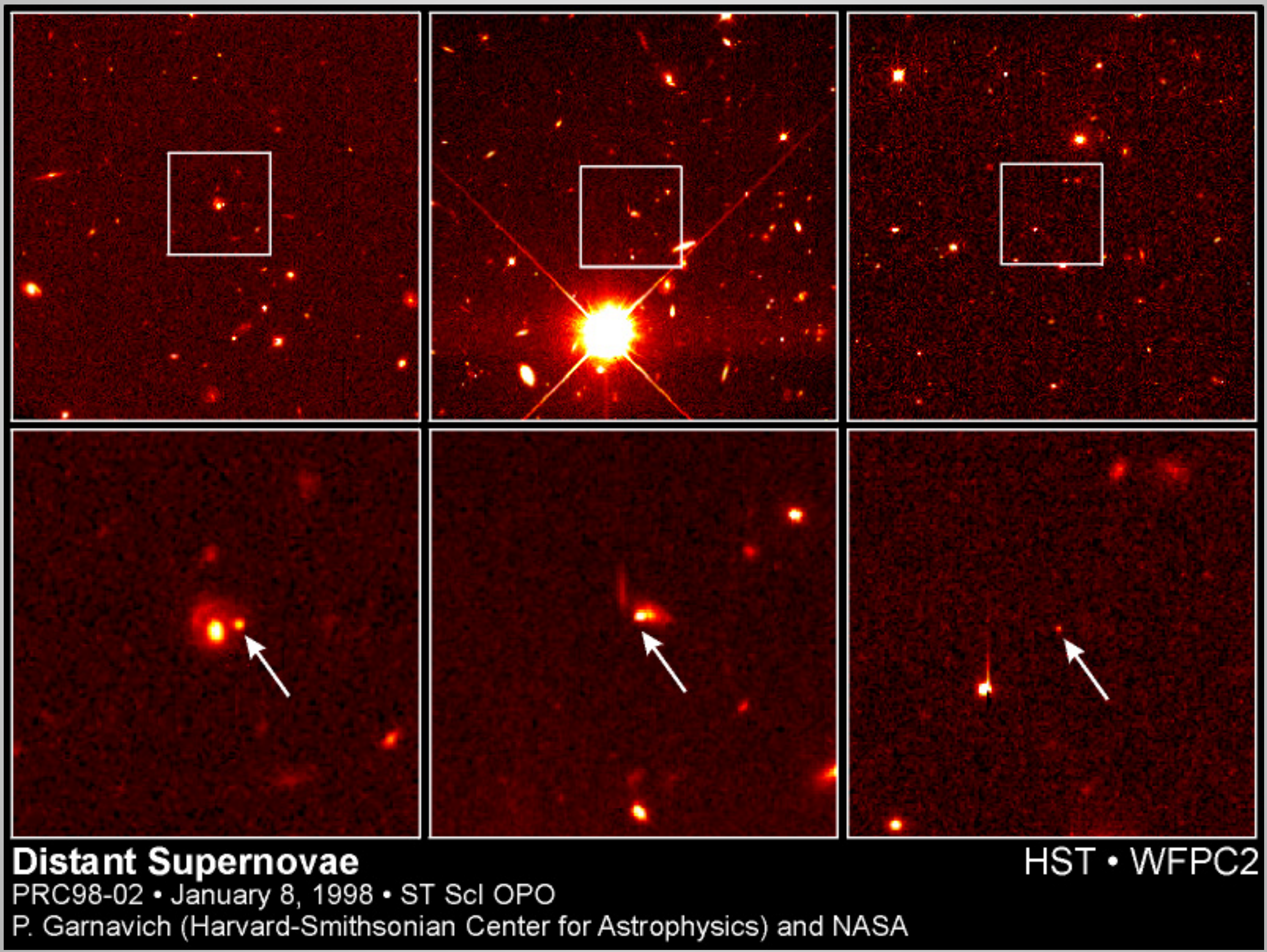
Supernovae and gamma-ray bursts

Supernovae

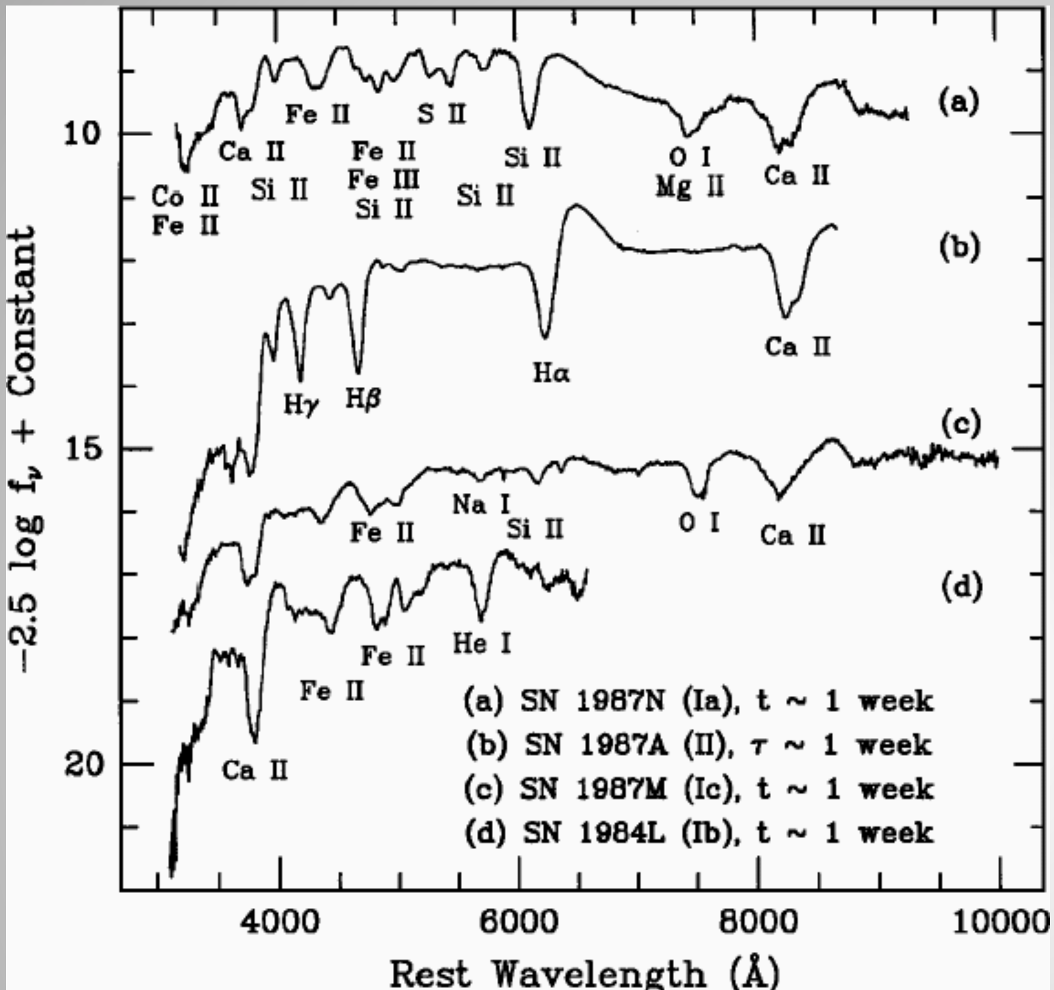
Observations: a star that temporarily becomes extremely bright, sometimes comparable to a whole galaxy

Supernovae


Distant Supernovae
PRC98-02 • January 8, 1998 • ST ScI OPO
P. Garnavich (Harvard-Smithsonian Center for Astrophysics) and NASA
HST • WFPC2

Supernovae

- Visible at very great distance (cosmology)
- What is the mechanism?



Supernovae

2 main types, distinguished observationally by their spectra

- Type 1: no hydrogen lines in spectra
- Type 2: do show hydrogen lines

Interpretation

- Type 2: hydrogen lines in spectra
  - "core collapse supernovae", collapse of the core of a massive star (> 8 M_{sun}), explosion propagates through stellar envelope containing hydrogen
- Type 1: no hydrogen lines
  - explosion initiated when a white dwarf, made of carbon and oxygen, exceeds the Chandraeskhar limit

Stellar evolution

