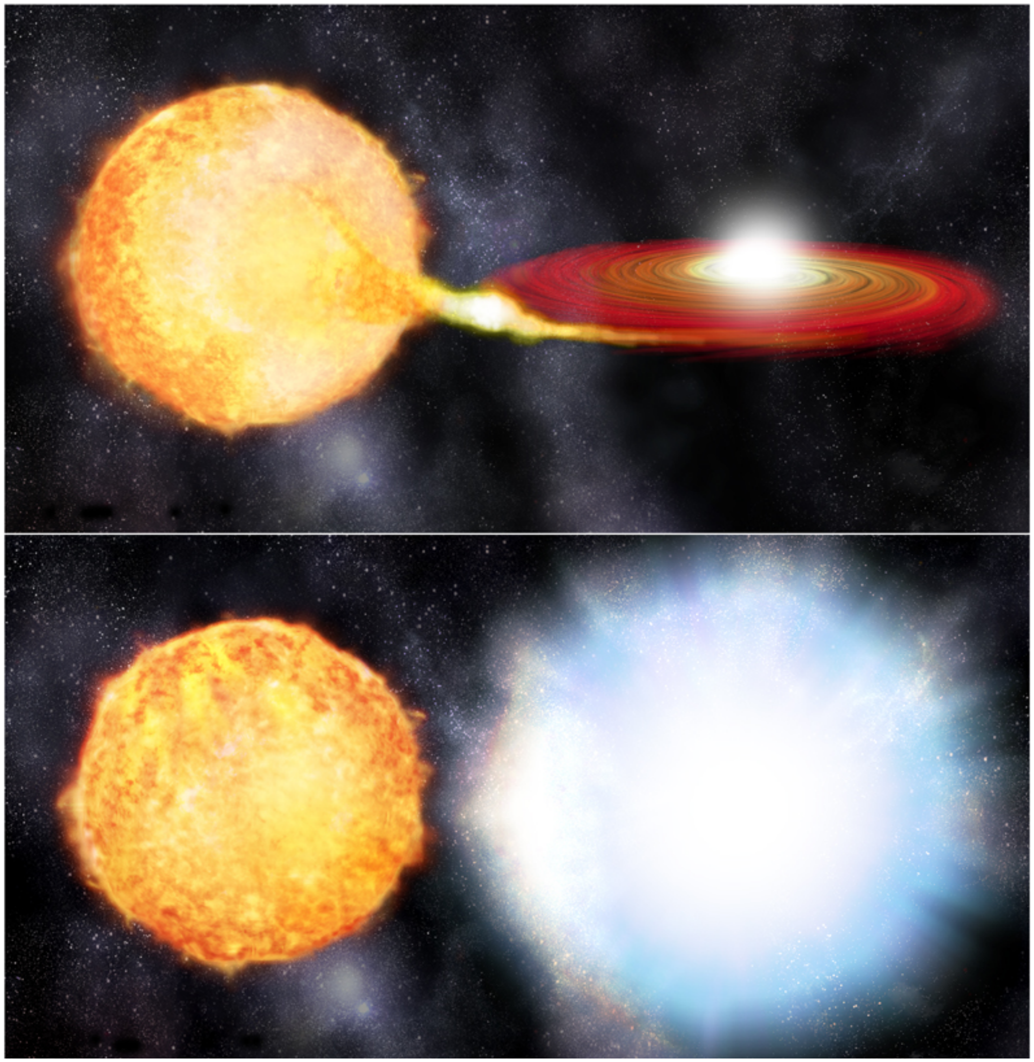
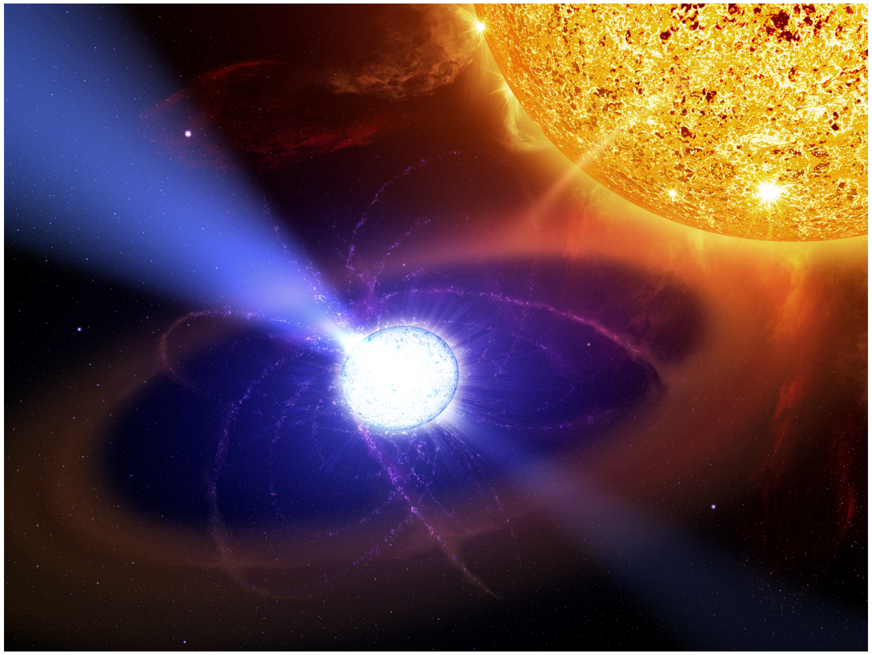
# Type Ia Supernova



