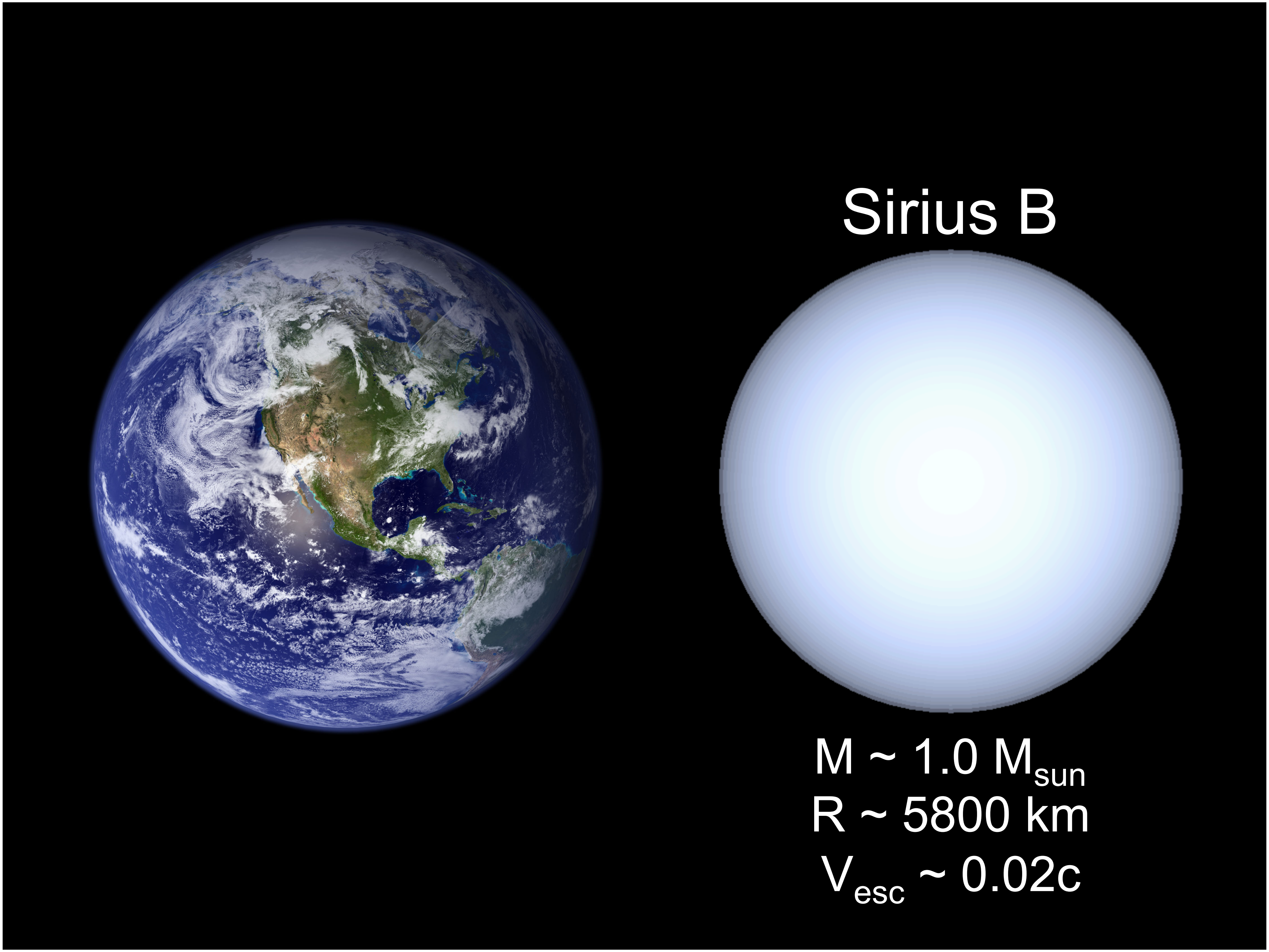
- Mass: $< 1.2\ M_{sun}$, Radius: $\sim R_{earth}$ ($\sim 0.01\ R_{sun}$)
- Density: $\sim 10^6$ g/cc
- Escape Speed: few% speed of light (0.01-0.03c)

Shine by residual heat: no fusion or contraction

Binary of Sirius and Sirius B



Sirius B


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

# Evolution of White Dwarfs

White dwarfs shine by leftover heat:

- 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?