Main sequence: core of a star is hot enough to fuse hydrogen (1 proton) into helium (with 2 protons, 2 neutrons)

Mass of 1 helium nucleus is *smaller* (by ~0.7%) than mass of 4 hydrogens

$$E = mc^2$$ → Energy release

Hydrogen fusion requires high T, as protons have positive electric charge and repel each other

Stellar evolution

Once hydrogen is core is exhausted…

Can proceed to fuse He into heavier elements, carbon, oxygen etc.

- requires even higher T, as He has twice the charge of H
- process can continue (carbon to silicon, etc) all the way up to iron (most stable nucleus), but *only* if the star is massive: core of a low mass star never gets hot enough

For stars with masses between 0.5 M_{sun} and 8 M_{sun}, core burning ends with the core a mixture of carbon and oxygen.

Envelope is now very large, and weakly bound to the core. Final stages of burning generate a lot of luminosity, which acts to blow away the envelope:

Planetary nebulae

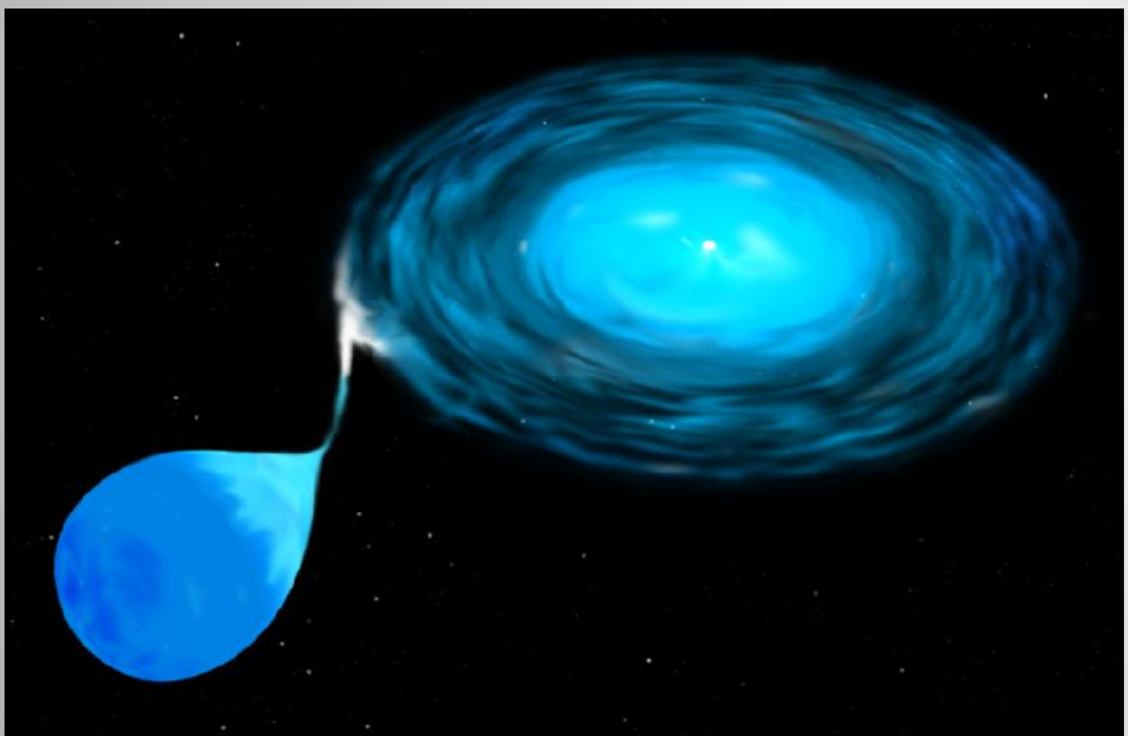
Exposed core cools to become a degenerate **white dwarf**