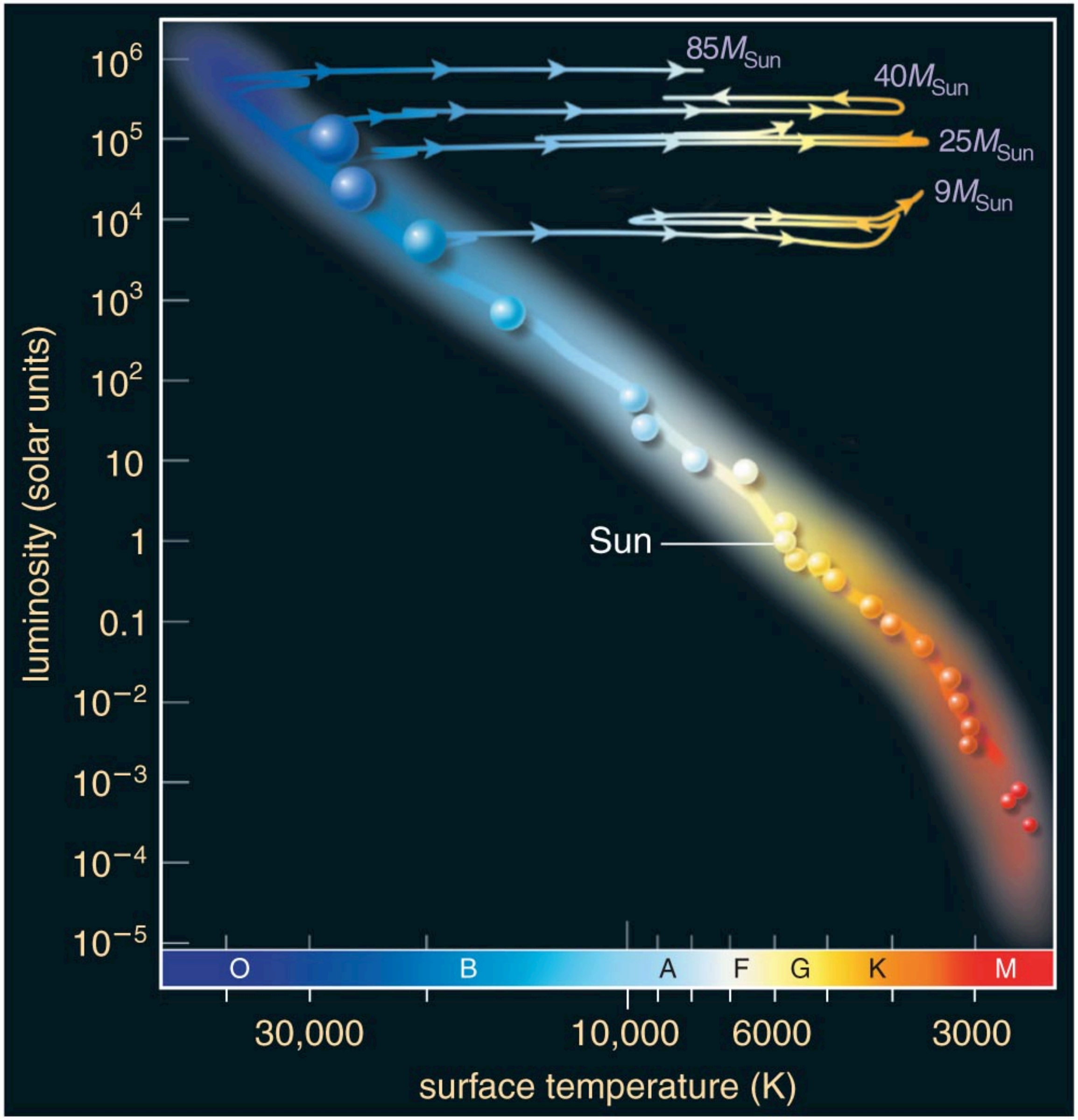
- White dwarf accumulates mass from (Giant) companion
- Exceeds Chandrasekar limit
- Goes supernova

Ia simul

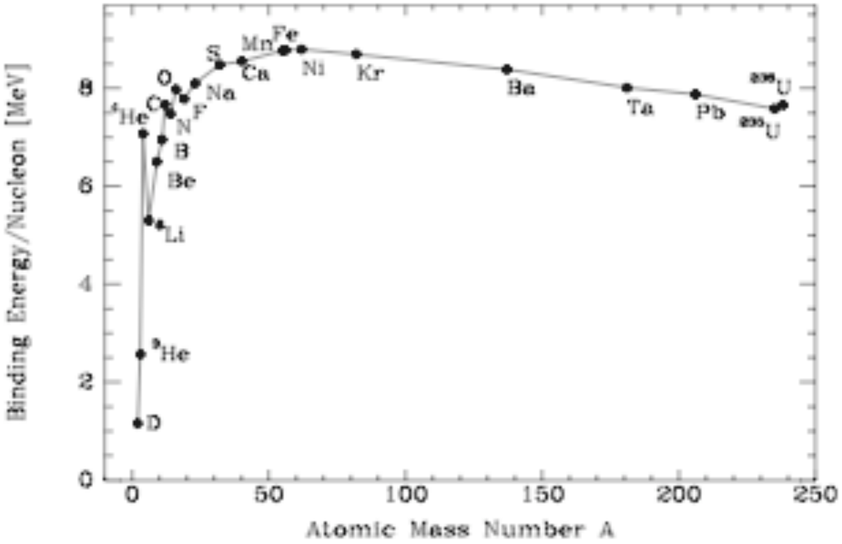


# Super Giant Stars

- Last stage of superheavy (>10 $M_\odot$) stars after completing Main Sequence existence
- Initially: Very hot, UV radiation
- Move mostly horizontally on H-R diagram (decreasing temperature, constant luminosity
  - Heaviest (100$M_\odot$) never go beyond blue SG stage
  - Others: red SGs