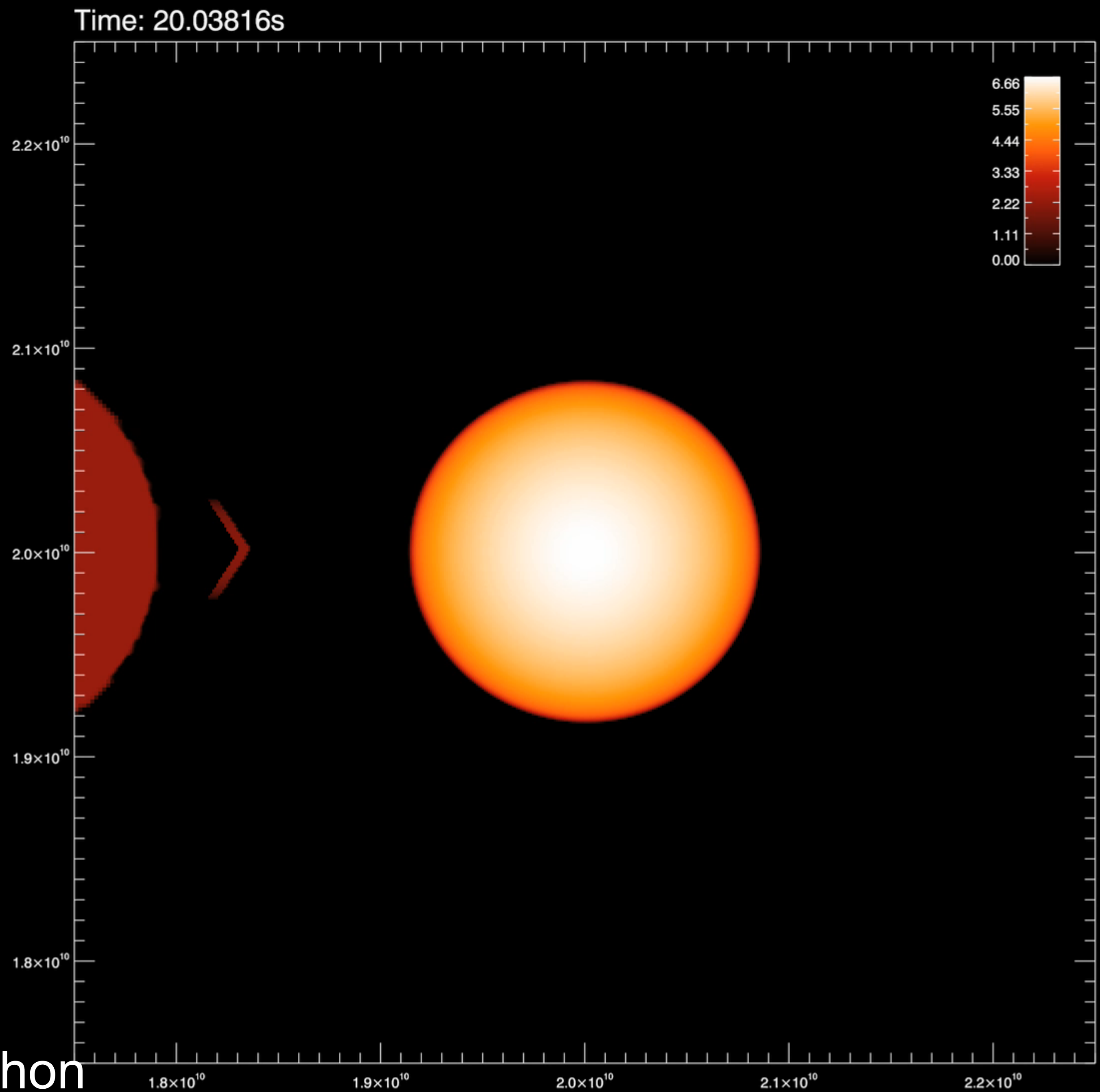
White dwarfs can "accrete" from a companion in a close binary system.

