



# The Explosive Death of Stars & The Birth of a New Astronomy

The 2013 Squire Lecture

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**Galaxy NGC 4526, Virgo constellation**

Distance: ~55 million lightyears



**Supernova!**  
**(SN 1994D)**

## Galaxy NGC 4526, Virgo constellation

Distance: ~55 million lightyears

- >1 Supernova per second in the Universe
- ~1 Supernova discovered per day
- ~1 Supernova per 50-100 years in the Milky Way



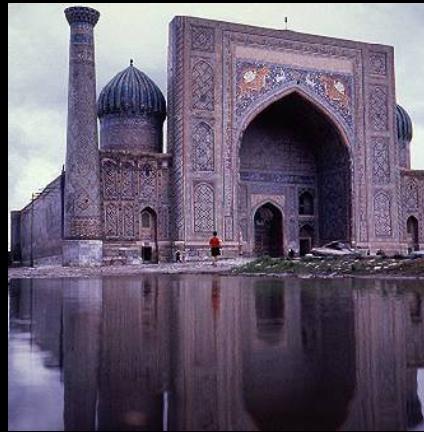
Supernova!  
(SN 1994D)

# Historic Supernovae in the Milky Way

## Records of Ancient & Medieval Astronomers



China: Gaocheng Observatory



Ulugh Beg Observatory,  
Samarkand, Uzbekistan



China: SNe 185, 369, 386, 393, 1006, 1054, 1181

Arabic/Persian: SNe 1006, 1054

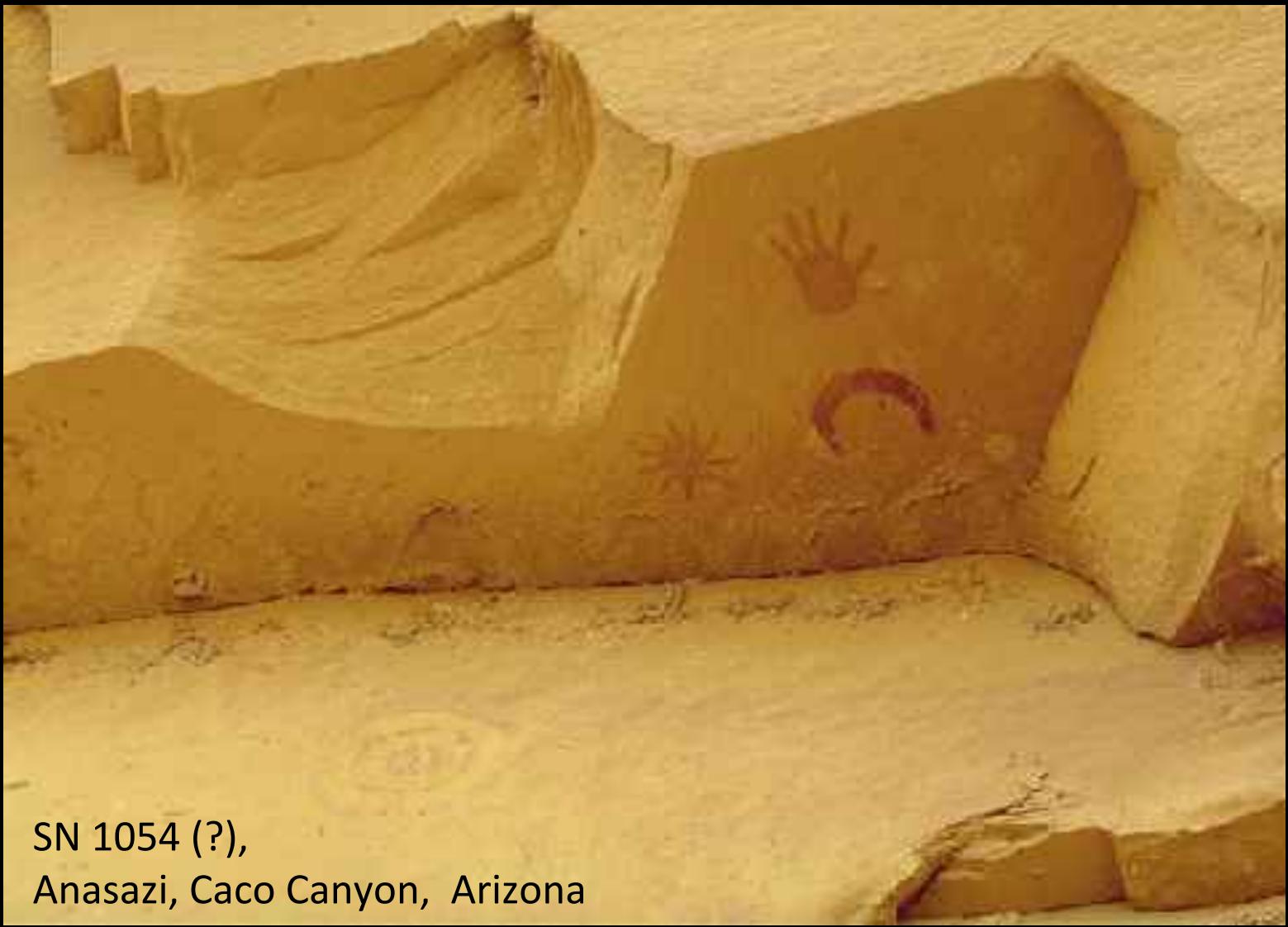
Japan: SNe 1006, 1054, 1181

Europe: SNe 1006, 1054

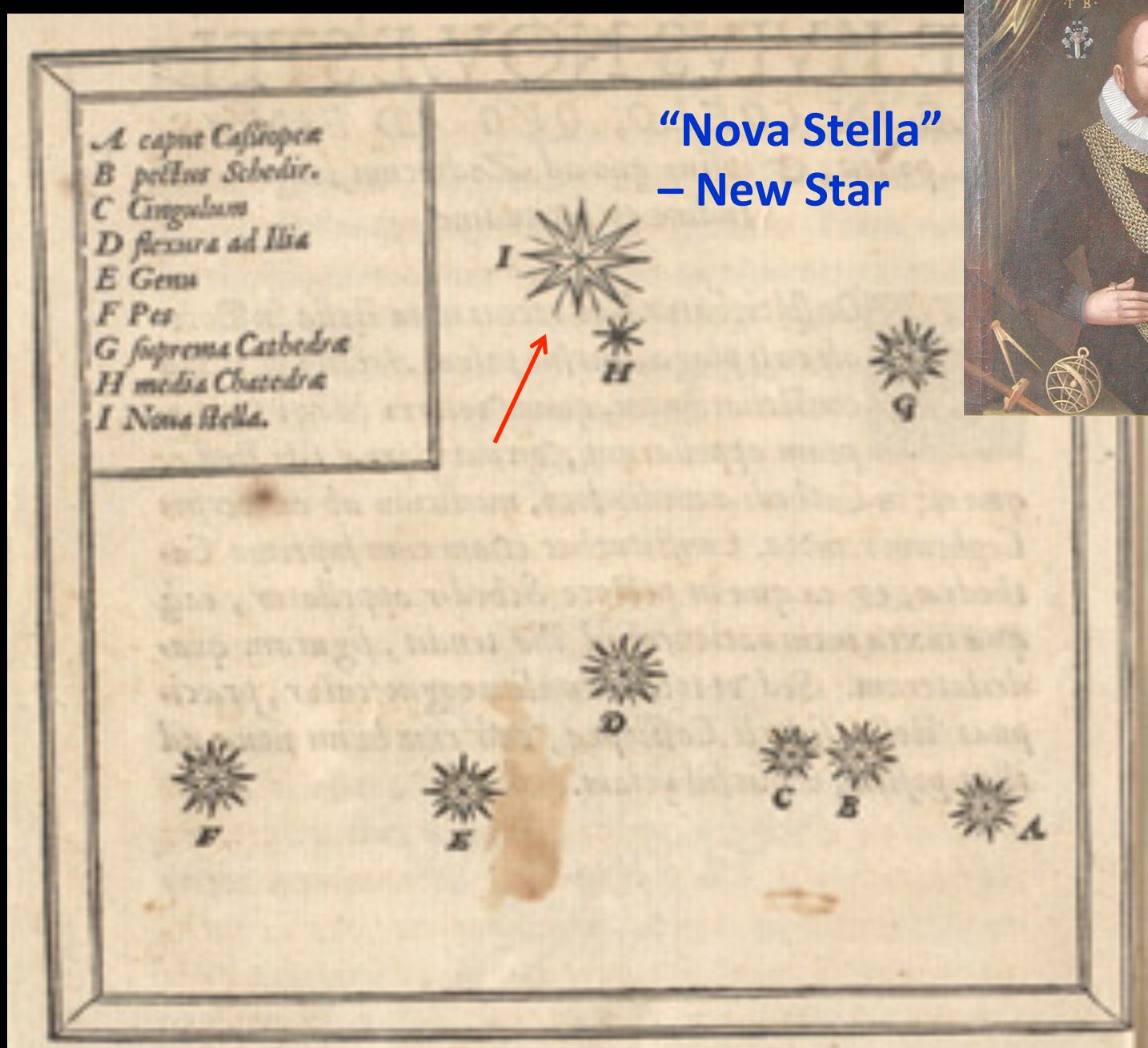


SN 1006:  
Brightest historical supernova –  
~15 x brighter than Venus  
~as bright as the crescent Moon.

Possible record of SN 1006 (?),  
Hohokam tribe, White Tank Mountains, Arizona



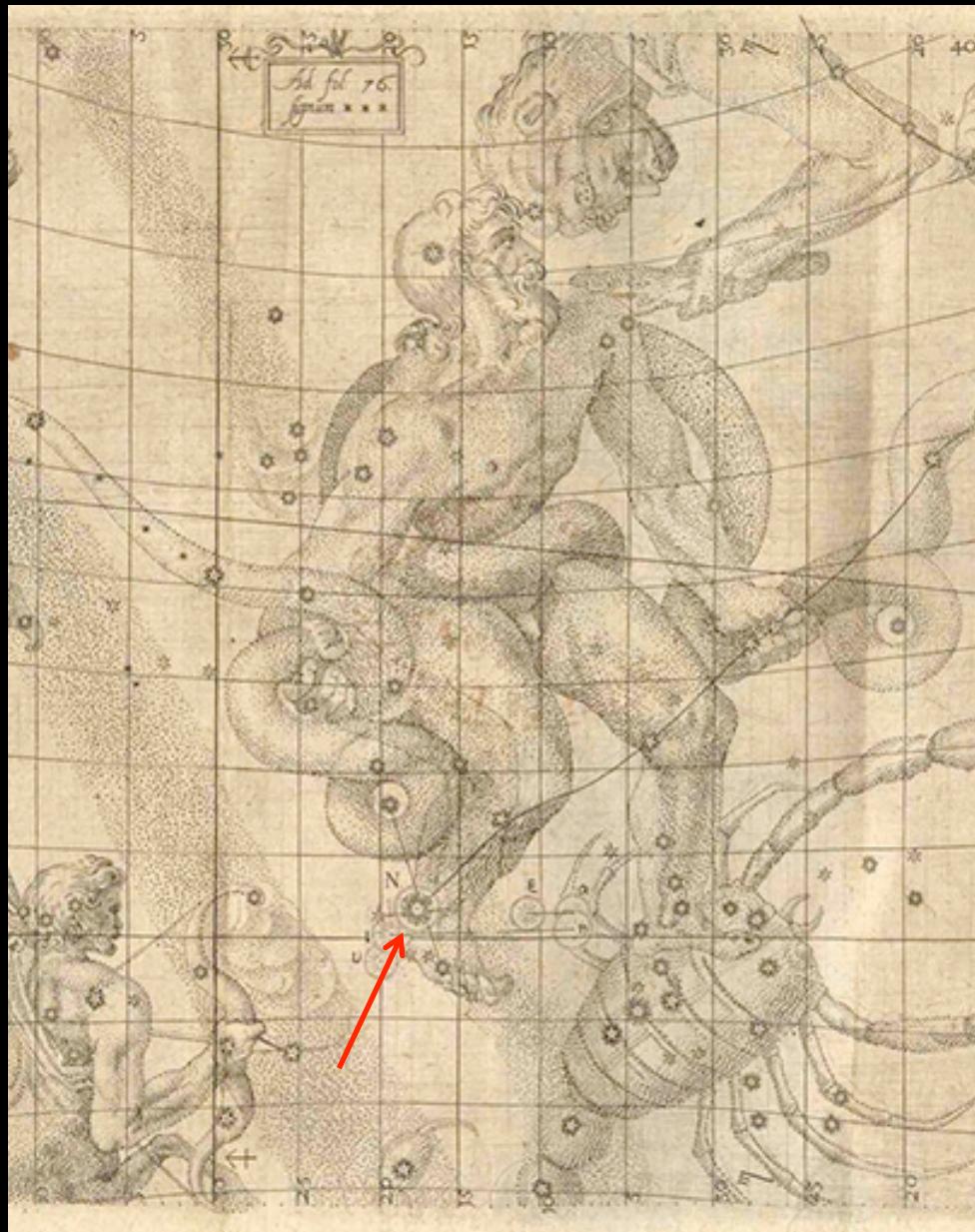
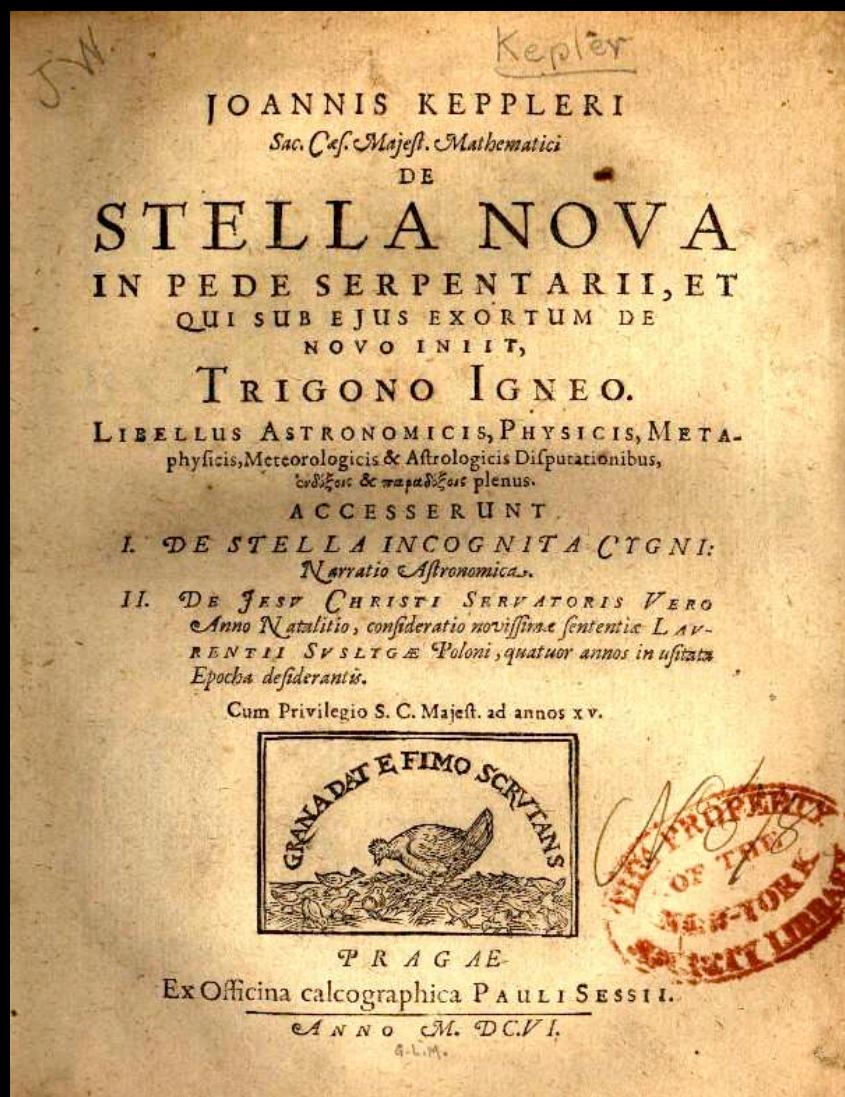
SN 1054 (?),  
Anasazi, Caco Canyon, Arizona