# Fusion for Supergiants



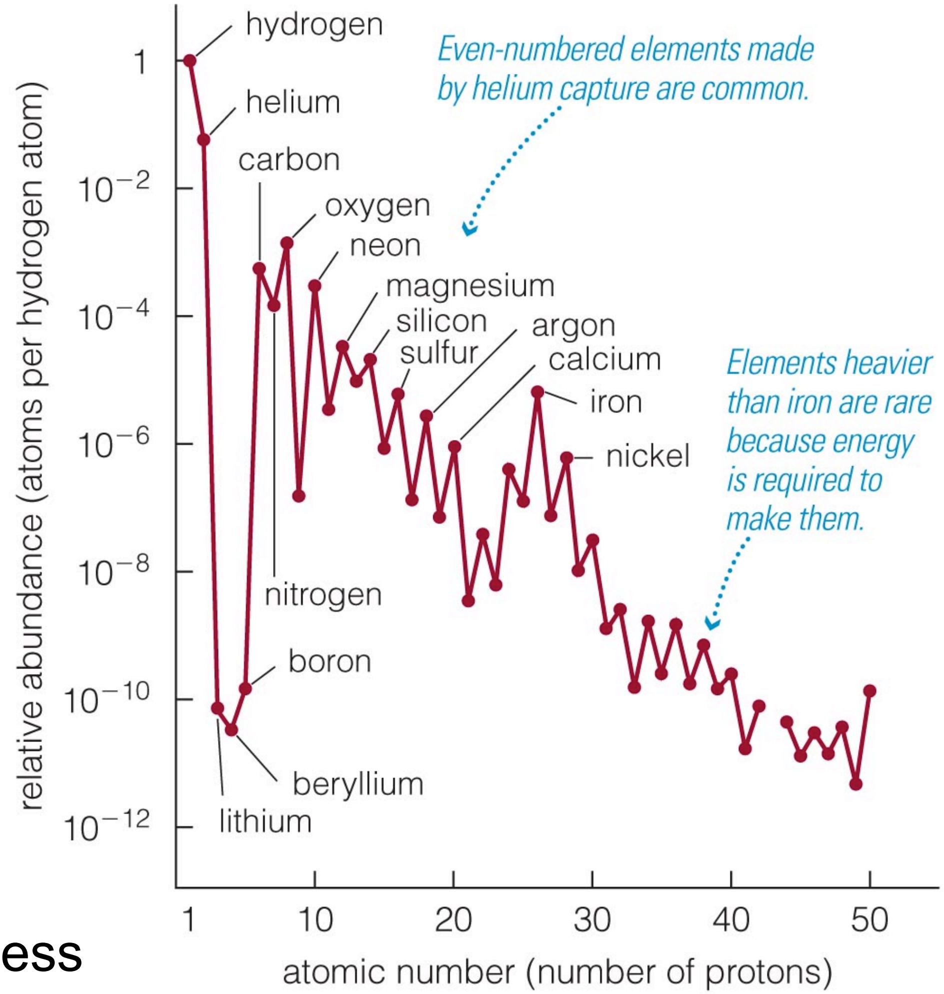
- Onion (25 $M_\odot$):
  - H burning: 5 Mio yr
  - $^4$He burning: 500,000 yr
  - $^{12}$C burning: 500 yr
  - Ne burning: 1 yr
  - Si burning: 1 day
  - Final state: inert Iron/Nickel core -> no more energy available from nuclear fusion (nor from fission!)

Liquid drop model:

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z) + a_{Grav} \frac{A^2}{A^{1/3}}$$

# Fusion for Supergiants

- Nuclear reactions in massive stars:
  - p+p , CNO cycle => 4p -> $^{4}$He = $\alpha$, $e^{+}$, $\nu$ + 26 MeV
  - Triple-alpha: 3$\alpha$ -> $^{12}$C + 7.2 MeV
  - $\alpha$ capture chain: $^{12}$C -> $^{16}$O -> $^{20}$Ne -> $^{24}$Mg…
  - Other reactions: $^{12}$C+$^{12}$C -> $^{20}$Ne + $\alpha$ C+O->$^{28}$Si, O+O->$^{31}$S+**n**, Si+Si->$^{56}$Ni->$^{56}$Co->$^{56}$Fe
  - Heavier elements through s-process



*Even-numbered elements made by helium capture are common.*

*Elements heavier than iron are rare because energy is required to make them.*

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z) \quad + a_{Grav} \frac{A^2}{A^{1/3}}$$

# Superheavy Elements

- During regular fusion, only elements up to Fe, Ni, Cu can be produced
- During supernova explosions, very high neutron flux
- …or neutron star mergers?
- => rapid (r) neutron capture process
- Followed by beta-decay
- => All heavier elements

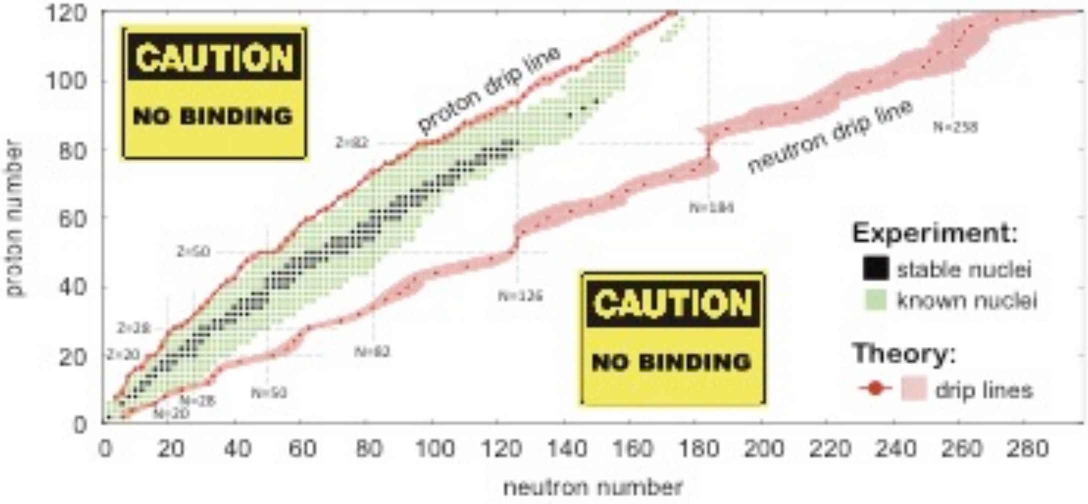
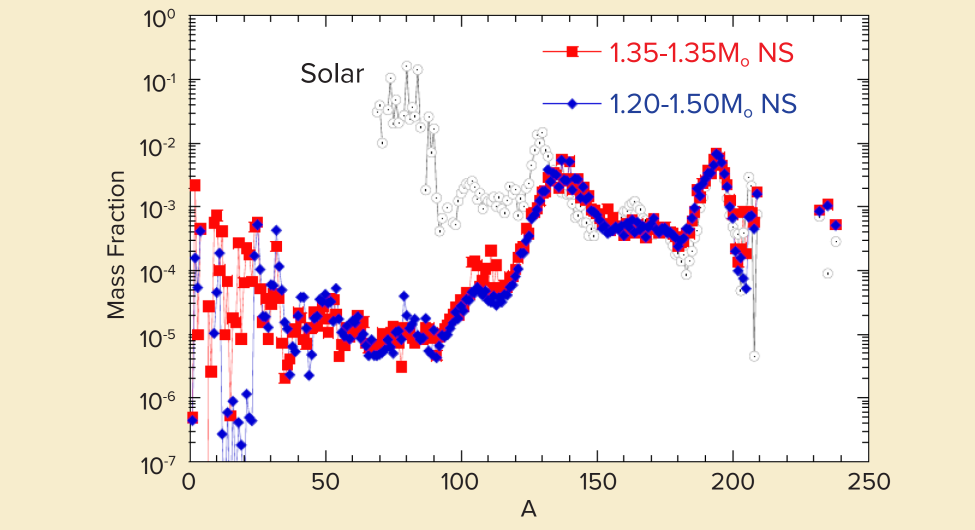