White dwarf formed from stellar evolution of a low mass star is **stable** – normally < 1 M_{Sun}

How can it be made to exceed the Chandrasekhar limit (1.4 M_{sun}). Not known for sure…

Exceeding the Chandrasekhar limiting mass

Suppose we add mass to a white dwarf, for example in a mass transfer binary system, to bring it up to the Chandrasekhar limit. What happens?



Possibility 1

Once M_{Ch} is reached, the pressure of degenerate electrons can no longer hold the star up:

→ collapse

Possibility 2

As M approaches M_{Ch}, the temperature and density in the core ignite fresh nuclear reactions.

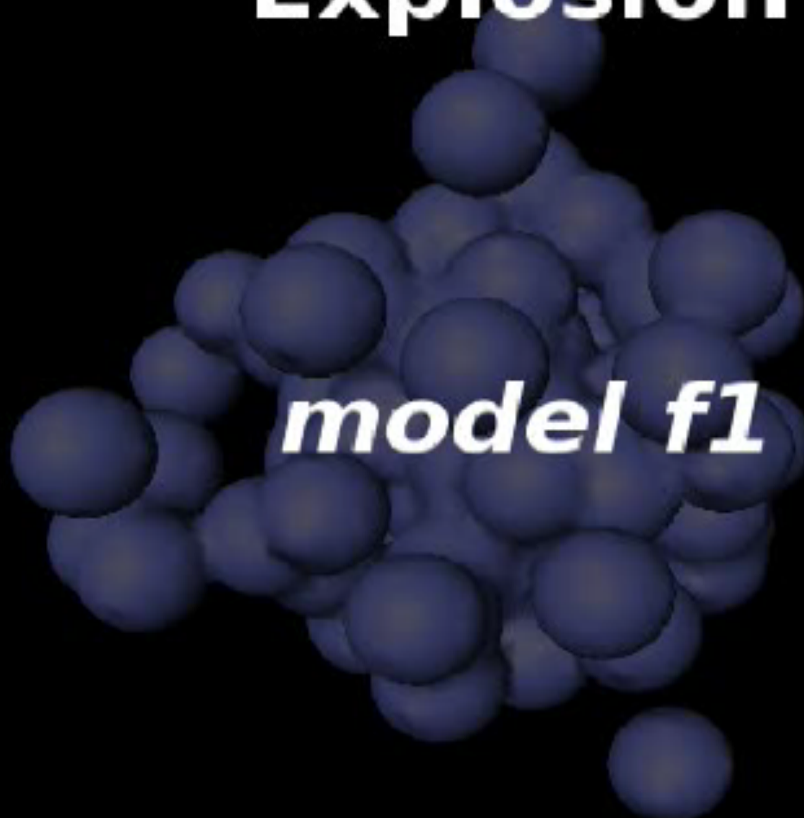
Unlike in the case of ordinary stellar nuclear reactions, this is devastating to the star. Recall: pressure of degenerate matter depends on density **only**, not temperature

Hence, large energy release from nuclear reactions heats the material up without changing the pressure or density.

Reactions runaway, eventually lifting the degeneracy but not before all the star has been burned:

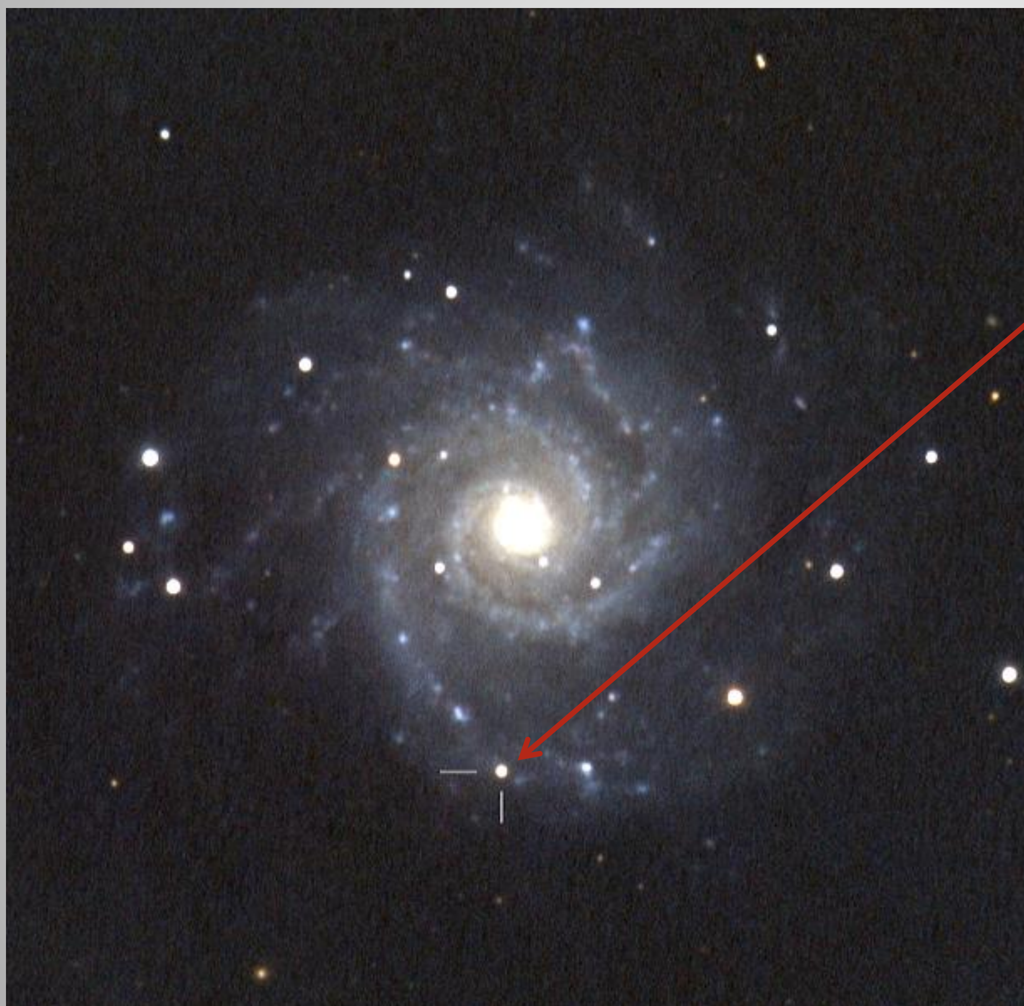
⇒ Supernova explosion, production of ~1 M_{sun} of radioactive nickel.