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


Time: 20.03816s
6.66
5.55
4.44
3.33
2.22
1.11
0.00
2.2×10¹⁰
2.1×10¹⁰
2.0×10¹⁰
1.9×10¹⁰
1.8×10¹⁰
1.8×10¹⁰
1.9×10¹⁰
2.0×10¹⁰
2.1×10¹⁰
2.2×10¹⁰

Guillochon

# "Type-Ia" Supernovae

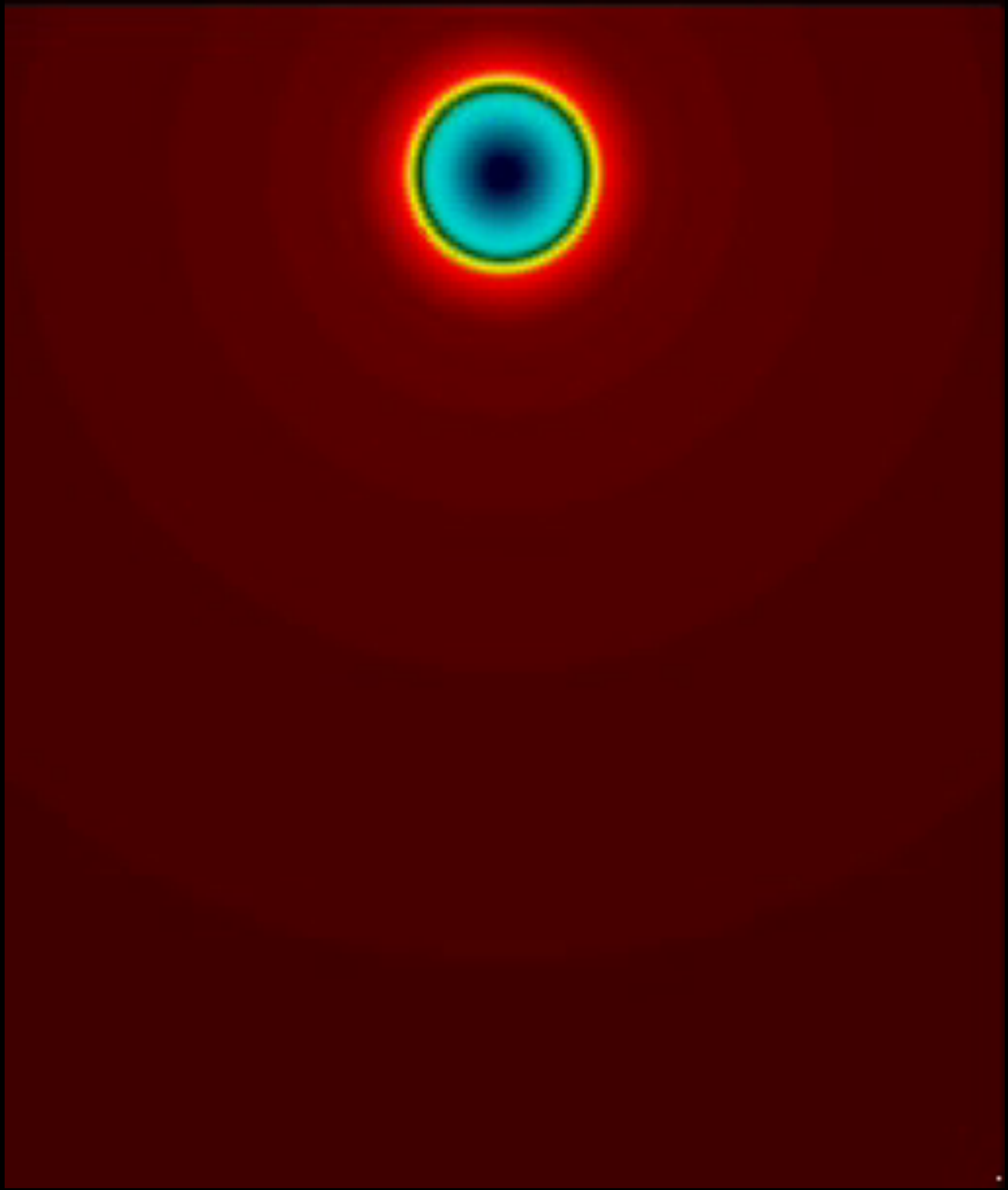
If $M > 1.4\ M_{sun}$? (Exceeds Chandrasekhar Mass)