“Nova Stella”  
– New Star



Tycho Brahe (1572): „De Nova Stella“



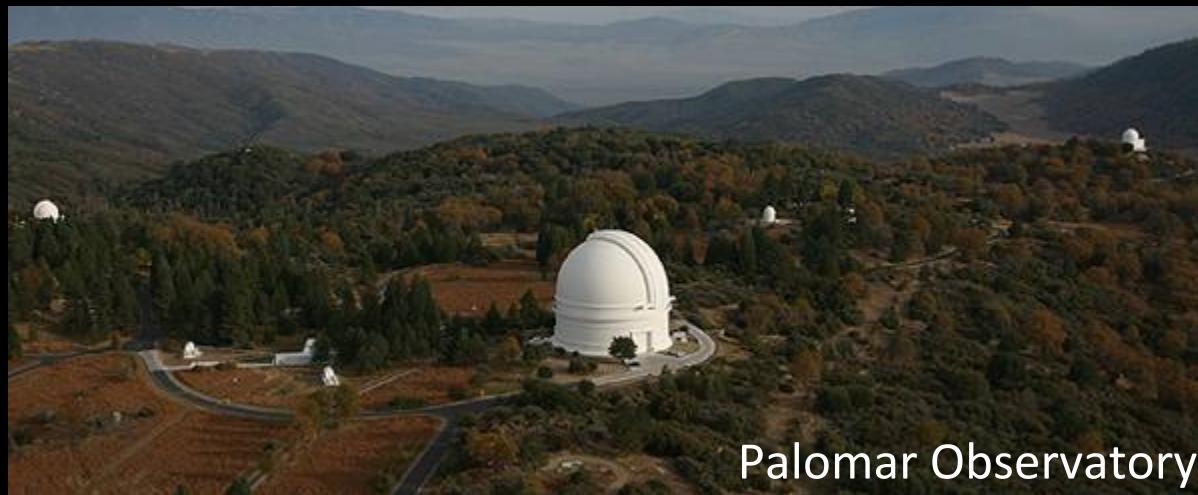
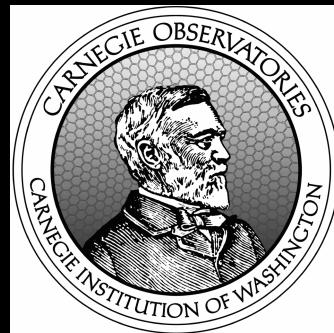
Johannes Kepler (1604): „De Stella Nova“

Mt. Wilson  
Observatory

Fritz Zwicky  
1898-1974



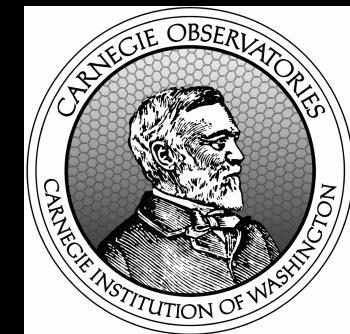
Walter Baade  
1893-1960



Palomar Observatory

Mt. Wilson  
Observatory

Fritz Zwicky  
1898-1974



Walter Baade  
1893-1960

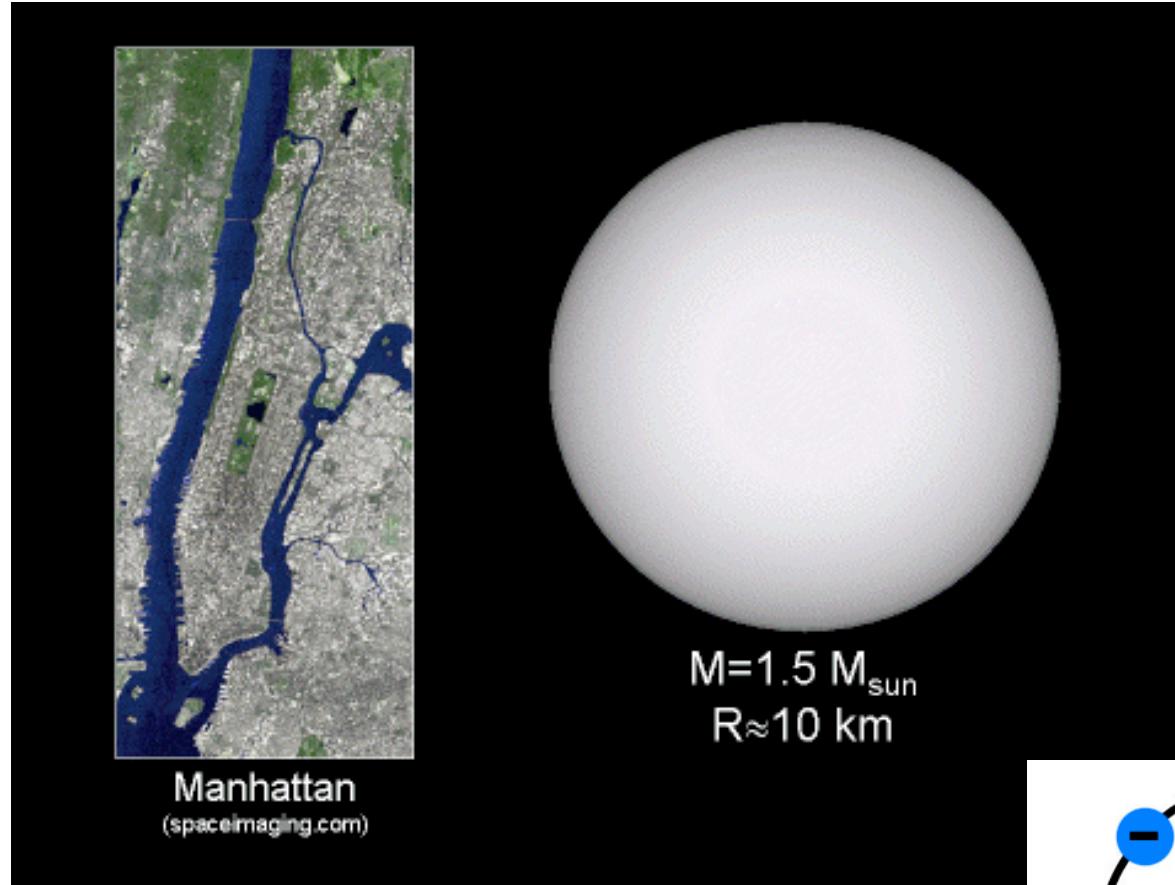
## “Supernova” (1934)

- There is a class of distant “nova stella” that is super-bright -> “supernova”
- **Postulate:** Supernovae come from stars that collapse (implode) to a “neutron star” and explosively eject their outer layers.

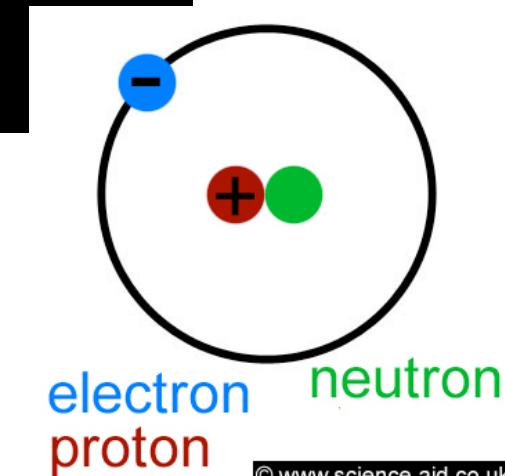


Palomar Observatory

# Neutron Stars

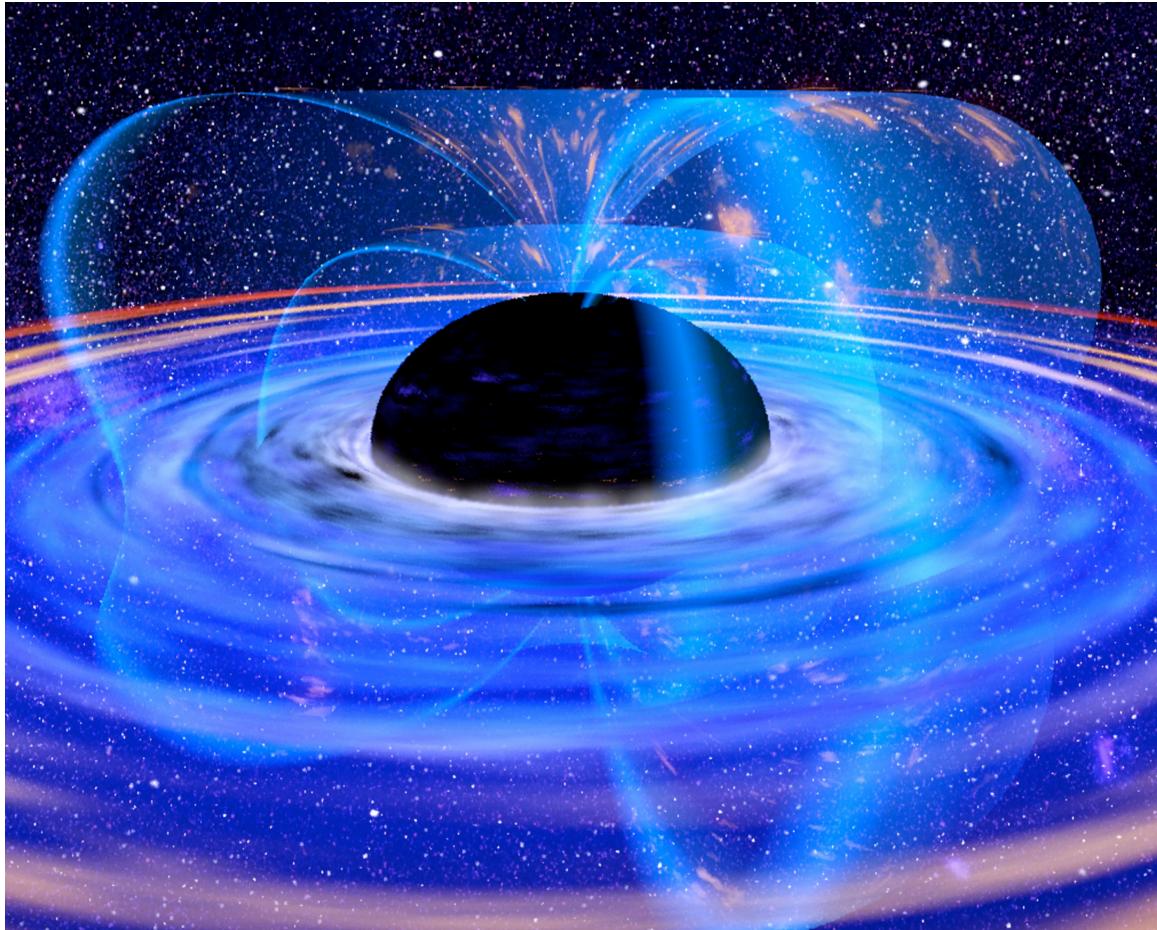


Hydrogen Atom:



- Density (Mass per volume) in a neutron star is  $\sim 10^{15} \text{ g/cm}^3$  (quadrillion times the density of water!)
  - Electrons get pushed into protons  $\rightarrow$  make neutrons
- $$p + e^- \longrightarrow n + \nu_e \quad (\nu_e = \text{"neutrino"})$$

# Black Holes

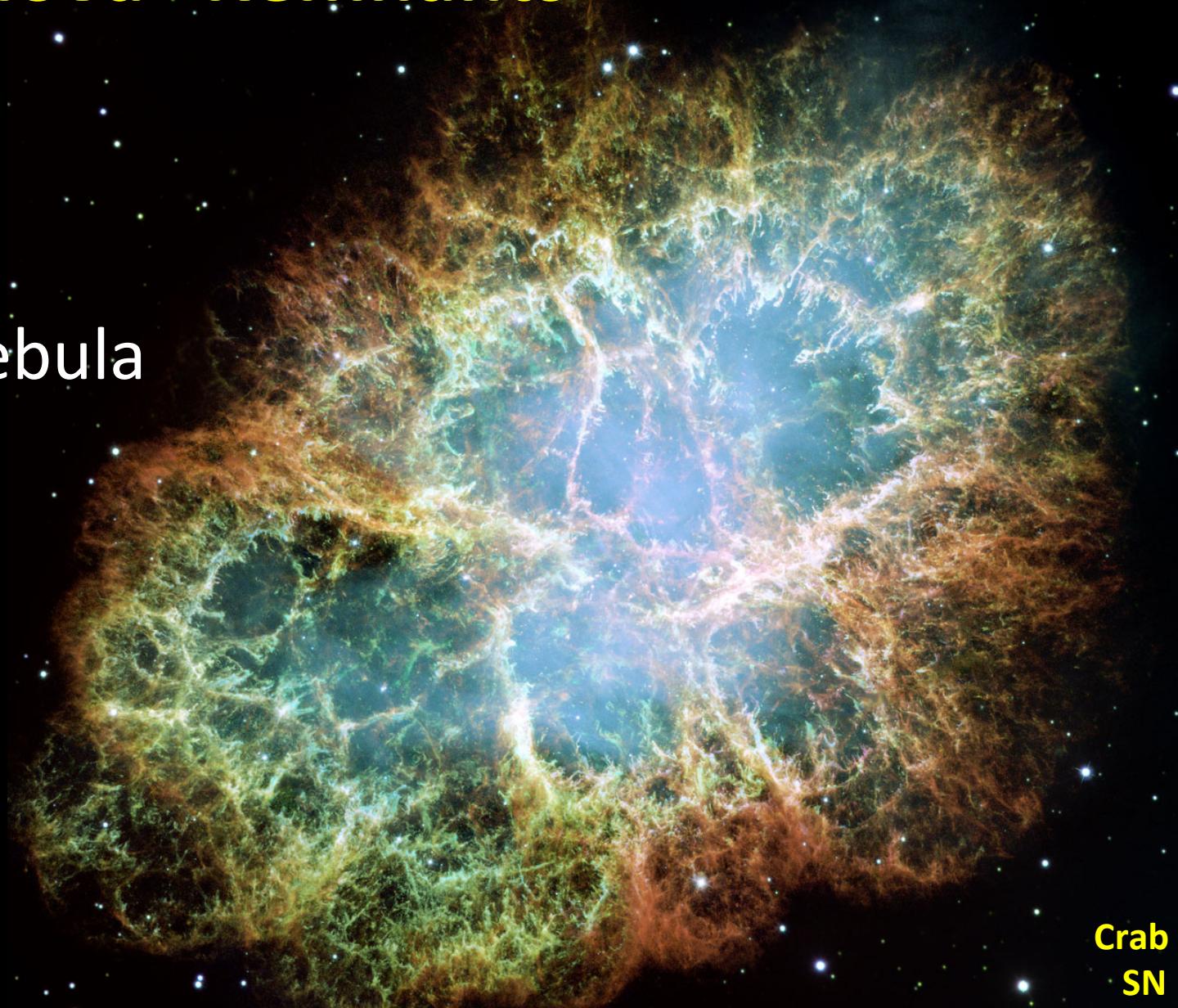


Wikipedia:  
Artist  
rendition of a  
black hole.

- When a neutron star gets too massive, it collapses to a black hole.
- Gravity in a black hole is so strong that not even light can escape.