Thermonuclear Supernova Explosion



Core collapse supernovae

Overwhelming observational evidence that Type II SN are associated with the endpoints of massive stars:



Association with spiral arms in spiral galaxies

Supernova in M75

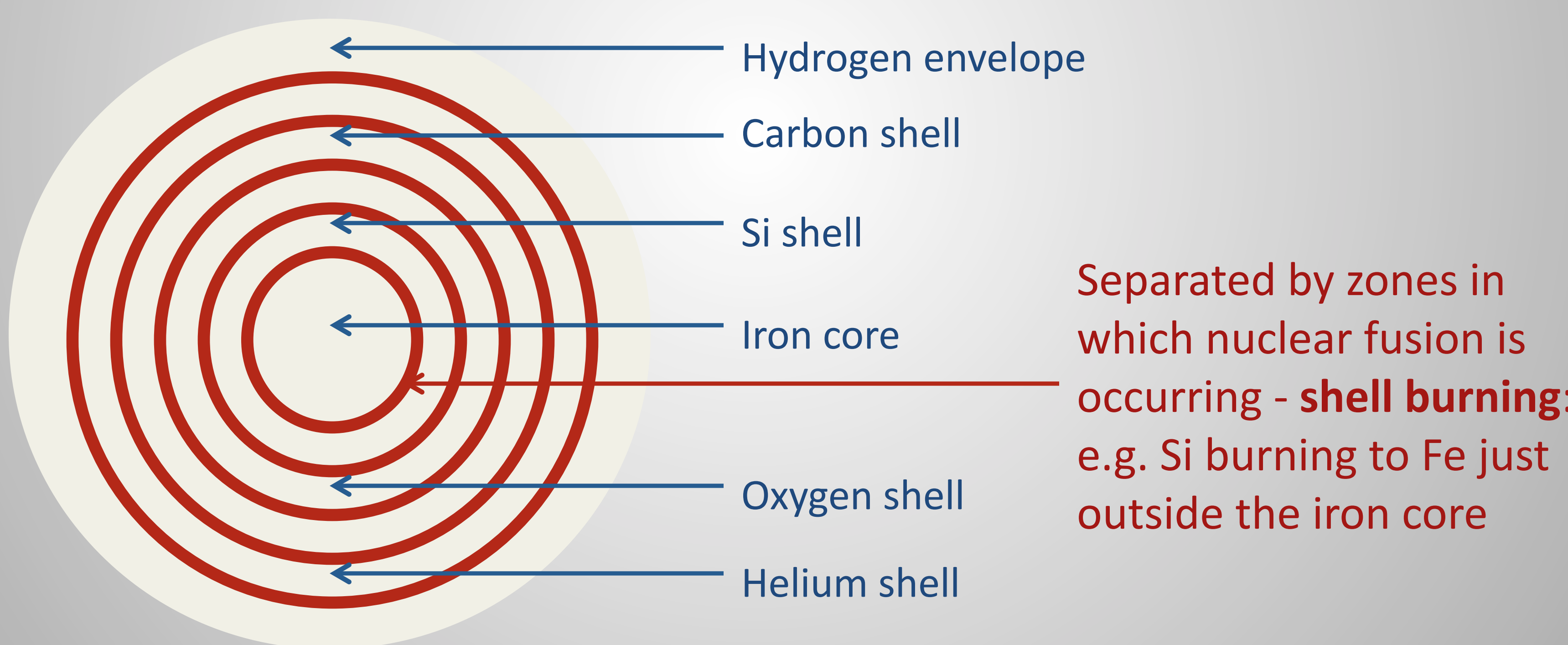
Identification of the progenitors of some core collapse SN

Thought to represent core collapse of massive stars with $M > 8\ M_{sun}$

Core collapse in massive stars

In a massive star, core temperature can be high enough that nuclear burning of Si to Fe can occur. Beyond Fe, further fusion is *endothermic*, and will not occur *under equilibrium conditions*. As an iron core develops, other reactions still proceed at larger radii:

`Onion shell' structure



Eventually iron core becomes too massive to be supported by electron degeneracy pressure:

- Can't explode like a white dwarf (Type I SN) - the core is *already* made of iron so no more exothermic nuclear reactions possible
- **Core collapses**

Once collapse starts, it proceeds very rapidly:

$$e^- + p \rightarrow n + \nu_e$$ Inverse beta decay

Robs the core of pressure support, accelerates the collapse, and drives the composition toward neutron rich matter.