- 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).

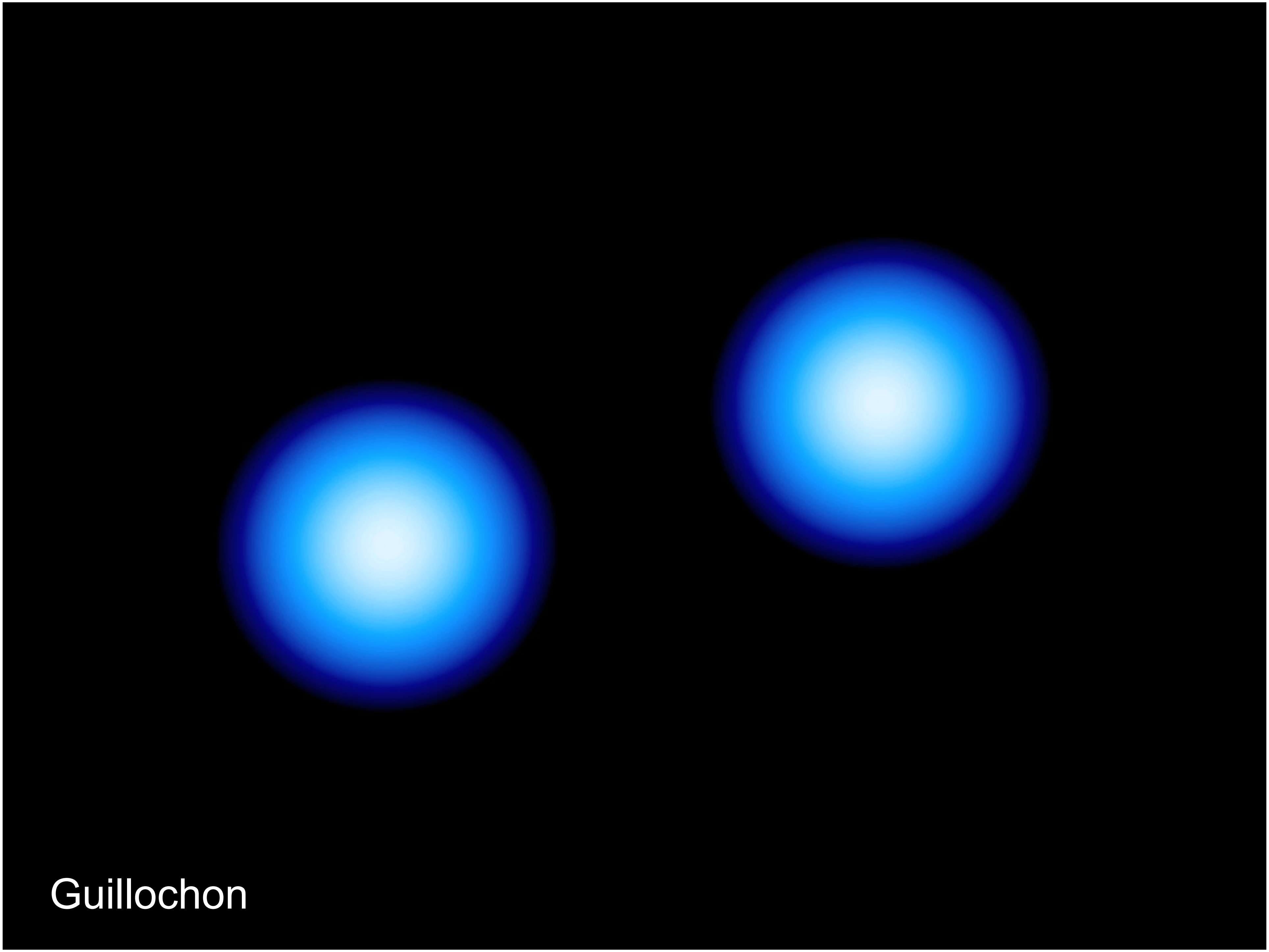
Another way: Slam two white dwarfs together.