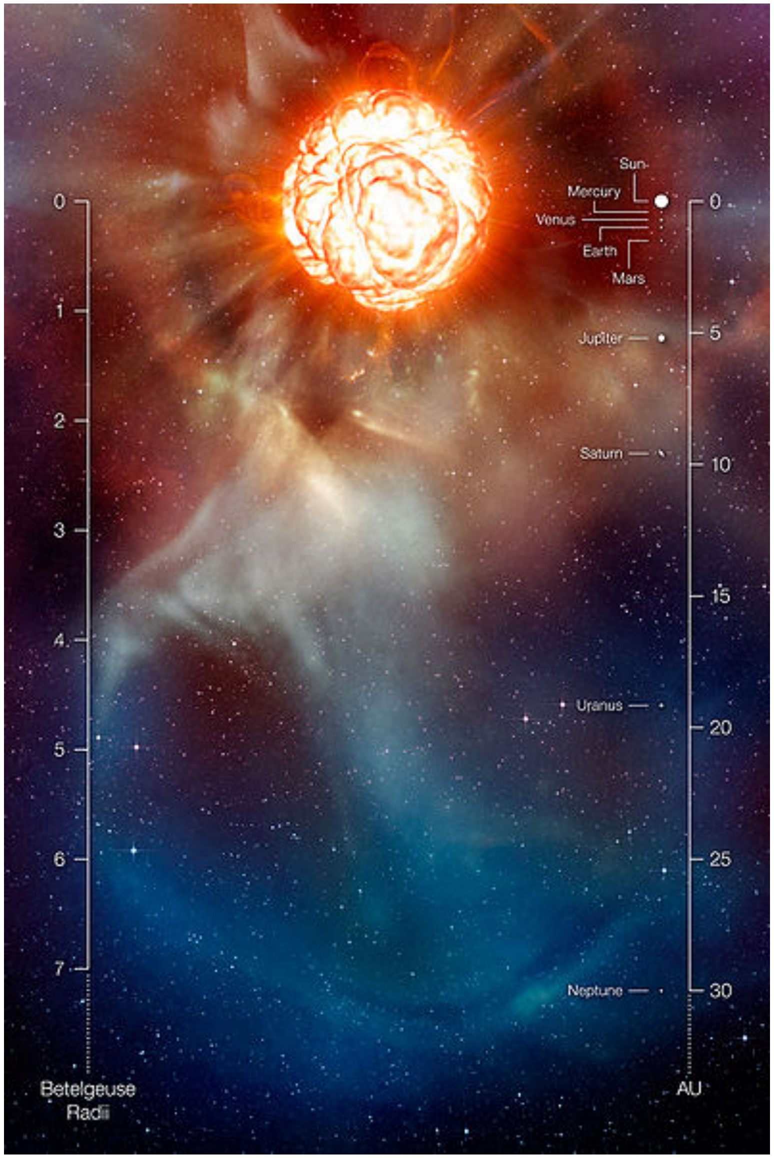
*Figure 3.1: Nuclear landscape. Map of bound nuclei as a function of Z and N. Mean drip lines, where the nuclear binding ends, and their uncertainties (red) were obtained by averaging the results of different theoretical models.*



*Nuclear abundance distributions as a function of atomic mass of the ejecta for two different combinations of neutron star mergers. The distributions are normalized to the solar r-process abundance distribution. Image credit: Stephane Goriely.*

# More about Betelgeuse

- Outer Layer extremely tenuous (pretty much vacuum) but optically dense
- Lots of gas (ejected?) even beyond that (all the way to "Neptune's orbit")
- Evidence of (asymmetric) mass loss - will it end with a bang or a whimper?



Publication: The Virginian-Pilot; Date: Feb 6, 2011; Section: Health+Science; Page: N1

# BOOM?

## Whenever giant Betelgeuse does go supernova, it will be the brightest star in the sky, other than our sun.

**By LONA O'CONNOR**

**Cox Newspapers**

TWO SUNS IN THE SKY. The news that the star Betelgeuse is about to explode so spectacularly that it will appear as a second sun in our sky has been floating around the Internet for months. It gained credibility when a physics lecturer at the University of South Queensland, Australia, was quoted as saying that such an event could happen next year, which happens to be when the Mayan calendar runs out. Some say 2012 is when the world will end . The possibility of a supernova adds weight to those who believe the Mayan apocalypse prophecy. Betelgeuse (pronounced BEET'l jooz) is a bright red supergiant star positioned in the right shoulder of the constellation Orion, the hunter, and easily seen in the night sky at this time of the year, rising in the east right after sunset. A Miami astronomer begs to differ, at least on some of the details. "We've known for a very long time that Betelgeuse is massive enough to end its life as a supernova," said Carolyn Simpson, physics professor at Florida International University. As for when this will happen, you can sit outside tonight and get a ringside seat for the event, but it could be a long wait. "It could go supernova in the next five minutes, or in a million years," said Simpson, who has a Ph.D in astronomy and loves debunking scientific misinformation.

"We have no way of telling."