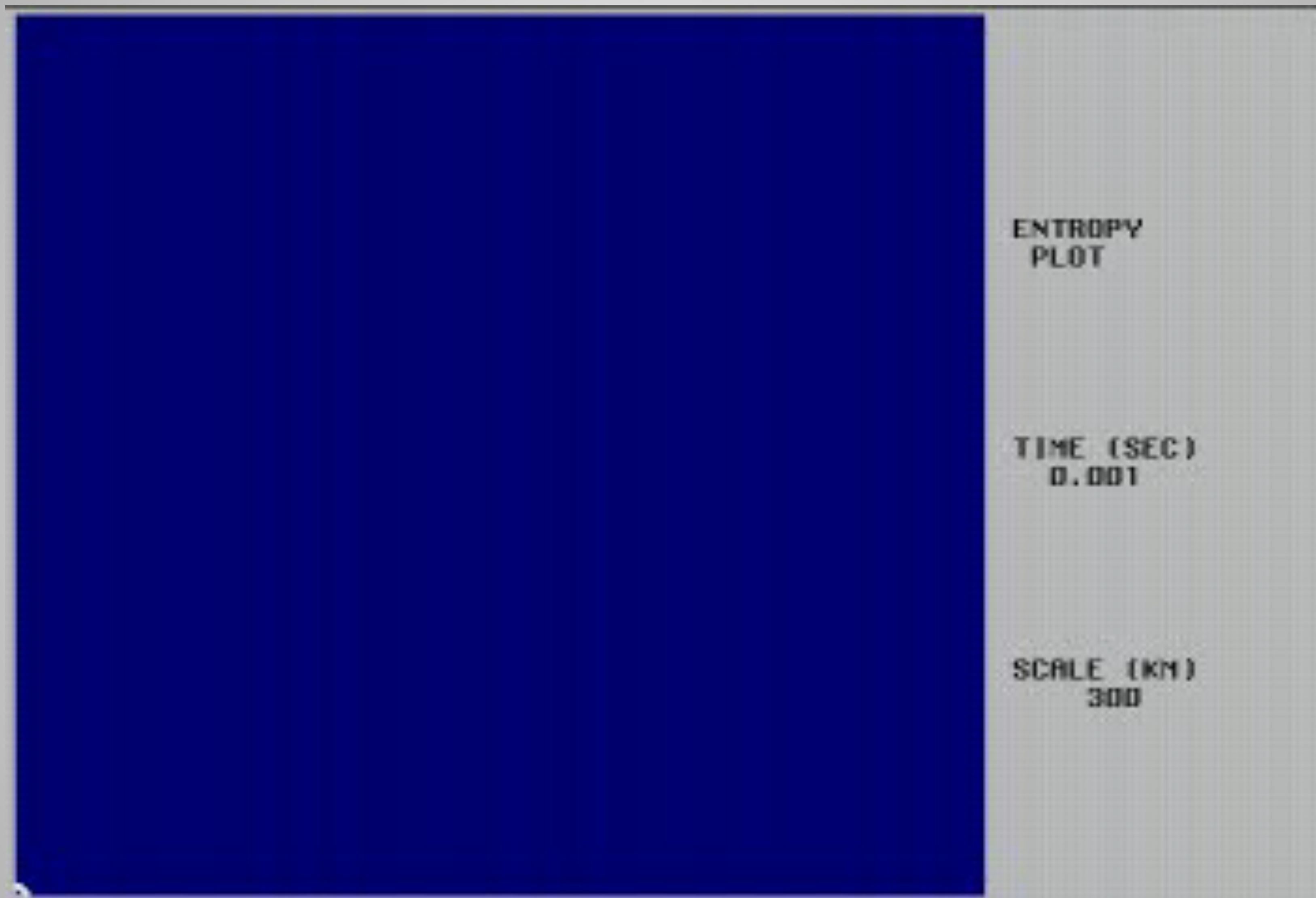
Once the core reaches nuclear densities - $\rho \sim 10^{15}$ g cm^{-3}, nuclear forces provide a new source of pressure support.

Scale is now ~10 km

Formation of a proto-neutron star stops the collapse, and produces a bounce which sends a shock wave back out into the star.

Shock wave can explode the star, *if it can propagate out through the infalling matter*.