# Supernova “Remnants”

Crab Nebula



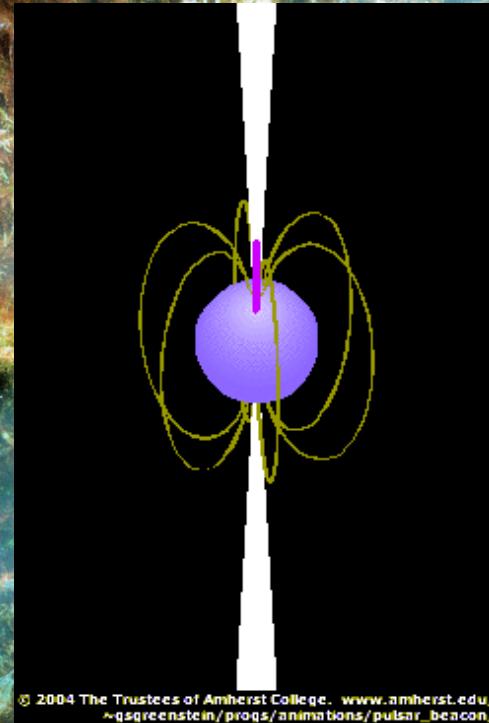
Crab SNR,  
SN 1054

Hubble Space Telescope/Chandra/Spitzer

# Pulsars:

## Radio-wave emitting neutron stars

1967: Discovery of  
Pulsars by Hewish & Bell  
Nobel 1974

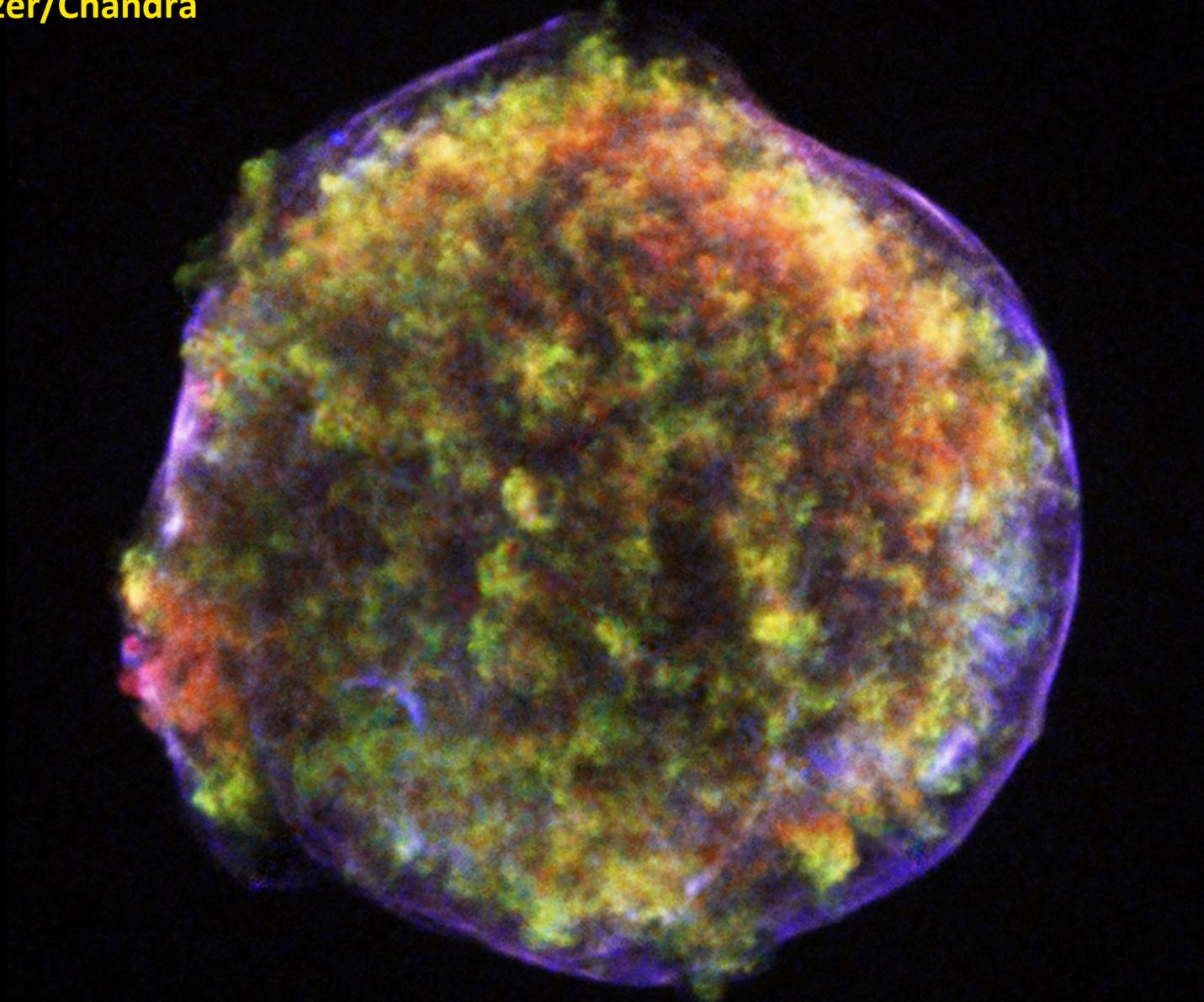


Hubble Space Telescope/Chandra/Spitzer

Crab SNR,  
SN 1054

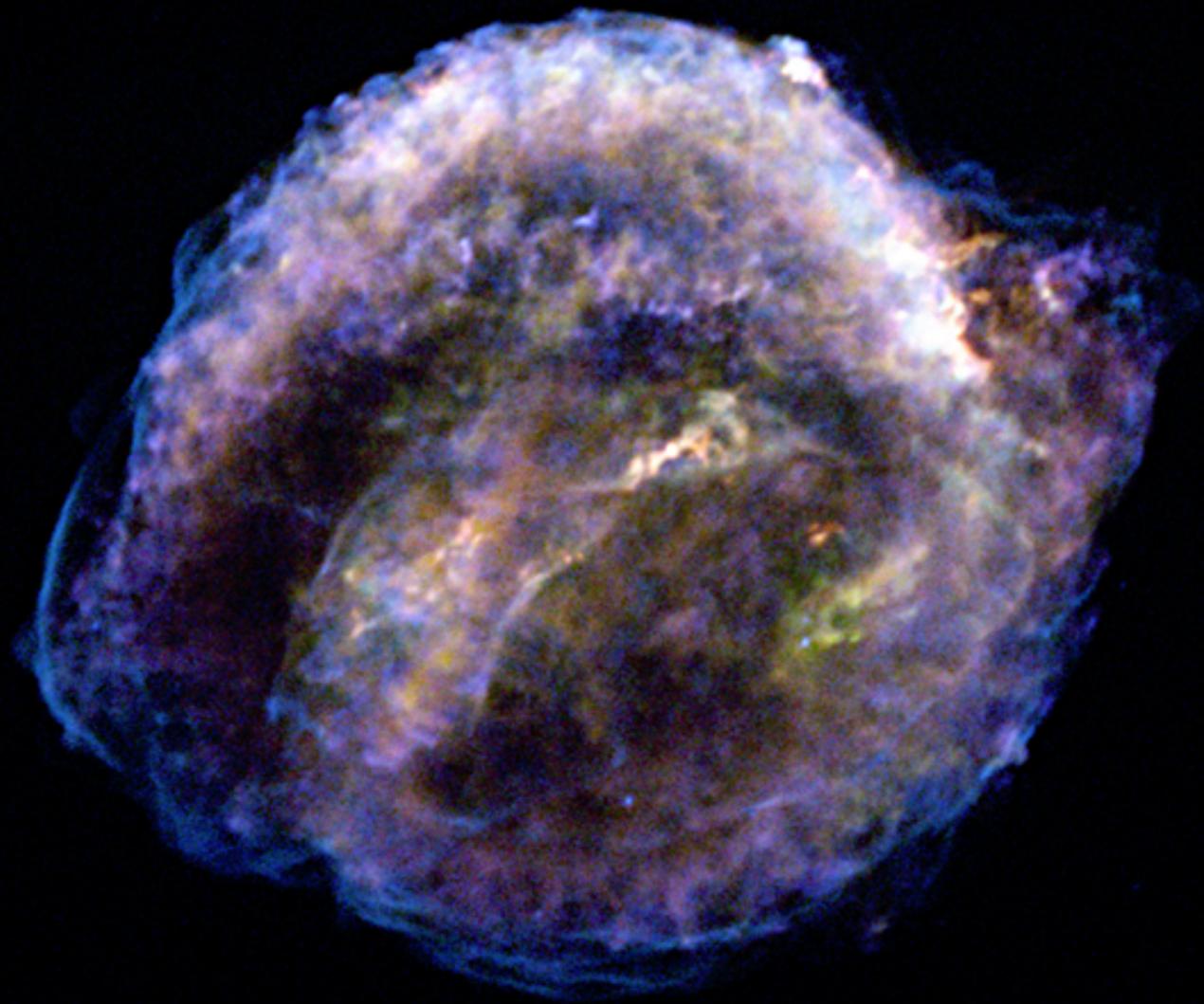
Tycho's SN 1572

NASA: Spitzer/Chandra



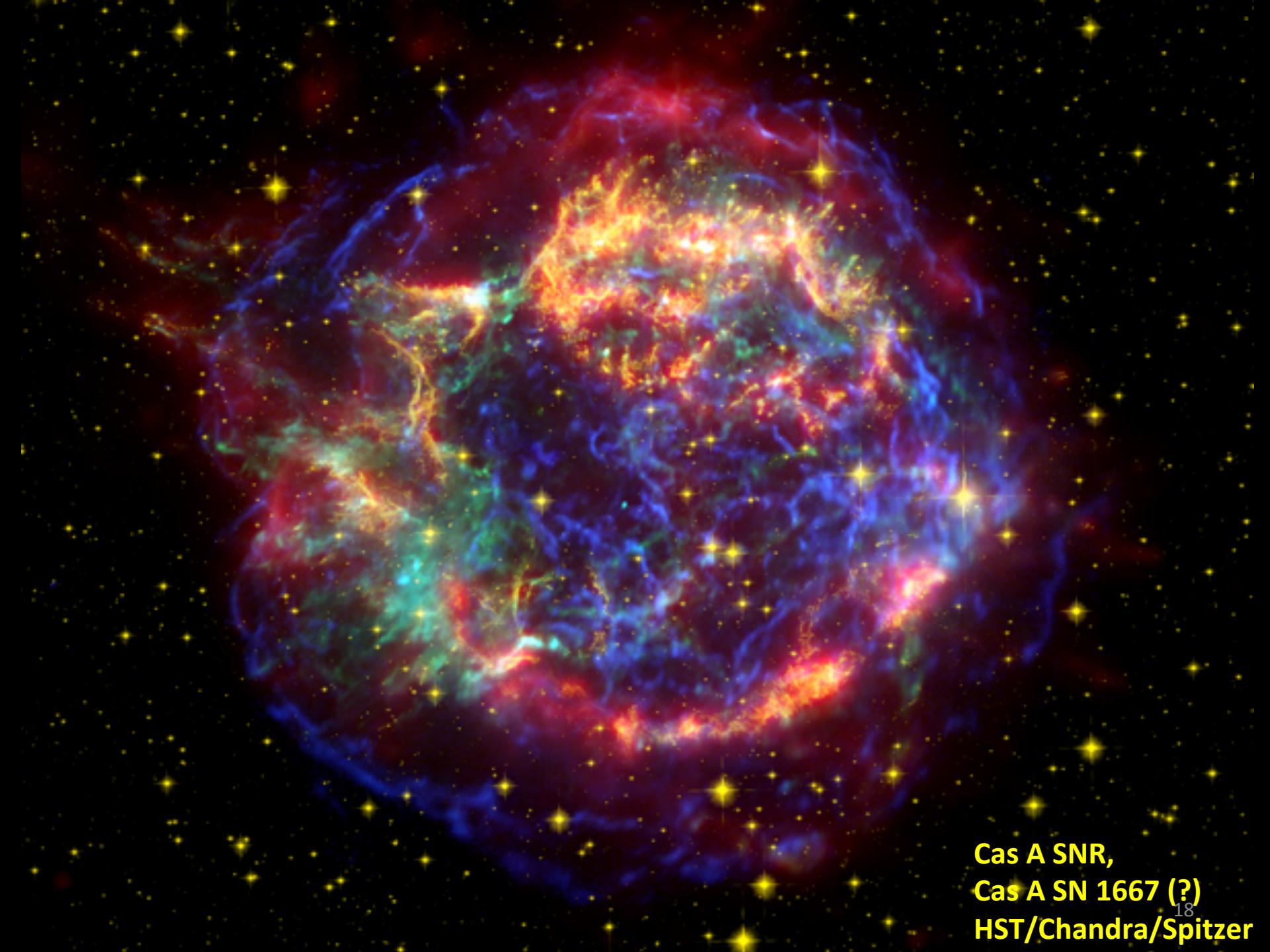
Kepler's SN 1604

NASA: Chandra Telescope



SN 1006



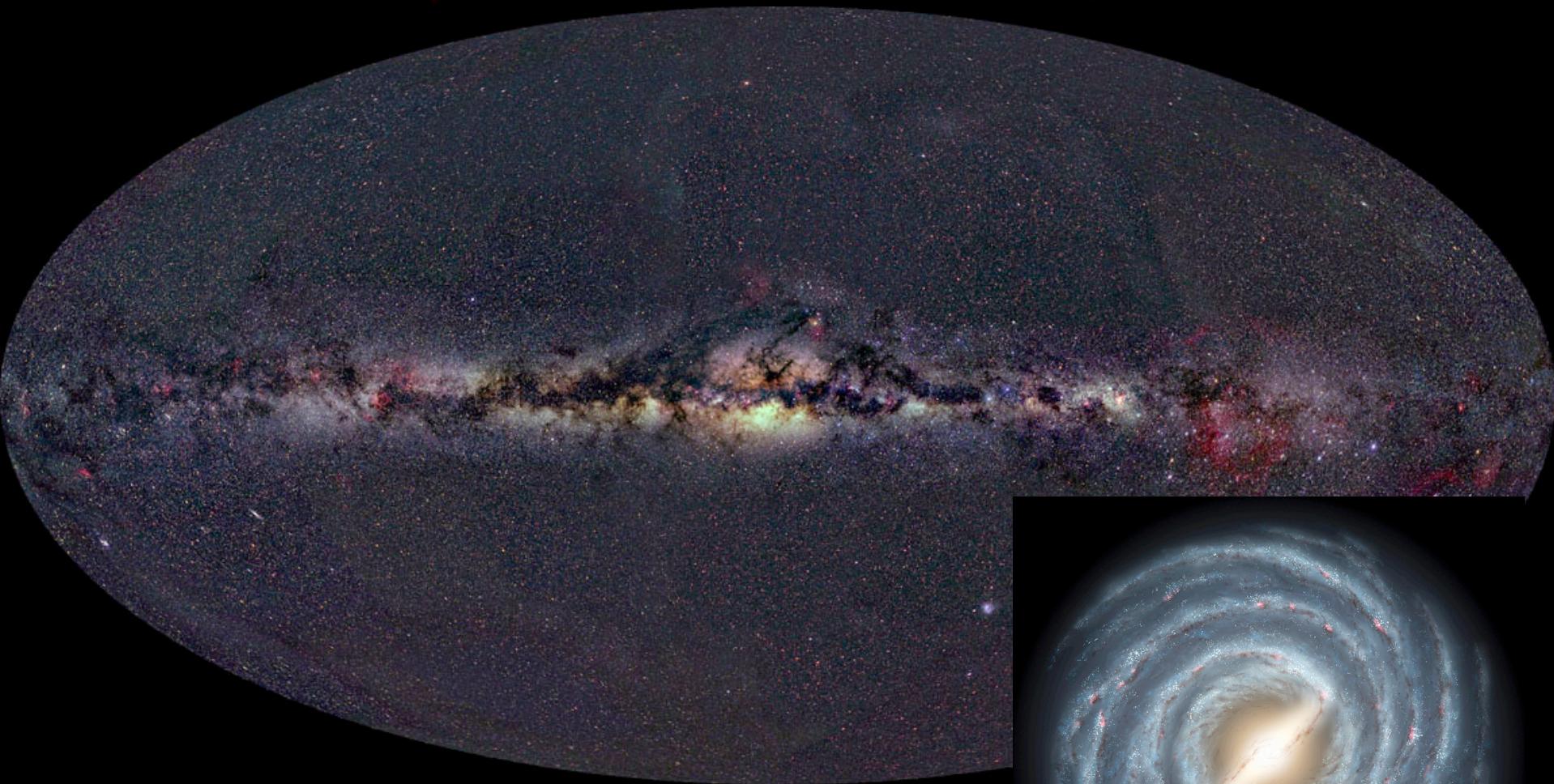


Cas A SNR,  
Cas A SN 1667 (?)  
<sup>18</sup>HST/Chandra/Spitzer

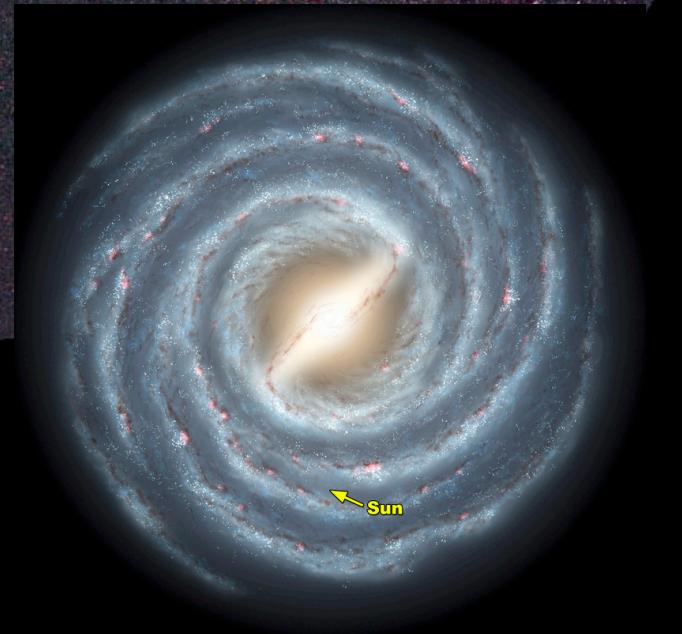


G1.9+0.3  
Explosion ~140 yrs ago.  
Near galactic center.

# “Dust” in the Milky Way



Dust absorbs visible light. Supernovae in the Milky Way often visible only in X-rays and Infrared radiation.





Magellanic clouds  
(visible in the southern hemisphere)



Rigel, D  $\approx$  800 ly

SN1987A, Large Magellanic Cloud

Progenitor star: Blue Supergiant star Sanduleak -69° 220a,  $18 M_{\text{Sun}}$

Also: First detection of neutrinos from a supernova.