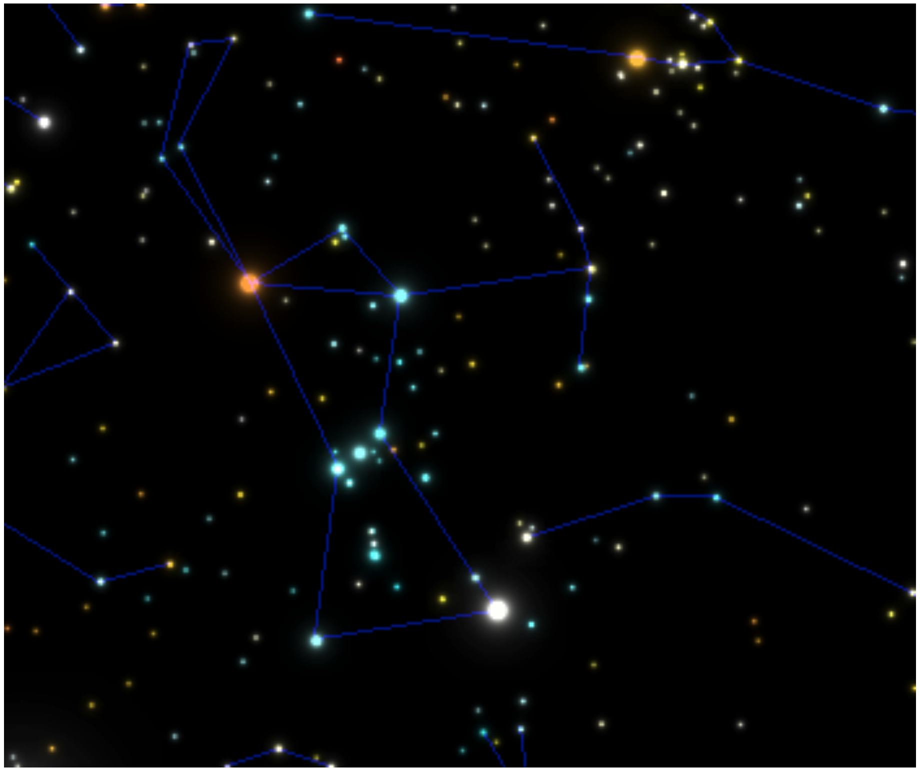
And it won't be as bright as our sun, though it could be brighter than a full moon – at night. It would be visible in the daytime, looking like a bright star or a pinprick in the daytime sky, then fading over days or weeks, Simpson said.

That might not sound like much, but it would be the only time such an event has occurred since 1054, when the Crab Nebula exploded.

"It will be the brightest star in the sky other than our sun," said Jim Kimball, president of the Astronomical Society of the Palm Beaches. "That will be extremely impressive."

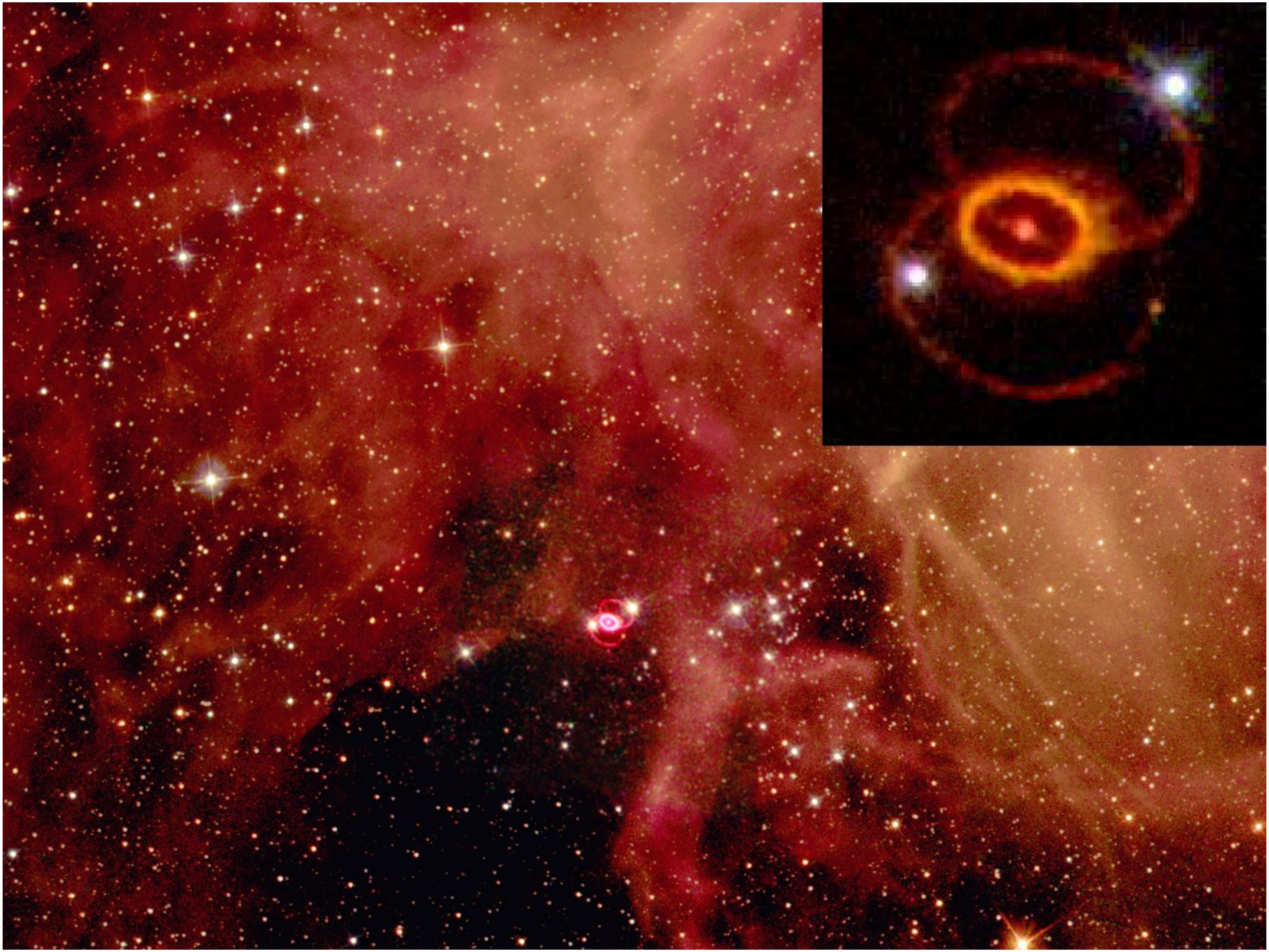
As for the 2012 connection, "The Mayan thing, that's just whacked," said Simpson, who says that the Internet and instant media are at least partly responsible for connecting the very real possibility of Betelgeuse exploding with the scientifically questionable date for the end of the world.

"We're humans – that's what we do," Simpson said. "We are pattern-finding creatures. It's our strongest survival mechanism. Randomness makes us nervous, so sometimes we find patterns where none exist."