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.


Guillochon

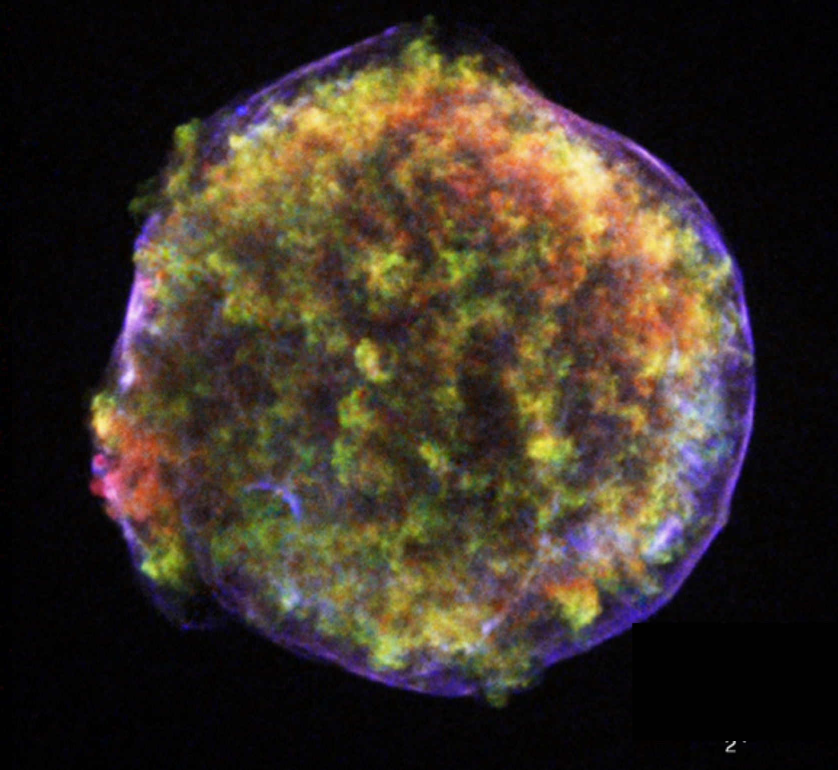
We see Type Ia Supernovae throughout the universe.