Core may leave a neutron star, or if it is too massive, collapse further to form a black hole.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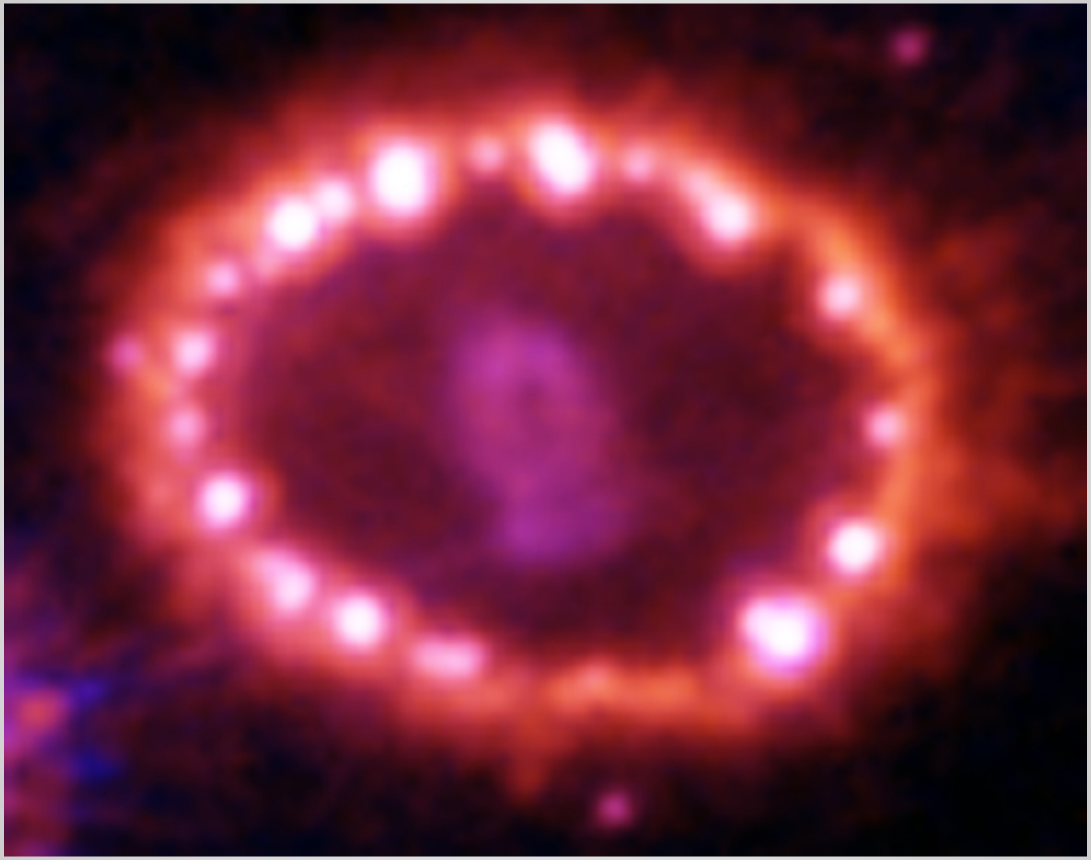
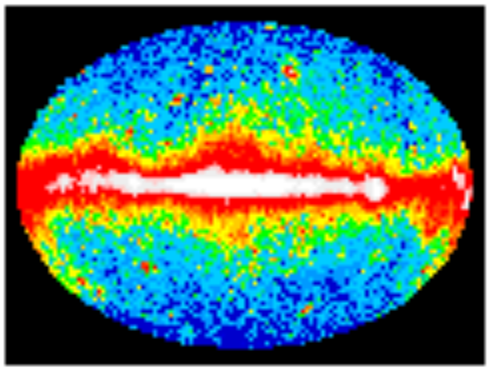
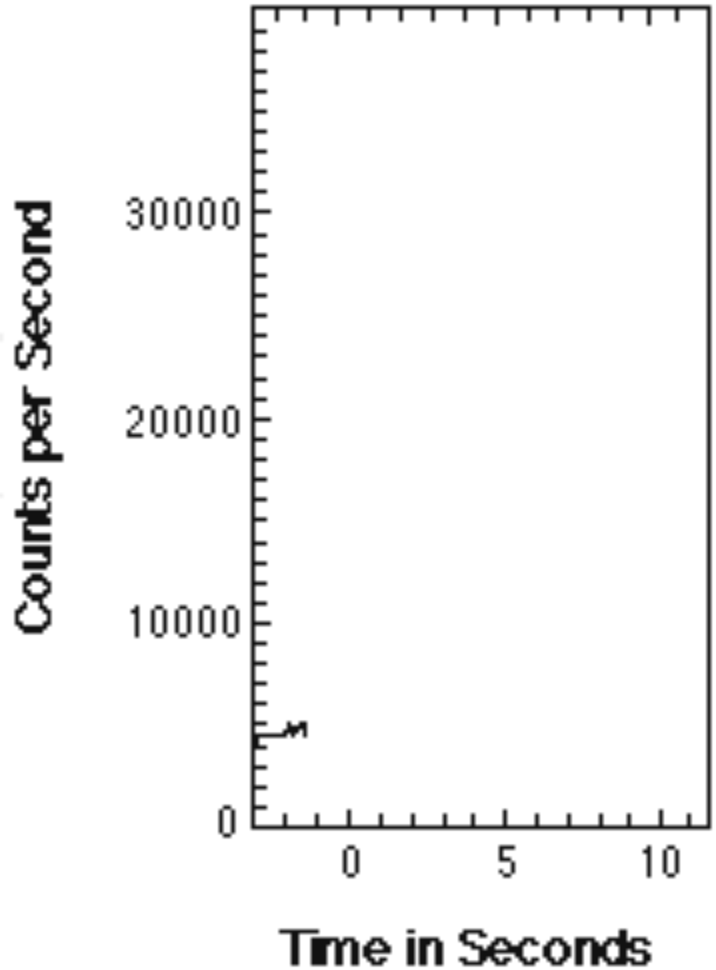


Is there an *observational* way to tell if a collapse produces a neutron star, or a black hole?

Possibly: think that *gamma-ray bursts* likely signal the formation of a black hole