# Core Collapse Supernovae

- Types Ib, Ic: no H lines due to shell loss (type Ia already discussed) Type II: Plenty of H left (standard end stage of SG)
- Onion (25 $M_\odot$):
  - H-He-C-O-Ne-Mg-Si shells
  - Final state: inert Iron/Nickel core
    -> no more energy available from nuclear fusion
    -> contraction, degeneracy pressure -> core collapse
    (1 $M_\odot$ collapses from Earth size to 10's of km in < 1 sec!)
- Core heats up, contracts (Chandrasekhar limit!) =>
  - photo-dissociation (nucleus -> nucleons)
  - e- capture: $e^- + p \rightarrow n + \nu_e$, n decay => large energy loss ($\nu$'s)!
  - core collapse (seconds!), shockwave, neutrino death ray, sudden luminosity increase ($3 \times 10^9\ L_\odot$ for weeks), blown off outer layer
  - Light fall-off controlled by nuclear decays
  - Huge number of n's -> r process



# Supernova remnant

- Neutron star:
  - nearly no p’s, $e^-$’s, just neutrons
  - Remember: $R_{\text{white dwarf}} \propto 1/m_e \, M^{-1/3}$
  - $m_n = 1840\, m_e$ => $R$ 1840 times smaller (really, about 500 times because only 1 e- per 2 neutrons) => of order 10 km!
  - Density: few $10^{44}/\text{m}^3 = 1/\text{fm}^3$ > nuclear density => nucleus with mass number $A = 10^{57}$
  - Chandrasekar limit: 5 solar masses (2-3 in reality?)
  - Lots depends on nuclear equation of state *), general relativity

*) Repulsive core / Nuclear superfluid / quark-gluon plasma / strange matter / pasta ?

# Fermi Gas Stability revisited:

Electron Fermi Gas: $R = \dfrac{\hbar^2 N_{tot}^{5/3}}{m_e G M^2}\left(\dfrac{9\pi}{4}\right)^{2/3}$

Neutron Star: replace $m_e$ with $m_n$ (1839 times larger), $N_{tot}$ doubled (since $N_{tot}$ = $N_n$ = number of all nucleons, not = ½ $N_{p+n}$ for electron Fermi gas.) => *R* is 580 times smaller (10 km)

Relativistic limit: $p_f = \hbar\left(3\pi^2\right)^{1/3} n^{1/3} = \hbar\left(3\pi^2\right)^{1/3}\left(\dfrac{N_{tot}}{V}\right)^{1/3} \propto M^{2/3}$

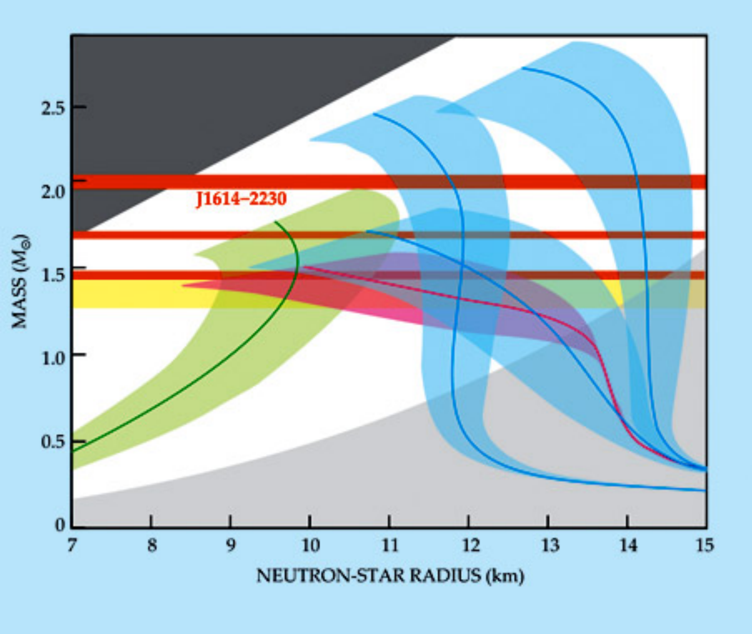
= 730 times larger for same mass *M*

⇒ $p_f/m$ =40% of ratio for electrons for same *M*

⇒ maximum $p_f$ could be 2.5x larger before relativity sets in => 4 times the mass (5.6 instead of 1.4 $M_{sun}$)

# Supernova remnants

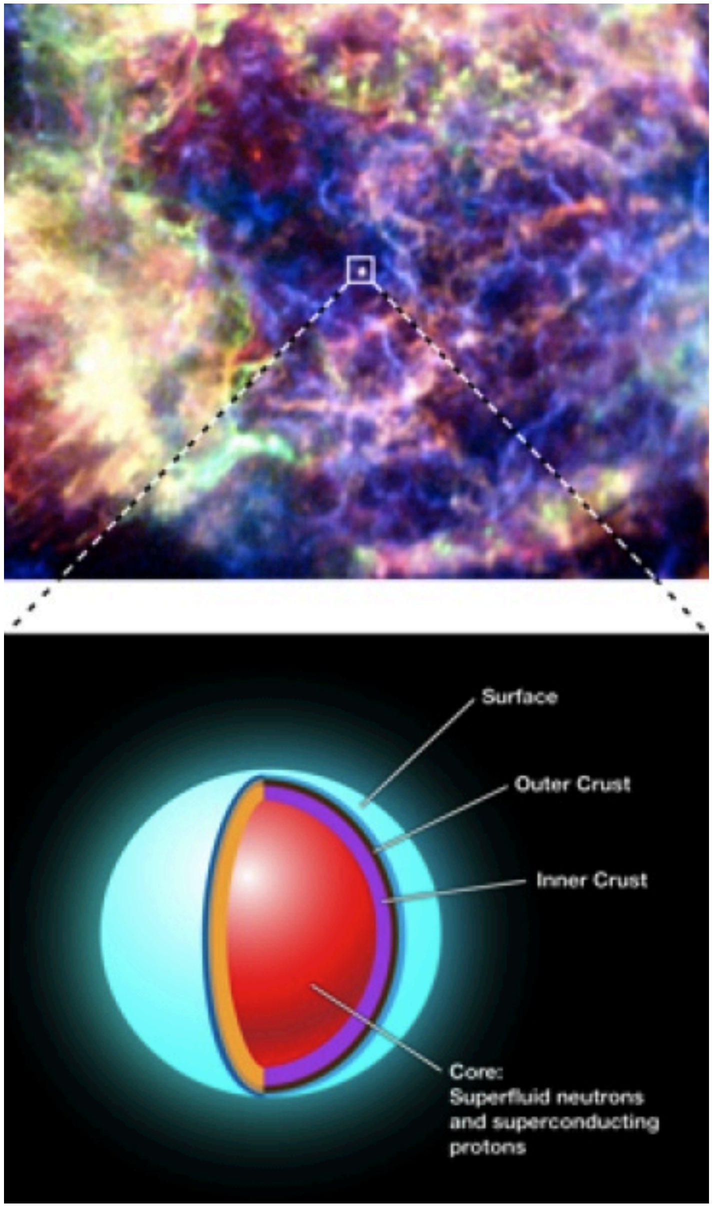
- Some new ideas:
  - Superfluid center
  - Partial deconfinement (cold plasma)
  - s quark matter (now ruled out?)