# Why do we care about Supernovae?

# Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																																																																																																																																																																																																																																																																																																																																																																														
1 <b>H</b> Hydrogen 1.00794	2 <b>He</b> Helium 4.002602	3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182	5 <b>C</b> Solid	6 <b>Hg</b> Liquid	7 <b>H</b> Gas	8 <b>Alkali metals</b>	Metals	Lanthanoids	Transition metals	Poor metals	Other nonmetals	Noble gases	5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.0107	7 <b>N</b> Nitrogen 14.0067	8 <b>O</b> Oxygen 15.9994	9 <b>F</b> Fluorine 18.9984032	10 <b>Ne</b> Neon 20.1797																																																																																																																																																																																																																																																																																																																																																																												
11 <b>Na</b> Sodium 22.98976928	12 <b>Mg</b> Magnesium 24.3050	13 <b>Sc</b> Scandium 44.955912	14 <b>Ti</b> Titanium 47.887	15 <b>V</b> Vanadium 50.9415	16 <b>Cr</b> Chromium 51.9981	17 <b>Mn</b> Manganese 54.938045	18 <b>Fe</b> Iron 55.845	19 <b>Co</b> Cobalt 58.933195	20 <b>Ni</b> Nickel 58.6934	21 <b>Cu</b> Copper 63.546	22 <b>Zn</b> Zinc 65.38	23 <b>Ga</b> Gallium 69.723	24 <b>Ge</b> Germanium 72.64	25 <b>As</b> Arsenic 74.92160	26 <b>Se</b> Selenium 78.95	27 <b>Br</b> Bromine 79.904	28 <b>Kr</b> Krypton 83.798	29 <b>Rb</b> Rubidium 85.4576	30 <b>Sr</b> Strontium 87.62	31 <b>Y</b> Yttrium 88.90685	32 <b>Zr</b> Zirconium 91.224	33 <b>Nb</b> Niobium 92.90638	34 <b>Mo</b> Molybdenum 95.96	35 <b>Tc</b> Technetium (97.9072)	36 <b>Ru</b> Ruthenium 101.07	37 <b>Rh</b> Rhodium 102.90550	38 <b>Pd</b> Palladium 106.42	39 <b>Ag</b> Silver 107.8862	40 <b>Cd</b> Cadmium 112.411	41 <b>In</b> Indium 114.818	42 <b>Sn</b> Tin 118.710	43 <b>Sb</b> Antimony 121.760	44 <b>Te</b> Tellurium 127.60	45 <b>I</b> Iodine 126.90447	46 <b>Xe</b> Xenon 131.293	47 <b>Rb</b> Rubidium 85.4576	48 <b>Sr</b> Strontium 87.62	49 <b>Y</b> Yttrium 88.90685	50 <b>Zr</b> Zirconium 91.224	51 <b>Nb</b> Niobium 92.90638	52 <b>Mo</b> Molybdenum 95.96	53 <b>Tc</b> Technetium (97.9072)	54 <b>Ru</b> Ruthenium 101.07	55 <b>Rh</b> Rhodium 102.90550	56 <b>Pd</b> Palladium 106.42	57 <b>Ag</b> Silver 107.8862	58 <b>Cd</b> Cadmium 112.411	59 <b>In</b> Indium 114.818	60 <b>Sn</b> Tin 118.710	61 <b>Sb</b> Antimony 121.760	62 <b>Te</b> Tellurium 127.60	63 <b>I</b> Iodine 126.90447	64 <b>Xe</b> Xenon 131.293	65 <b>Rb</b> Rubidium 85.4576	66 <b>Sr</b> Strontium 87.62	67 <b>Y</b> Yttrium 88.90685	68 <b>Zr</b> Zirconium 91.224	69 <b>Nb</b> Niobium 92.90638	70 <b>Mo</b> Molybdenum 95.96	71 <b>Tc</b> Technetium (97.9072)	72 <b>Ru</b> Ruthenium 101.07	73 <b>Zr</b> Zirconium 91.224	74 <b>W</b> Tungsten 183.84	75 <b>Tc</b> Technetium (97.9072)	76 <b>Ru</b> Ruthenium 101.07	77 <b>Rh</b> Rhodium 102.90550	78 <b>Pd</b> Palladium 106.42	79 <b>Ag</b> Silver 107.8862	80 <b>Cd</b> Cadmium 112.411	81 <b>In</b> Indium 114.818	82 <b>Sn</b> Tin 118.710	83 <b>Sb</b> Antimony 121.760	84 <b>Te</b> Tellurium 127.60	85 <b>I</b> Iodine 126.90447	86 <b>Xe</b> Xenon 131.293	87 <b>Rb</b> Rubidium 85.4576	88 <b>Sr</b> Strontium 87.62	89 <b>Y</b> Yttrium 88.90685	90 <b>Zr</b> Zirconium 91.224	91 <b>Nb</b> Niobium 92.90638	92 <b>Mo</b> Molybdenum 95.96	93 <b>Tc</b> Technetium (97.9072)	94 <b>Ru</b> Ruthenium 101.07	95 <b>Rh</b> Rhodium 102.90550	96 <b>Pd</b> Palladium 106.42	97 <b>Ag</b> Silver 107.8862	98 <b>Cd</b> Cadmium 112.411	99 <b>In</b> Indium 114.818	100 <b>Sn</b> Tin 118.710	101 <b>Sb</b> Antimony 121.760	102 <b>Te</b> Tellurium 127.60	103 <b>I</b> Iodine 126.90447	104 <b>Xe</b> Xenon 131.293	105 <b>Rb</b> Rubidium 85.4576	106 <b>Sr</b> Strontium 87.62	107 <b>Y</b> Yttrium 88.90685	108 <b>Zr</b> Zirconium 91.224	109 <b>Nb</b> Niobium 92.90638	110 <b>Mo</b> Molybdenum 95.96	111 <b>Tc</b> Technetium (97.9072)	112 <b>Ru</b> Ruthenium 101.07	113 <b>Rh</b> Rhodium 102.90550	114 <b>Pd</b> Palladium 106.42	115 <b>Ag</b> Silver 107.8862	116 <b>Cd</b> Cadmium 112.411	117 <b>In</b> Indium 114.818	118 <b>Sn</b> Tin 118.710	119 <b>Sb</b> Antimony 121.760	120 <b>Te</b> Tellurium 127.60	121 <b>I</b> Iodine 126.90447	122 <b>Xe</b> Xenon 131.293	123 <b>Rb</b> Rubidium 85.4576	124 <b>Sr</b> Strontium 87.62	125 <b>Y</b> Yttrium 88.90685	126 <b>Zr</b> Zirconium 91.224	127 <b>Nb</b> Niobium 92.90638	128 <b>Mo</b> Molybdenum 95.96	129 <b>Tc</b> Technetium (97.9072)	130 <b>Ru</b> Ruthenium 101.07	131 <b>Rh</b> Rhodium 102.90550	132 <b>Pd</b> Palladium 106.42	133 <b>Ag</b> Silver 107.8862	134 <b>Cd</b> Cadmium 112.411	135 <b>In</b> Indium 114.818	136 <b>Sn</b> Tin 118.710	137 <b>Sb</b> Antimony 121.760	138 <b>Te</b> Tellurium 127.60	139 <b>I</b> Iodine 126.90447	140 <b>Xe</b> Xenon 131.293	141 <b>Rb</b> Rubidium 85.4576	142 <b>Sr</b> Strontium 87.62	143 <b>Y</b> Yttrium 88.90685	144 <b>Zr</b> Zirconium 91.224	145 <b>Nb</b> Niobium 92.90638	146 <b>Mo</b> Molybdenum 95.96	147 <b>Tc</b> Technetium (97.9072)	148 <b>Ru</b> Ruthenium 101.07	149 <b>Rh</b> Rhodium 102.90550	150 <b>Pd</b> Palladium 106.42	151 <b>Ag</b> Silver 107.8862	152 <b>Cd</b> Cadmium 112.411	153 <b>In</b> Indium 114.818	154 <b>Sn</b> Tin 118.710	155 <b>Sb</b> Antimony 121.760	156 <b>Te</b> Tellurium 127.60	157 <b>I</b> Iodine 126.90447	158 <b>Xe</b> Xenon 131.293	159 <b>Rb</b> Rubidium 85.4576	160 <b>Sr</b> Strontium 87.62	161 <b>Y</b> Yttrium 88.90685	162 <b>Zr</b> Zirconium 91.224	163 <b>Nb</b> Niobium 92.90638	164 <b>Mo</b> Molybdenum 95.96	165 <b>Tc</b> Technetium (97.9072)	166 <b>Ru</b> Ruthenium 101.07	167 <b>Rh</b> Rhodium 102.90550	168 <b>Pd</b> Palladium 106.42	169 <b>Ag</b> Silver 107.8862	170 <b>Cd</b> Cadmium 112.411	171 <b>In</b> Indium 114.818	172 <b>Sn</b> Tin 118.710	173 <b>Sb</b> Antimony 121.760	174 <b>Te</b> Tellurium 127.60	175 <b>I</b> Iodine 126.90447	176 <b>Xe</b> Xenon 131.293	177 <b>Rb</b> Rubidium 85.4576	178 <b>Sr</b> Strontium 87.62	179 <b>Y</b> Yttrium 88.90685	180 <b>Zr</b> Zirconium 91.224	181 <b>Nb</b> Niobium 92.90638	182 <b>Mo</b> Molybdenum 95.96	183 <b>Tc</b> Technetium (97.9072)	184 <b>Ru</b> Ruthenium 101.07	185 <b>Rh</b> Rhodium 102.90550	186 <b>Pd</b> Palladium 106.42	187 <b>Ag</b> Silver 107.8862	188 <b>Cd</b> Cadmium 112.411	189 <b>In</b> Indium 114.818	190 <b>Sn</b> Tin 118.710	191 <b>Sb</b> Antimony 121.760	192 <b>Te</b> Tellurium 127.60	193 <b>I</b> Iodine 126.90447	194 <b>Xe</b> Xenon 131.293	195 <b>Rb</b> Rubidium 85.4576	196 <b>Sr</b> Strontium 87.62	197 <b>Y</b> Yttrium 88.90685	198 <b>Zr</b> Zirconium 91.224	199 <b>Nb</b> Niobium 92.90638	200 <b>Mo</b> Molybdenum 95.96	201 <b>Tc</b> Technetium (97.9072)	202 <b>Ru</b> Ruthenium 101.07	203 <b>Rh</b> Rhodium 102.90550	204 <b>Pd</b> Palladium 106.42	205 <b>Ag</b> Silver 107.8862	206 <b>Cd</b> Cadmium 112.411	207 <b>In</b> Indium 114.818	208 <b>Sn</b> Tin 118.710	209 <b>Sb</b> Antimony 121.760	210 <b>Te</b> Tellurium 127.60	211 <b>I</b> Iodine 126.90447	212 <b>Xe</b> Xenon 131.293	213 <b>Rb</b> Rubidium 85.4576	214 <b>Sr</b> Strontium 87.62	215 <b>Y</b> Yttrium 88.90685	216 <b>Zr</b> Zirconium 91.224	217 <b>Nb</b> Niobium 92.90638	218 <b>Mo</b> Molybdenum 95.96	219 <b>Tc</b> Technetium (97.9072)	220 <b>Ru</b> Ruthenium 101.07	221 <b>Rh</b> Rhodium 102.90550	222 <b>Pd</b> Palladium 106.42	223 <b>Ag</b> Silver 107.8862	224 <b>Cd</b> Cadmium 112.411	225 <b>In</b> Indium 114.818	226 <b>Sn</b> Tin 118.710	227 <b>Sb</b> Antimony 121.760	228 <b>Te</b> Tellurium 127.60	229 <b>I</b> Iodine 126.90447	230 <b>Xe</b> Xenon 131.293	231 <b>Rb</b> Rubidium 85.4576	232 <b>Sr</b> Strontium 87.62	233 <b>Y</b> Yttrium 88.90685	234 <b>Zr</b> Zirconium 91.224	235 <b>Nb</b> Niobium 92.90638	236 <b>Mo</b> Molybdenum 95.96	237 <b>Tc</b> Technetium (97.9072)	238 <b>Ru</b> Ruthenium 101.07	239 <b>Rh</b> Rhodium 102.90550	240 <b>Pd</b> Palladium 106.42	241 <b>Ag</b> Silver 107.8862	242 <b>Cd</b> Cadmium 112.411	243 <b>In</b> Indium 114.818	244 <b>Sn</b> Tin 118.710	245 <b>Sb</b> Antimony 121.760	246 <b>Te</b> Tellurium 127.60	247 <b>I</b> Iodine 126.90447	248 <b>Xe</b> Xenon 131.293	249 <b>Rb</b> Rubidium 85.4576	250 <b>Sr</b> Strontium 87.62	251 <b>Y</b> Yttrium 88.90685	252 <b>Zr</b> Zirconium 91.224	253 <b>Nb</b> Niobium 92.90638	254 <b>Mo</b> Molybdenum 95.96	255 <b>Tc</b> Technetium (97.9072)	256 <b>Ru</b> Ruthenium 101.07	257 <b>Rh</b> Rhodium 102.90550	258 <b>Pd</b> Palladium 106.42	259 <b>Ag</b> Silver 107.8862	260 <b>Cd</b> Cadmium 112.411	261 <b>In</b> Indium 114.818	262 <b>Sn</b> Tin 118.710	263 <b>Sb</b> Antimony 121.760	264 <b>Te</b> Tellurium 127.60	265 <b>I</b> Iodine 126.90447	266 <b>Xe</b> Xenon 131.293	267 <b>Rb</b> Rubidium 85.4576	268 <b>Sr</b> Strontium 87.62	269 <b>Y</b> Yttrium 88.90685	270 <b>Zr</b> Zirconium 91.224	271 <b>Nb</b> Niobium 92.90638	272 <b>Mo</b> Molybdenum 95.96	273 <b>Tc</b> Technetium (97.9072)	274 <b>Ru</b> Ruthenium 101.07	275 <b>Rh</b> Rhodium 102.90550	276 <b>Pd</b> Palladium 106.42	277 <b>Ag</b> Silver 107.8862	278 <b>Cd</b> Cadmium 112.411	279 <b>In</b> Indium 114.818	280 <b>Sn</b> Tin 118.710	281 <b>Sb</b> Antimony 121.760	282 <b>Te</b> Tellurium 127.60	283 <b>I</b> Iodine 126.90447	284 <b>Xe</b> Xenon 131.293	285 <b>Rb</b> Rubidium 85.4576	286 <b>Sr</b> Strontium 87.62	287 <b>Y</b> Yttrium 88.90685	288 <b>Zr</b> Zirconium 91.224	289 <b>Nb</b> Niobium 92.90638	290 <b>Mo</b> Molybdenum 95.96	291 <b>Tc</b> Technetium (97.9072)	292 <b>Ru</b> Ruthenium 101.07	293 <b>Rh</b> Rhodium 102.90550	294 <b>Pd</b> Palladium 106.42	295 <b>Ag</b> Silver 107.8862	296 <b>Cd</b> Cadmium 112.411	297 <b>In</b> Indium 114.818	298 <b>Sn</b> Tin 118.710	299 <b>Sb</b> Antimony 121.760	300 <b>Te</b> Tellurium 127.60	301 <b>I</b> Iodine 126.90447	302 <b>Xe</b> Xenon 131.293	303 <b>Rb</b> Rubidium 85.4576	304 <b>Sr</b> Strontium 87.62	305 <b>Y</b> Yttrium 88.90685	306 <b>Zr</b> Zirconium 91.224	307 <b>Nb</b> Niobium 92.90638	308 <b>Mo</b> Molybdenum 95.96	309 <b>Tc</b> Technetium (97.9072)	310 <b>Ru</b> Ruthenium 101.07	311 <b>Rh</b> Rhodium 102.90550	312 <b>Pd</b> Palladium 106.42	313 <b>Ag</b> Silver 107.8862	314 <b>Cd</b> Cadmium 112.411	315 <b>In</b> Indium 114.818	316 <b>Sn</b> Tin 118.710	317 <b>Sb</b> Antimony 121.760	318 <b>Te</b> Tellurium 127.60	319 <b>I</b> Iodine 126.90447	320 <b>Xe</b> Xenon 131.293	321 <b>Rb</b> Rubidium 85.4576	322 <b>Sr</b> Strontium 87.62	323 <b>Y</b> Yttrium 88.90685	324 <b>Zr</b> Zirconium 91.224	325 <b>Nb</b> Niobium 92.90638	326 <b>Mo</b> Molybdenum 95.96	327 <b>Tc</b> Technetium (97.9072)	328 <b>Ru</b> Ruthenium 101.07	329 <b>Rh</b> Rhodium 102.90550	330 <b>Pd</b> Palladium 106.42	331 <b>Ag</b> Silver 107.8862	332 <b>Cd</b> Cadmium 112.411	333 <b>In</b> Indium 114.818	334 <b>Sn</b> Tin 118.710	335 <b>Sb</b> Antimony 121.760	336 <b>Te</b> Tellurium 127.60	337 <b>I</b> Iodine 126.90447	338 <b>Xe</b> Xenon 131.293	339 <b>Rb</b> Rubidium 85.4576	340 <b>Sr</b> Strontium 87.62	341 <b>Y</b> Yttrium 88.90685	342 <b>Zr</b> Zirconium 91.224	343 <b>Nb</b> Niobium 92.90638	344 <b>Mo</b> Molybdenum 95.96	345 <b>Tc</b> Technetium (97.9072)	346 <b>Ru</b> Ruthenium 101.07	347 <b>Rh</b> Rhodium 102.90550	348 <b>Pd</b> Palladium 106.42	349 <b>Ag</b> Silver 107.8862	350 <b>Cd</b> Cadmium 112.411	351 <b>In</b> Indium 114.818	352 <b>Sn</b> Tin 118.710	353 <b>Sb</b> Antimony 121.760	354 <b>Te</b> Tellurium 127.60	355 <b>I</b> Iodine 126.90447	356 <b>Xe</b> Xenon 131.293	357 <b>Rb</b> Rubidium 85.4576	358 <b>Sr</b> Strontium 87.62	359 <b>Y</b> Yttrium 88.90685	360 <b>Zr</b> Zirconium 91.224	361 <b>Nb</b> Niobium 92.90638	362 <b>Mo</b> Molybdenum 95.96	363 <b>Tc</b> Technetium (97.9072)	364 <b>Ru</b> Ruthenium 101.07	365 <b>Rh</b> Rhodium 102.90550	366 <b>Pd</b> Palladium 106.42	367 <b>Ag</b> Silver 107.8862	368 <b>Cd</b> Cadmium 112.411	369 <b>In</b> Indium 114.818	370 <b>Sn</b> Tin 118.710	371 <b>Sb</b> Antimony 121.760	372 <b>Te</b> Tellurium 127.60	373 <b>I</b> Iodine 126.90447	374 <b>Xe</b> Xenon 131.293	375 <b>Rb</b> Rubidium 85.4576	376 <b>Sr</b> Strontium 87.62	377 <b>Y</b> Yttrium 88.90685	378 <b>Zr</b> Zirconium 91.224	379 <b>Nb</b> Niobium 92.90638	380 <b>Mo</b> Molybdenum 95.96	381 <b>Tc</b> Technetium (97.9072)	382 <b>Ru</b> Ruthenium 101.07	383 <b>Rh</b> Rhodium 102.90550	384 <b>Pd</b> Palladium 106.42	385 <b>Ag</b> Silver 107.8862	386 <b>Cd</b> Cadmium 112.411	387 <b>In</b> Indium 114.818	388 <b>Sn</b> Tin 118.710	389 <b>Sb</b> Antimony 121.760	390 <b>Te</b> Tellurium 127.60	391 <b>I</b> Iodine 126.90447	392 <b>Xe</b> Xenon 131.293	393 <b>Rb</b> Rubidium 85.4576	394 <b>Sr</b> Strontium 

# Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18			
1 <b>H</b> Hydrogen 1.00794	2 <b>He</b> Helium 4.002602	3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182	5 <b>Na</b> Sodium 22.98976928	6 <b>Mg</b> Magnesium 24.3050	7 <b>C</b> Solid	8 <b>Hg</b> Liquid	9 <b>H</b> Gas	10 <b>Rf</b> Unknown	11 Metals	12 Nonmetals	13 Metals	14 Nonmetals	15 Metals	16 Nonmetals	17 Metals	18 Nonmetals			
1 <b>Li</b> Lithium 6.941	2 <b>He</b> Helium 4.002602	3 <b>Na</b> Sodium 22.98976928	4 <b>Be</b> Beryllium 9.012182	5 <b>Sc</b> Scandium 44.955912	6 <b>Ti</b> Titanium 47.887	7 <b>V</b> Vanadium 50.9415	8 <b>Cr</b> Chromium 51.9981	9 <b>Mn</b> Manganese 54.9386	10 <b>B</b> Boron 10.811	11 <b>C</b> Carbon 12.0107	12 <b>N</b> Nitrogen 14.0067	13 <b>O</b> Oxygen 15.9994	14 <b>F</b> Fluorine 18.9984032	15 <b>Ne</b> Neon 20.1797	16 <b>Ar</b> Argon 39.949	17 <b>K</b> Potassium 39.0983	18 <b>Ca</b> Calcium 40.078			
2 <b>Rb</b> Rubidium 85.4676	3 <b>Sr</b> Strontium 87.62	4 <b>Y</b> Yttrium 88.90585	5 <b>Zr</b> Zirconium 91.224	6 <b>Nb</b> Niobium 92.90638	7 <b>Mo</b> Molybdenum 95.96	8 <b>Tc</b> Technetium (97.907)	9 <b>Hf</b> Hafnium 178.49	10 <b>Ta</b> Tantalum 180.94788	11 <b>W</b> Tungsten 183.84	12 <b>Re</b> Rhenium 186.201	13 <b>Fr</b> Francium (223)	14 <b>Ra</b> Radium (226)	15 <b>Ac</b> Actinium (227)	16 <b>Ce</b> Cerium 140.116	17 <b>Pr</b> Praseodymium 140.90765	18 <b>Nd</b> Neodymium 144.242				
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.955912	22 <b>Ti</b> Titanium 47.887	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9981	25 <b>Mn</b> Manganese 54.9386	26 <b>Y</b> Yttrium 88.90585	27 <b>Zr</b> Zirconium 91.224	28 <b>Nb</b> Niobium 92.90638	29 <b>Mo</b> Molybdenum 95.96	30 <b>Tc</b> Technetium (97.907)	31 <b>Hf</b> Hafnium 178.49	32 <b>Ta</b> Tantalum 180.94788	33 <b>W</b> Tungsten 183.84	34 <b>Re</b> Rhenium 186.201	35 <b>Fr</b> Francium (223)	36 <b>Ra</b> Radium (226)			
37 <b>Rb</b> Rubidium 85.4676	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.96	43 <b>Tc</b> Technetium (97.907)	44 <b>Hf</b> Hafnium 178.49	45 <b>Ta</b> Tantalum 180.94788	46 <b>W</b> Tungsten 183.84	47 <b>Re</b> Rhenium 186.201	48 <b>Fr</b> Francium (223)	49 <b>Ra</b> Radium (226)	50 <b>Ac</b> Actinium (227)	51 <b>Ce</b> Cerium 140.116	52 <b>Pr</b> Praseodymium 140.90765	53 <b>Nd</b> Neodymium 144.242				
55 <b>Cs</b> Caesium 132.9054519	56 <b>Ba</b> Barium 137.327	57-71 89-103	58 <b>La</b> Lanthanum 138.90547	59 <b>Ce</b> Cerium 140.116	60 <b>Pr</b> Praseodymium 140.90765	61 <b>Nd</b> Neodymium 144.242	62 <b>Th</b> Thorium 232.03806	63 <b>Pa</b> Protactinium 231.03588	64 <b>U</b> Uranium 238.02891	65 <b>Np</b> Neptunium (237)	66 <b>Pu</b> Plutonium (244)	67 <b>Am</b> Americium (243)	68 <b>Cm</b> Curium (247)	69 <b>Bk</b> Berkelium (247)	70 <b>Cf</b> Californium (251)	71 <b>Es</b> Einsteinium (252)	72 <b>Fm</b> Fermium (257)	73 <b>Md</b> Mendelevium (258)	74 <b>No</b> Nobelium (259)	75 <b>Lr</b> Lawrencium (262)
For elements with no Design and Int																				

Made in the Big Bang

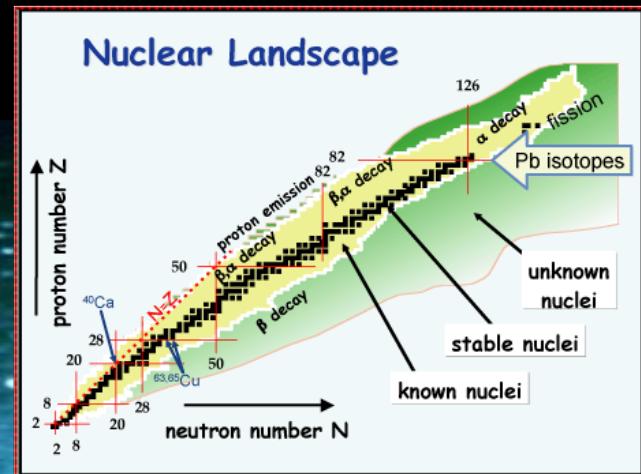
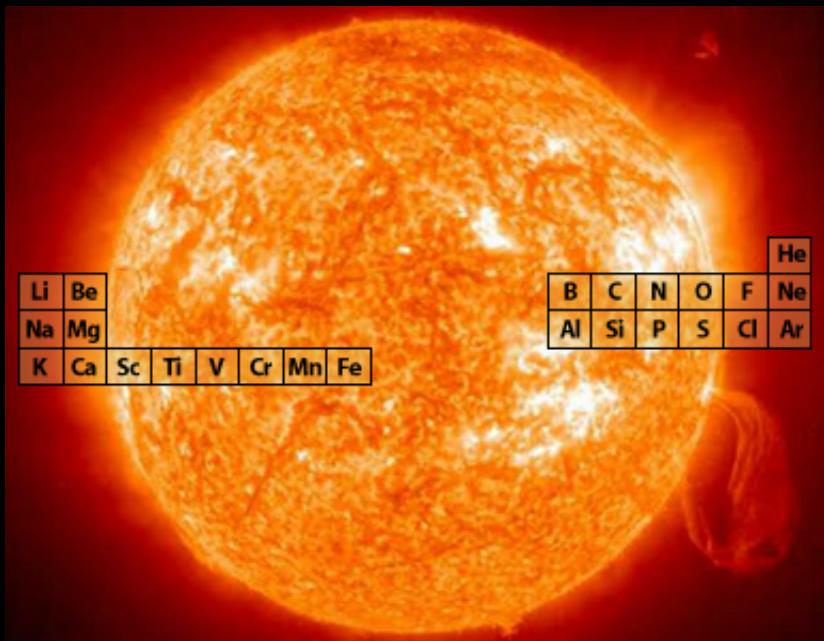
Distribution in the Universe:

Hydrogen	73,90%
Helium	24,00%
Oxygen	1.04%
Carbon	0.46%
Neon	0.13%
Iron	0.11%
Nitrogen	0.09%
Silicon	0.06%
Magnesium	0.06%
Sulfur	0.04%
others	0.11%

Thermonuclear fusion in  
Stars / Supernovae

# Why do we care about Supernovae?

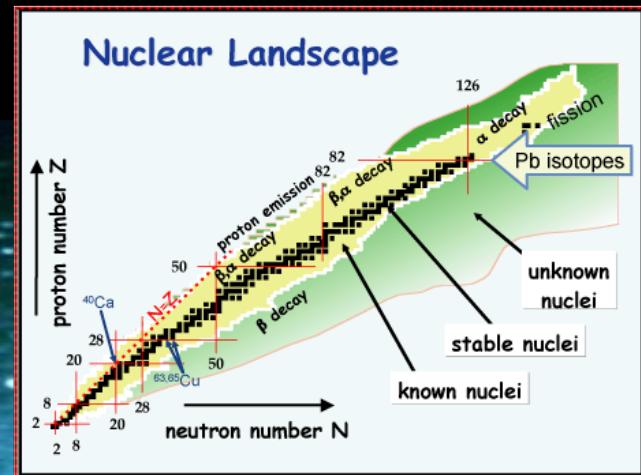
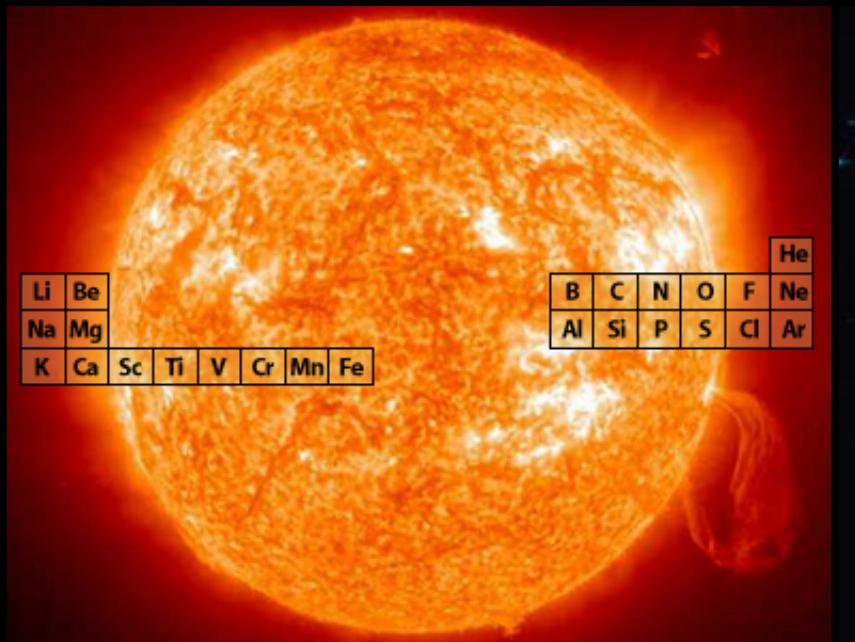
- SNe are the main cosmic polluters.