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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
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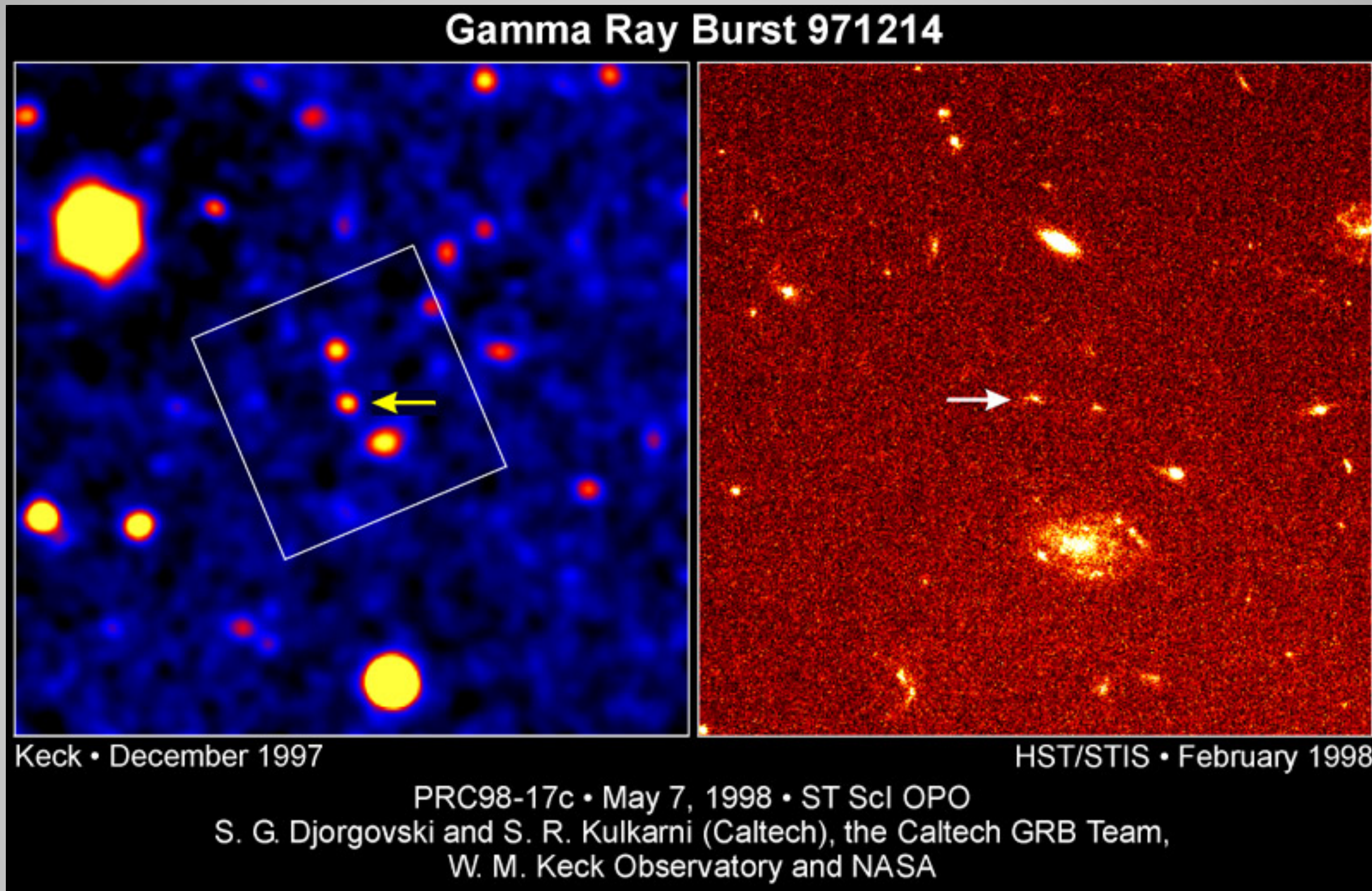
ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to $\sim$30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