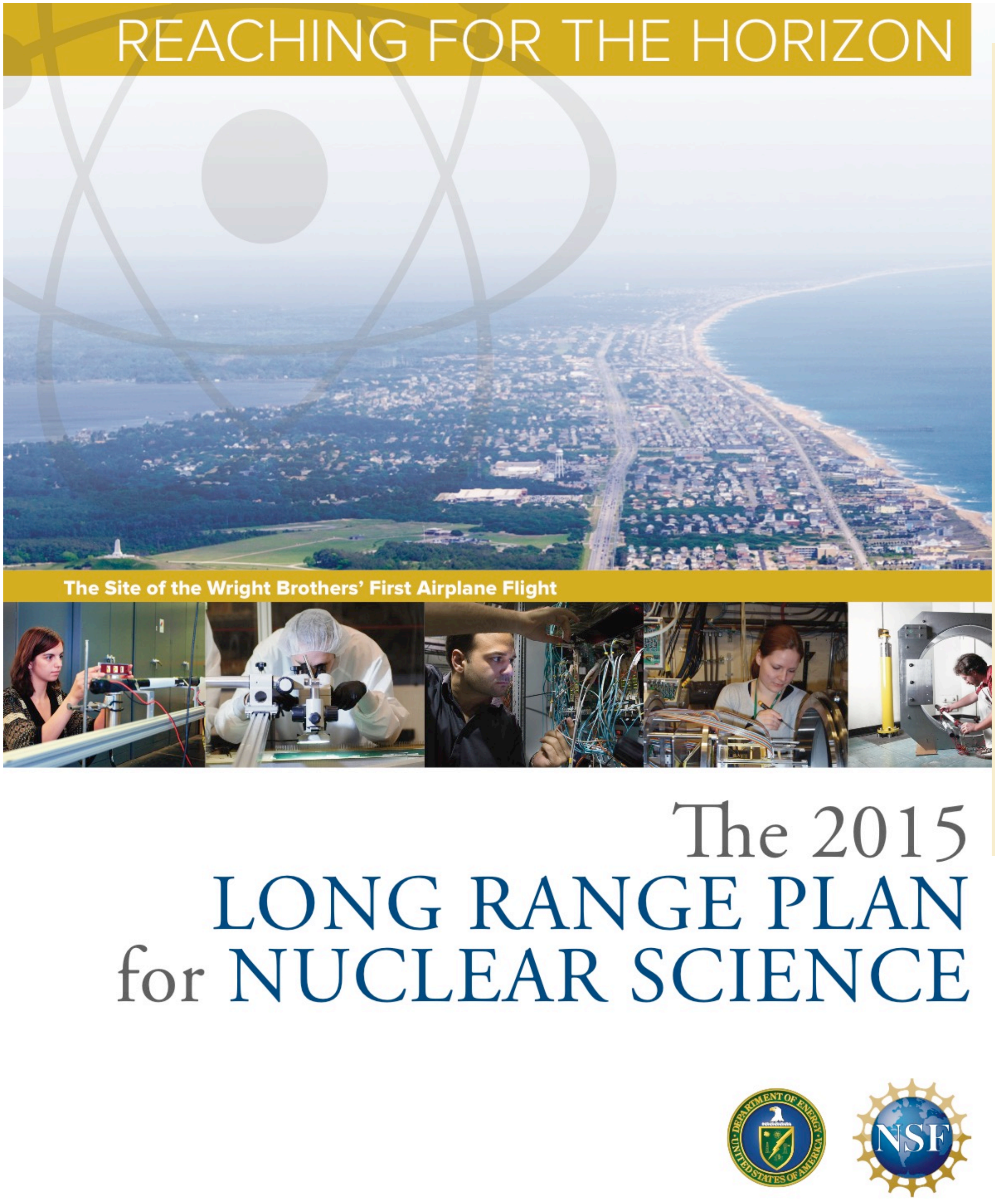


n matter

hyperons

s quark matter





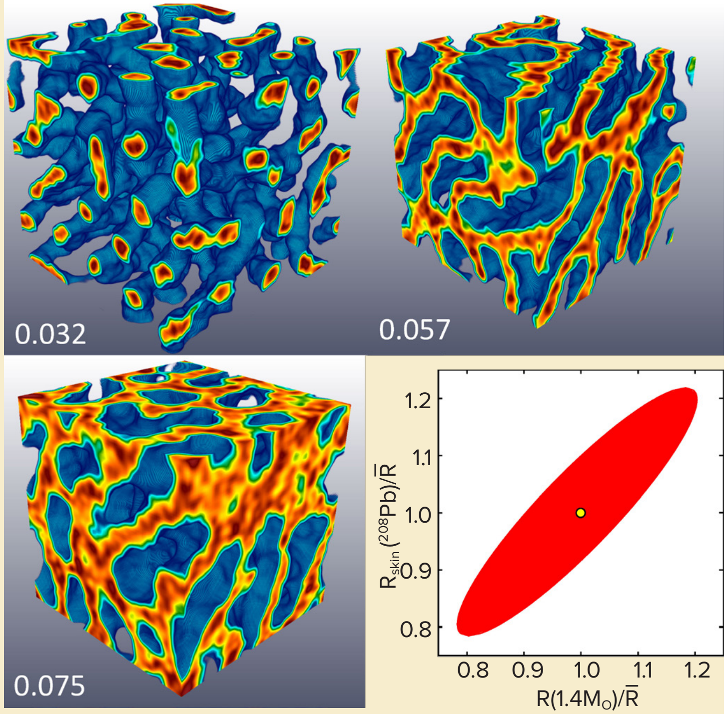
REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