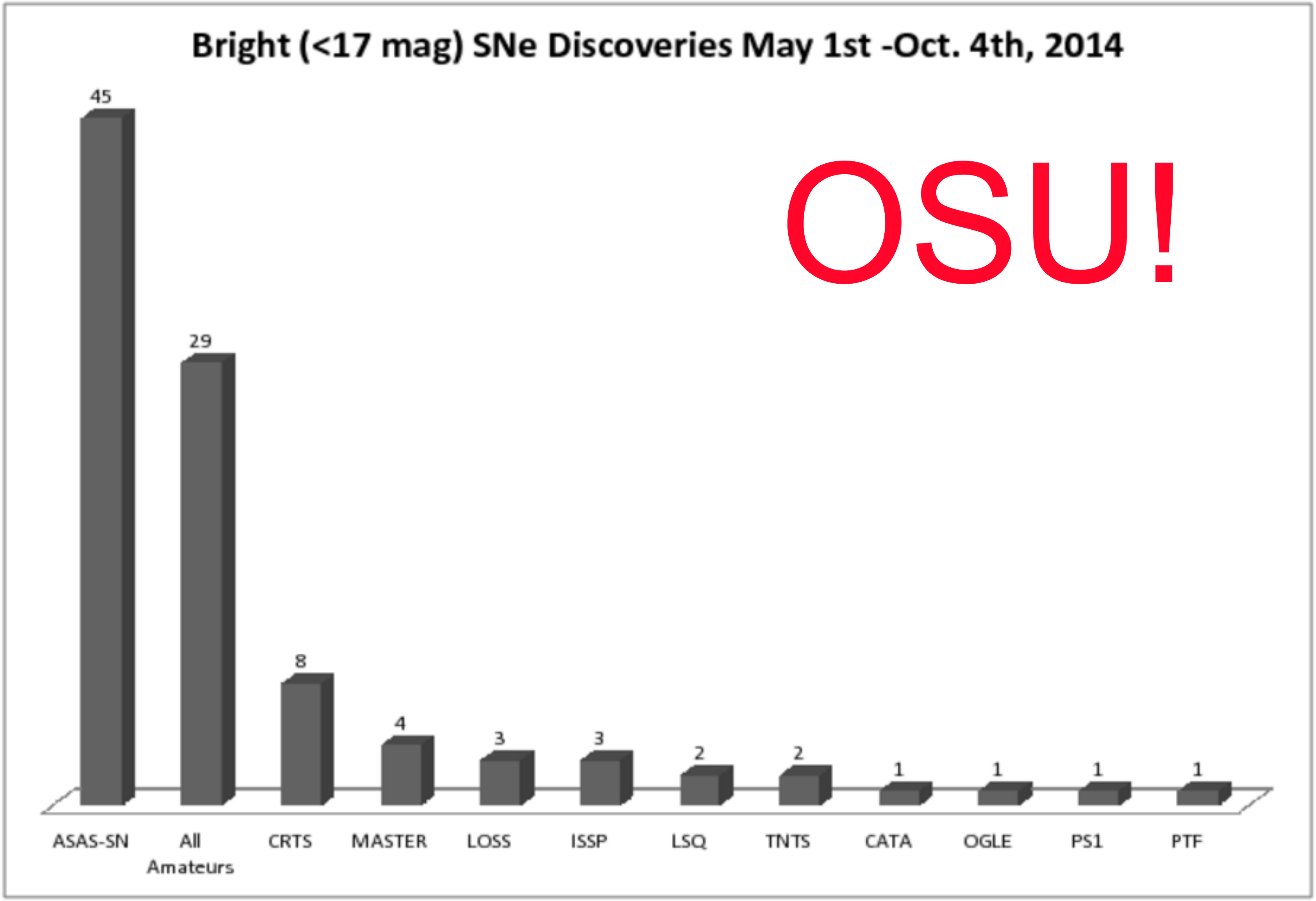
Ia supernova exploding in a galaxy by HST