Source: NASA

# Why do we care about Supernovae?

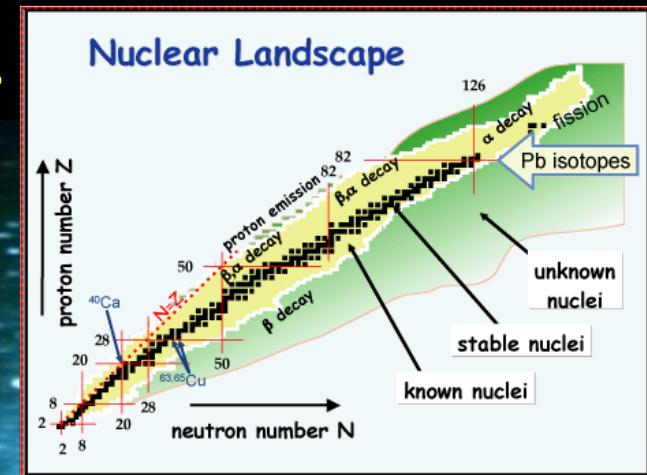
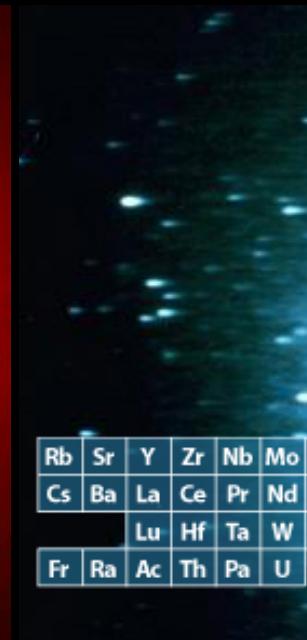
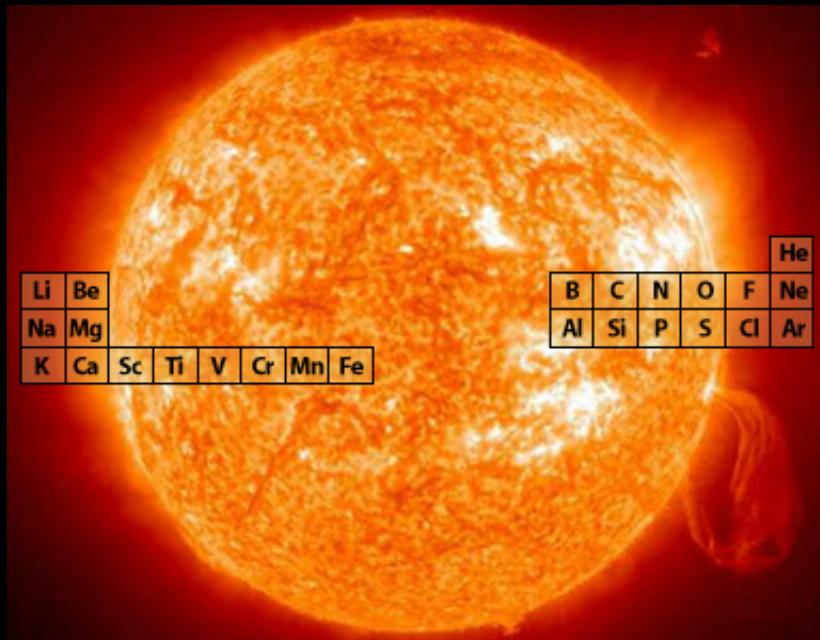
- SNe are the main cosmic polluters.



- Dynamical impact on galaxy evolution.

# Why do we care about Supernovae?

- SNe are the main cosmic polluters.

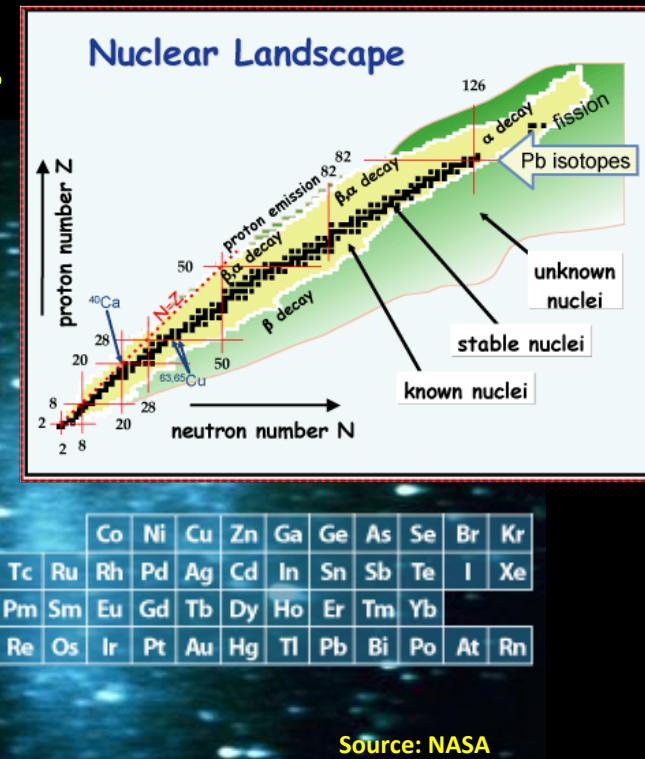
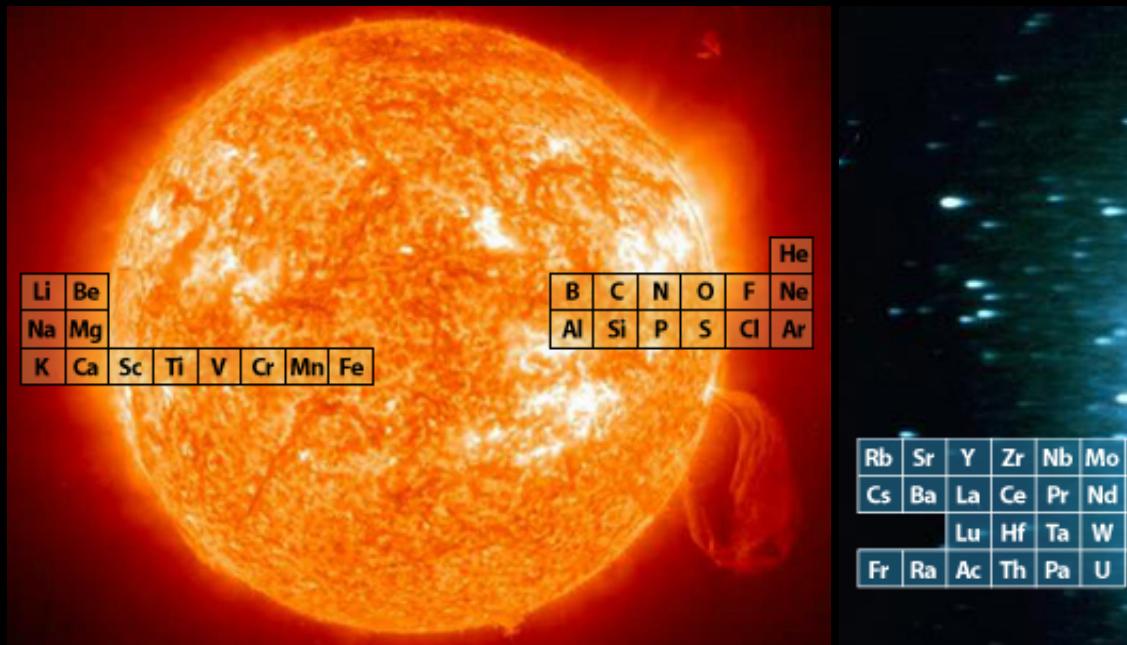


Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
	Lu	Hf	Ta	W	Re	Os	Ir	Gd	Tb	Dy	Ho	Er	Tm	Yb			
Fr	Ra	Ac	Th	Pa	U		Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		

- Dynamical impact on galaxy evolution.
- At least for some supernovae:  
Birth sites of neutron stars and black holes.

# Why do we care about Supernovae?

- SNe are the main cosmic polluters.

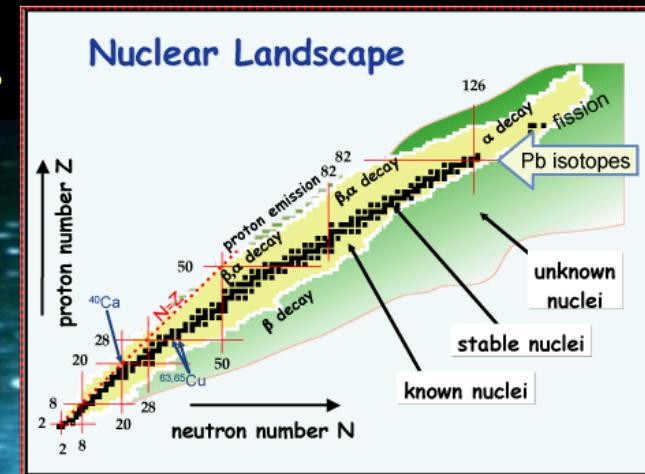
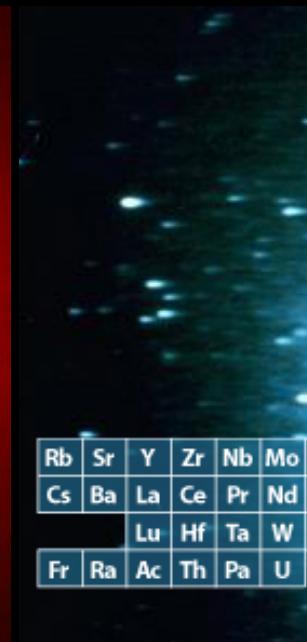
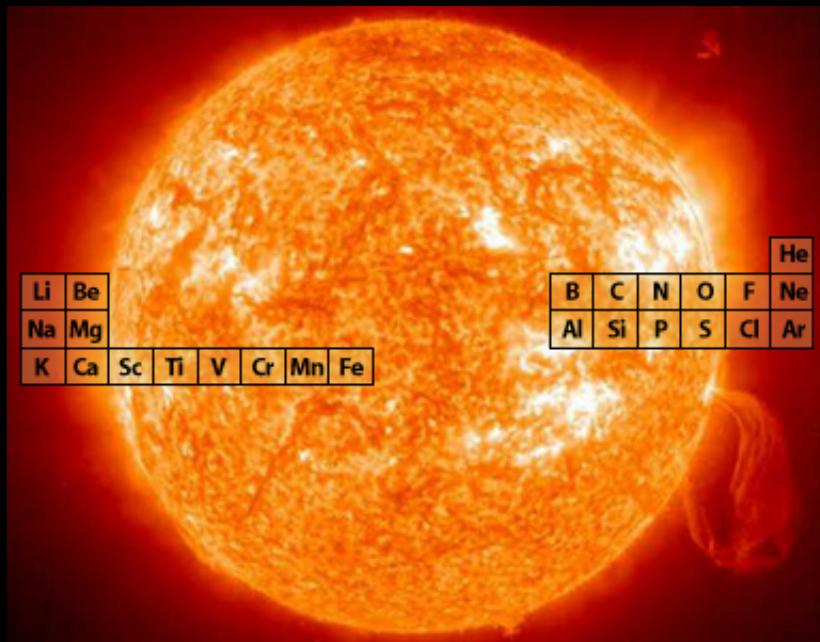


Source: NASA

- Dynamical impact on galaxy evolution.
- At least for some supernovae:  
Birth sites of neutron stars and black holes.
- Gigantic cosmic laboratories for fundamental physics.

# Why do we care about Supernovae?

- SNe are the main cosmic polluters.

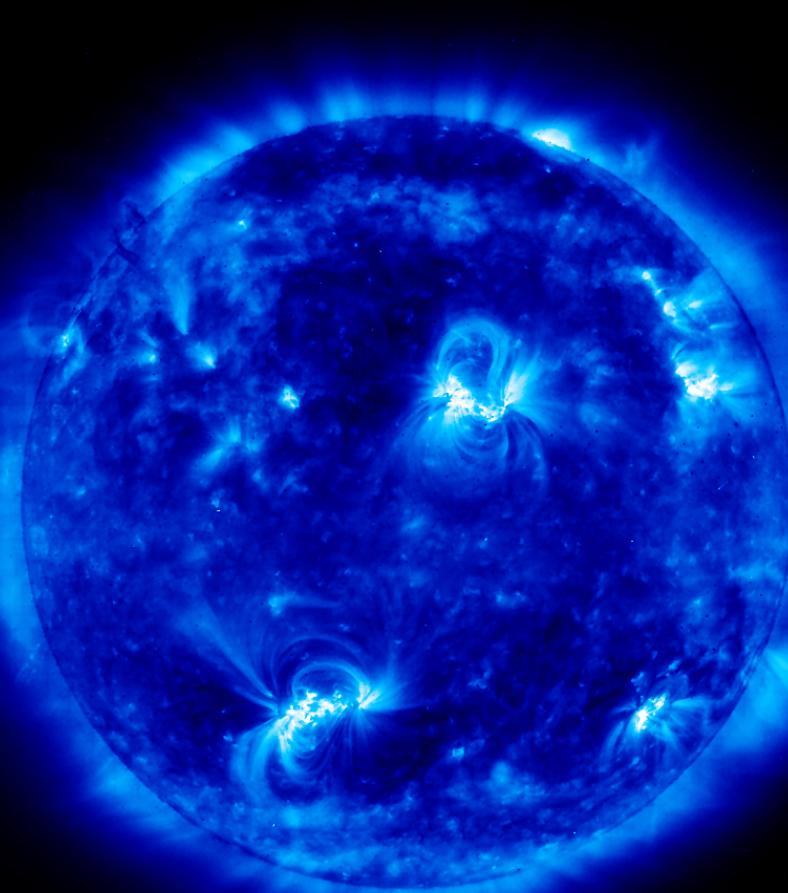


Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
	Lu	Hf	Ta	W	Re	Os	Ir	Gd	Tb	Dy	Ho	Er	Tm	Yb			
Fr	Ra	Ac	Th	Pa	U		Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		

- Dynamical impact on galaxy evolution.
- At least for some supernovae:  
Birth sites of neutron stars and black holes.
- Gigantic cosmic laboratories for fundamental physics.
- Cosmic standard candles (-> Nobel Prize in Physics 2011).