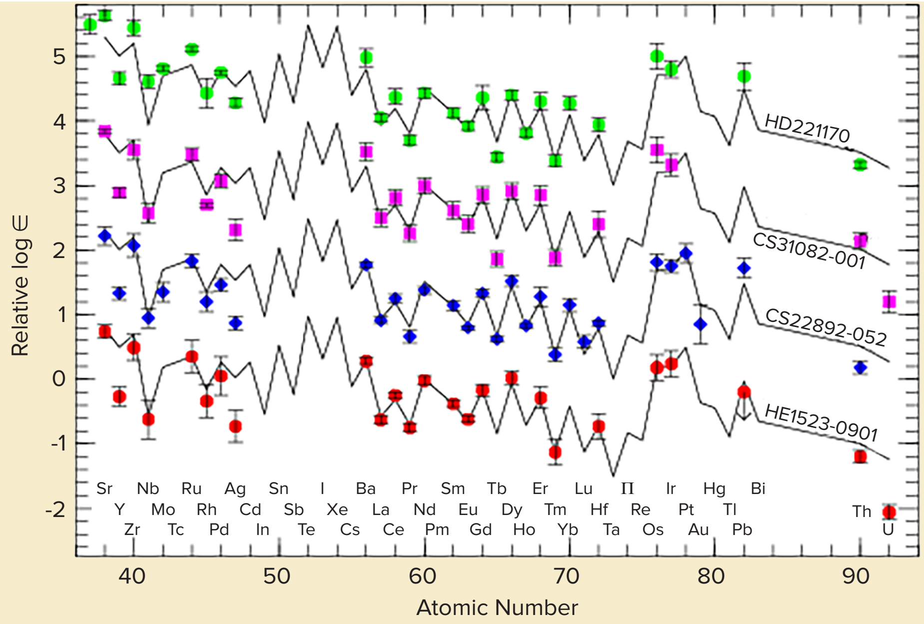
The 2015

LONG RANGE PLAN

for NUCLEAR SCIENCE



*Top and bottom left: Molecular dynamics simulations of nuclear pasta in a (100 fm)*$^3$ *cube containing 38,400 nucleons. The colors indicate the density of nuclear matter from blue (low) to brown (high). The neutron density (in fm*$^{-3}$*) is indicated. An average nuclear matter density is 0.16fm*$^{-3}$*. Bottom right: A model correlation between the neutron radius of* $^{208}$*Pb and the radius of a 1.4 solar-mass neutron star.*



*Abundance pattern of heavy elements in old, metal-poor stars compared to the relative solar r-process distribution (solid lines). The absolute scales have been chosen arbitrarily for better presentation. Image credit: Anna Frebel.*

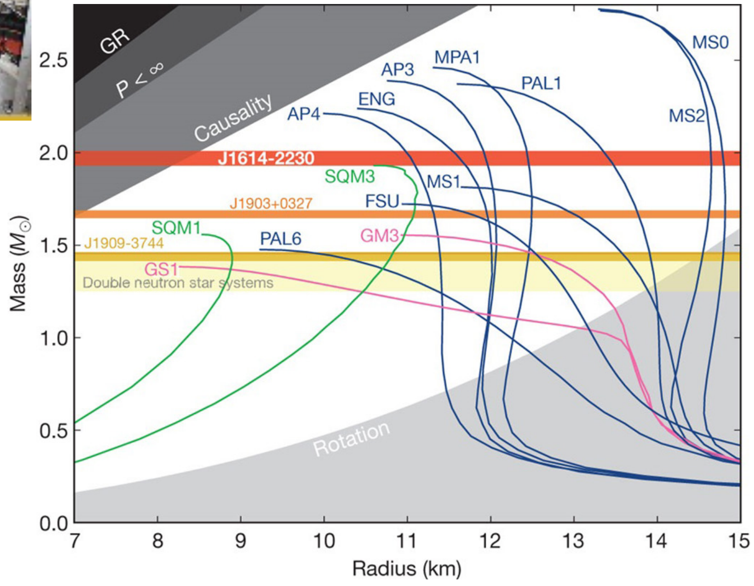
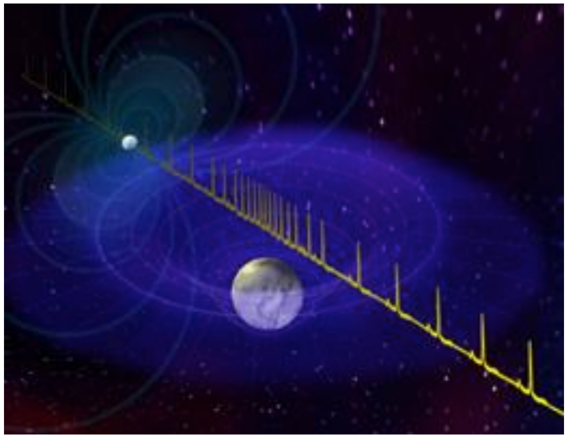
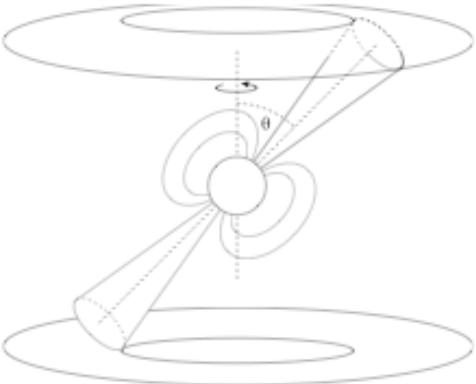


***Figure 4.3:*** *Astrophysical measurements of masses and radii of neutron stars can provide key insights into the equation of ultra-dense neutron star matter. Image credit: P.B. Demorest et al. Nature 467, 1081 (2010).*



# Pulsars



- Sources of periodic radio emission ($T$ = 0.001 - 1 s)
  - Example: Crab pulsar $T$ = 33 ms, $\omega$ = 190/s (1/trillion precision!)
  - Frequency slowing down slowly over time
  - Rotation? Requires $GM/R^2 > R\,\omega^2$ => assuming 1 solar mass => neutron star! $R < \sqrt[3]{\frac{GM}{\omega^2}} \approx 155\ \mathrm{km}$
  - Why so fast? Angular momentum conservation: $5 \cdot 10^4$ times smaller radius -> $25 \cdot 10^8$ times larger $\omega$ => from months to ms
  - Source of radio waves: rotating magnetic dipole of order $10^8$-$10^{10}$ T
  - Why so huge? 2 arguments:
    - field@surface $\propto$ magnetic moment/$R^3$ $\propto$ angular momentum (conserved)
    - $-d\Phi/dt$ = EMF, Lenz' law, plenty of free charges (plasma) -> $\Phi$ remains constant during collapse -> $B$ increases like $1/R^2$