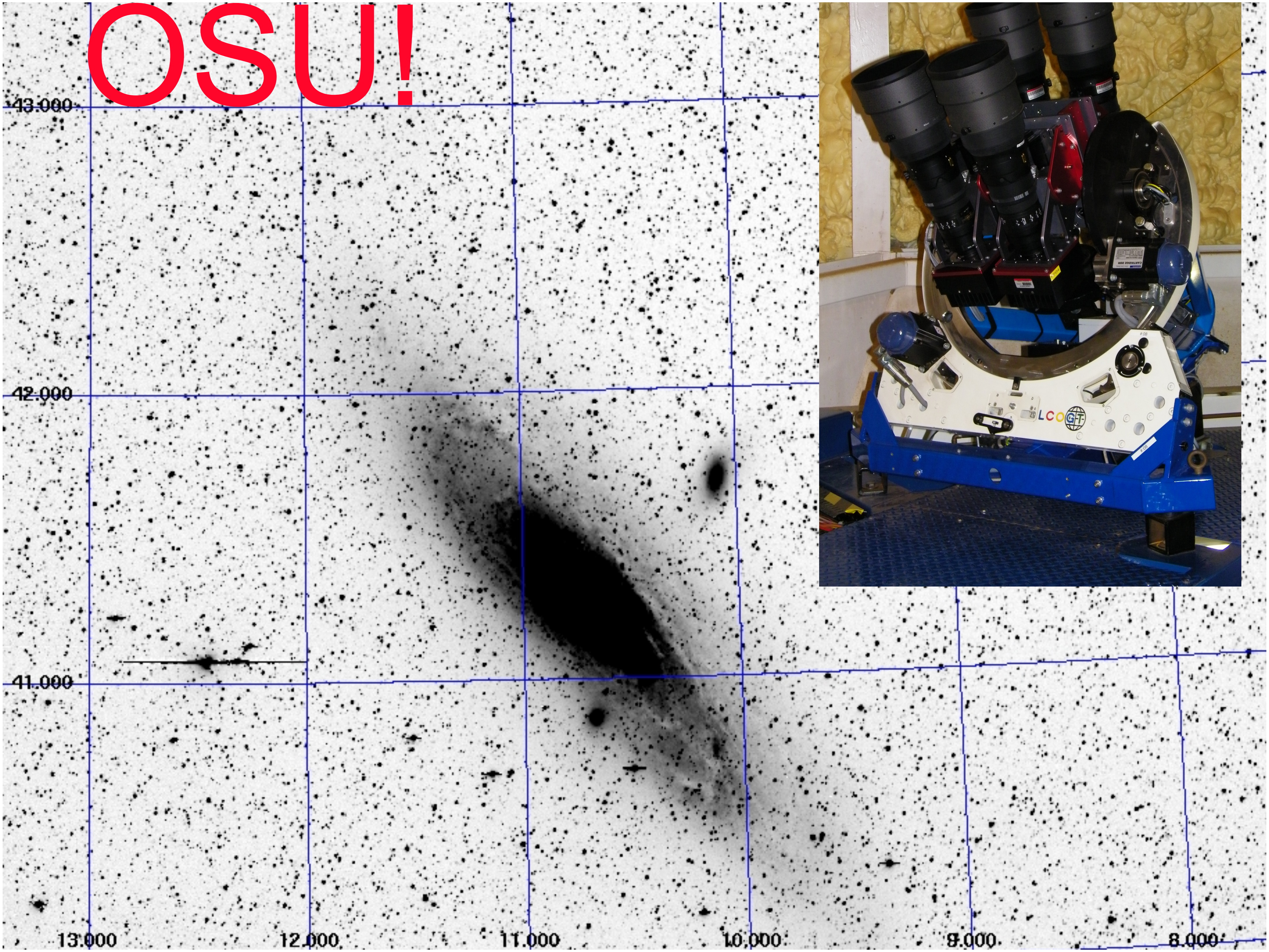
We see Type Ia Supernovae in our galaxy: 1 every 200yr.

Kepler's Supernova

Tycho's Supernova




Bright (<17 mag) SNe Discoveries May 1st -Oct. 4th, 2014
OSU!
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!
43.000
42.000
41.000
13.000
12.000
11.000
10.000
9.000
8.000
LCOGT

End Oct 17