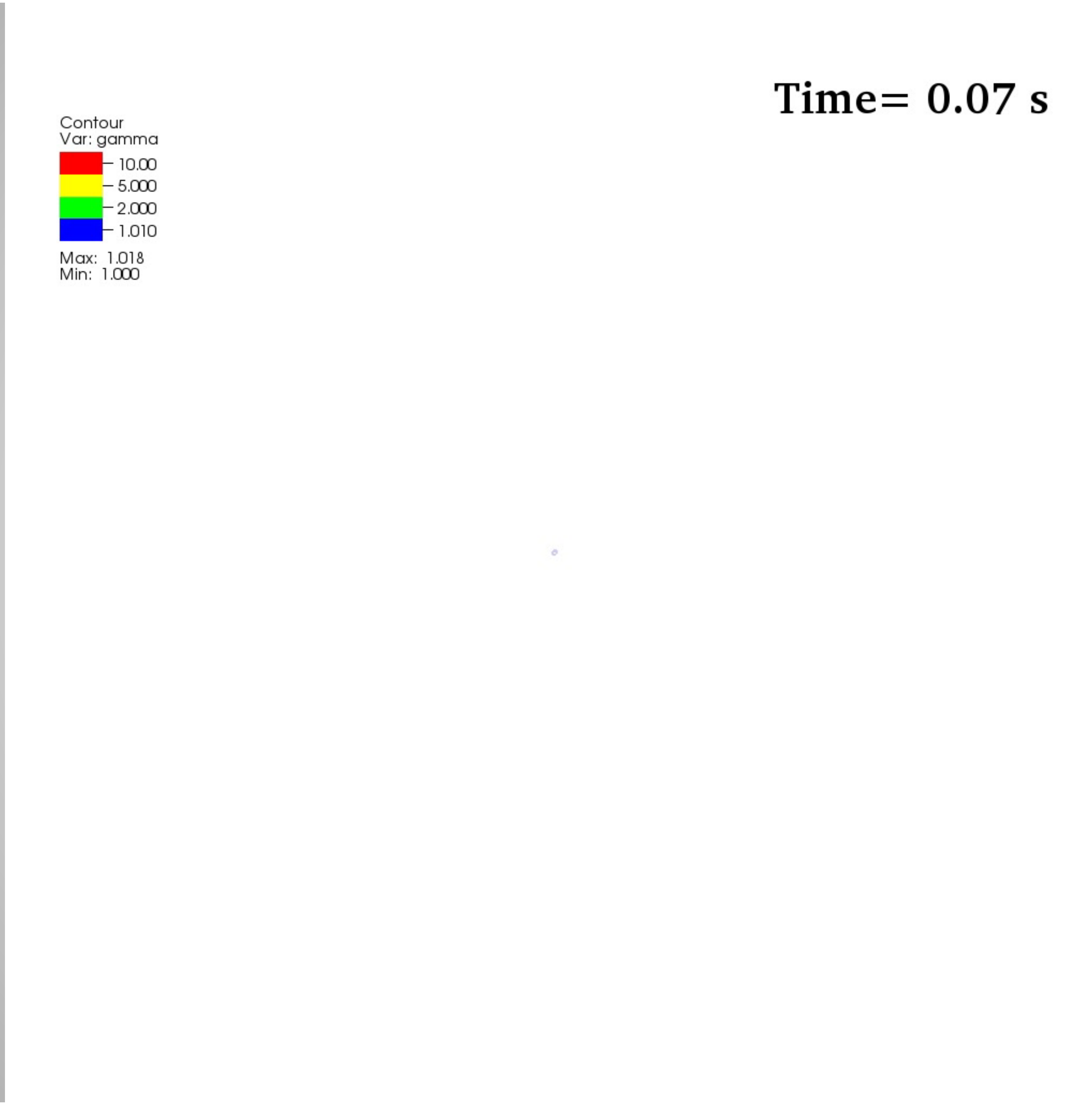


After gamma-rays have faded: see X-ray and optical emission from location of (usually) distant galaxies. Bursts of long duration accompanied by later supernovae.

Interpretation

Formation of a black hole in a core collapse leads to the production of a relativistic jet of material, which punches its way out of the star

If the jet is pointed in our direction, see very bright gamma-ray emission, if it misses, we just see the subsequent supernova explosion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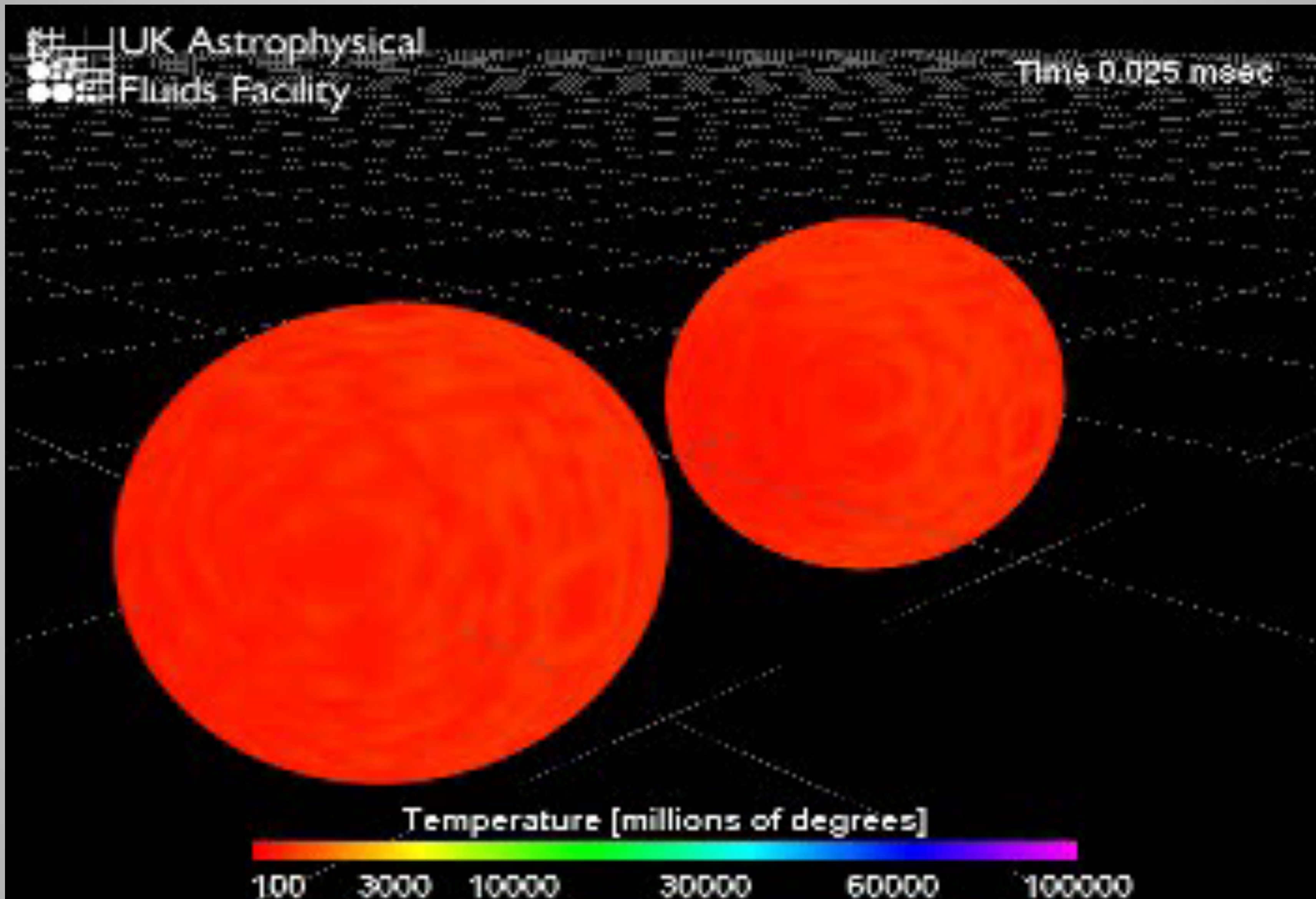
But there are other ways to make black holes… could merge 2 neutron stars

These events may also produce gamma-ray bursts, though of shorter duration that the ones associated with core collapse


UK Astrophysical
Fluids Facility
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