# Understanding Supernovae

- Must first understand “Stellar Evolution”: How stars live their lives.

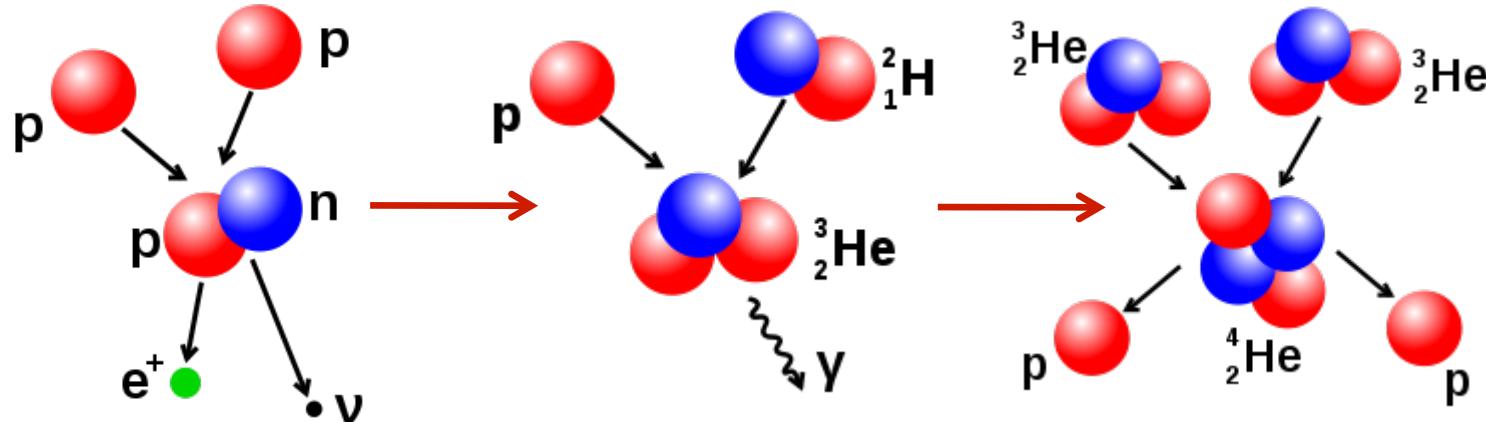


**Soho**  
**NASA/ESA**

The Sun in  
X-rays

# Stellar Evolution

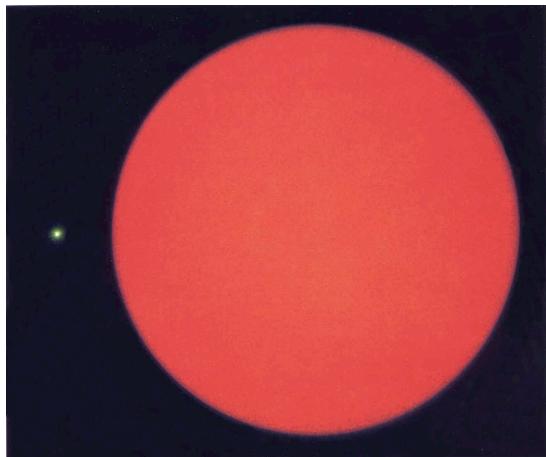
- Stars are powered by thermonuclear fusion reactions:



- Fusion of lighter elements into heavier elements releases energy.
- Hydrogen->Helium->Carbon/Oxygen->Oxygen/Neon->Silicon->**Iron**.
- No energy gain from fusion past **iron**.
- **Temperature in the star determines how far fusion goes.**
- **Stars with more mass have higher temperature!**

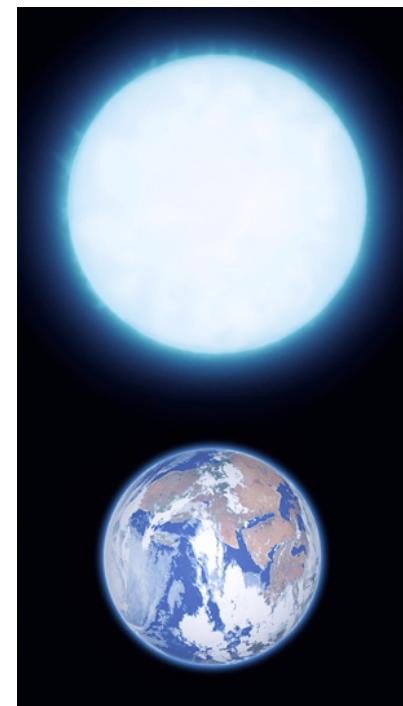
# Stellar Evolution

- Stellar Mass M:  $\sim 0.5 \text{ M}_{\text{Sun}} - 6 \text{ M}_{\text{Sun}}$   
Hydrogen->Helium->Carbon/Oxygen.
- Stellar Mass M:  $\sim 6 \text{ M}_{\text{Sun}} - 9 \text{ M}_{\text{Sun}}$  (exact range uncertain)  
Hydrogen->Helium->Carbon/Oxygen->Oxygen/Neon



“Red giant” star

Outer stellar  
envelope ejected.  
                          
(takes thousands  
of years)



“White  
dwarf”  
star

Eskimo Nebula

NASA/Hubble Space Telescope



Red giant star ejecting its envelope: a White Dwarf star remains.

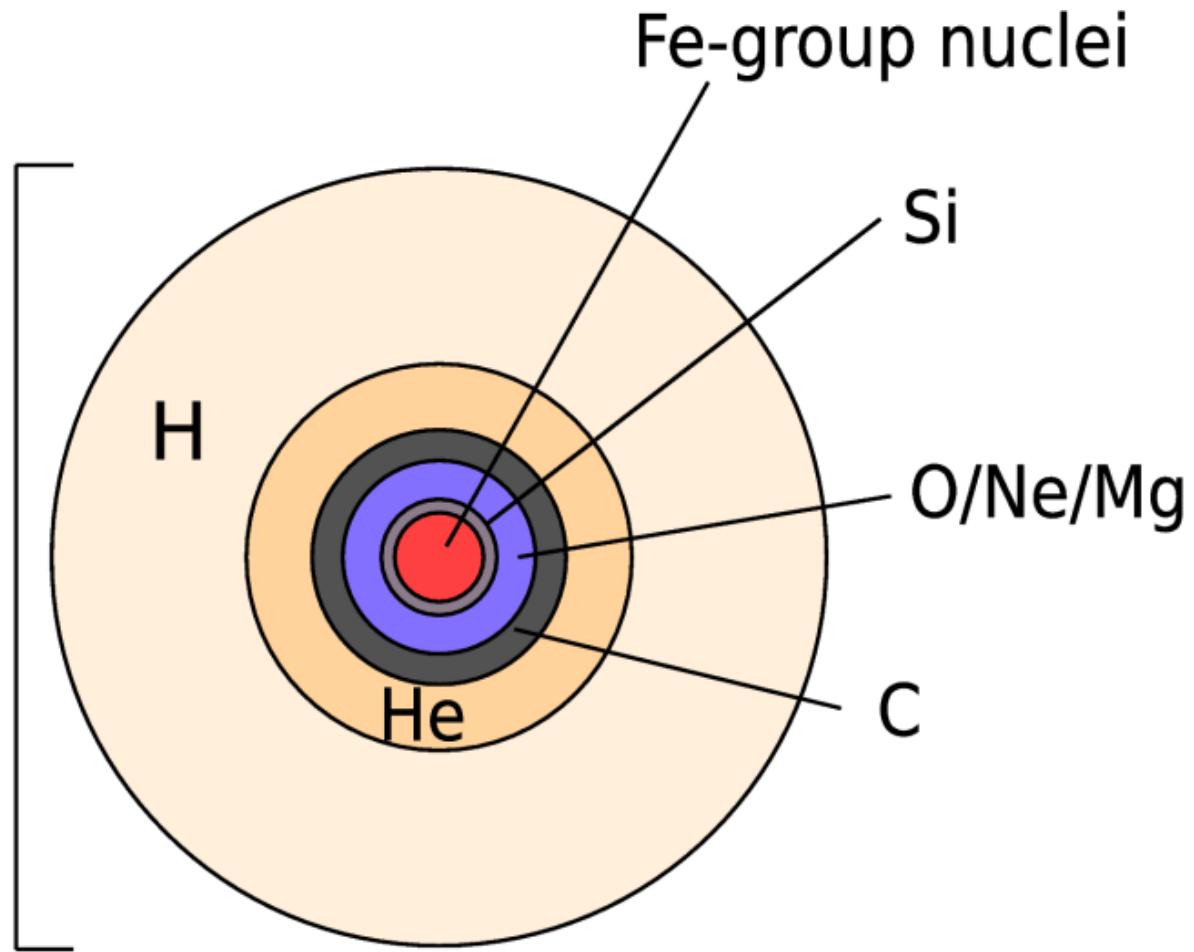
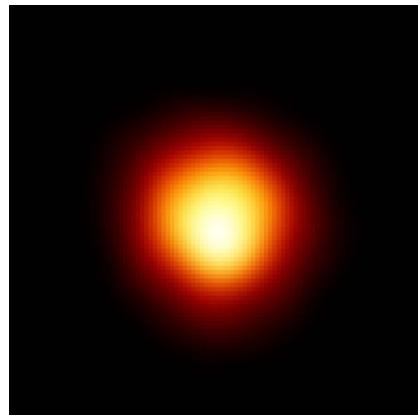
# Stellar Evolution

- Stellar Mass  $M > 9\text{-}10 M_{\text{Sun}}$

Hydrogen->Helium->Carbon/Oxygen->Oxygen/Neon->Silicon->Iron.

“Red Supergiant” star

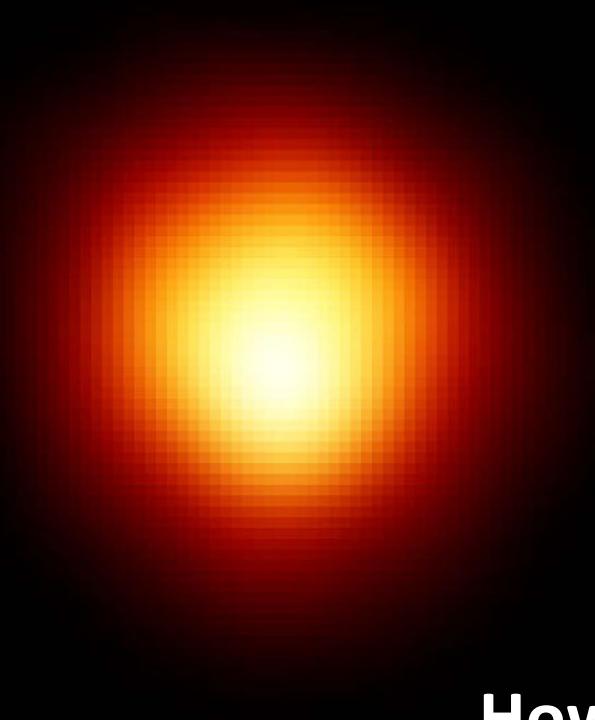
Betelgeuse:  $\sim 10^9 \text{ km}$



# Back to Supernova Explosions:



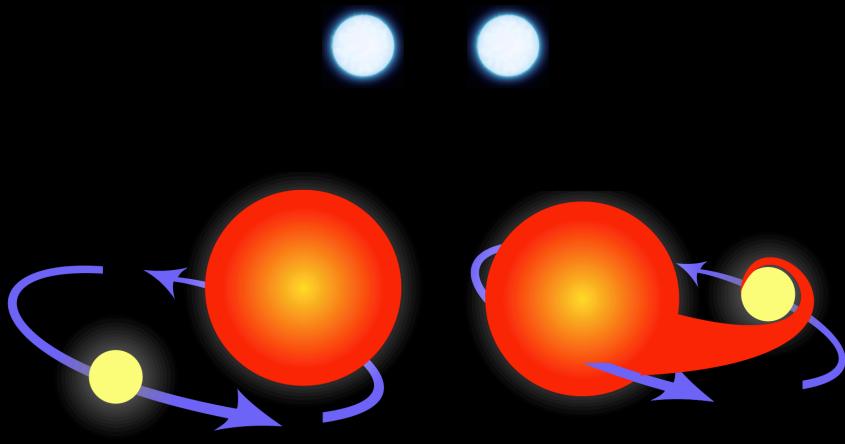
White Dwarfs



Supergiants

**How do we get them to blow up?**

# White Dwarf Supernovae: Thermonuclear Explosions



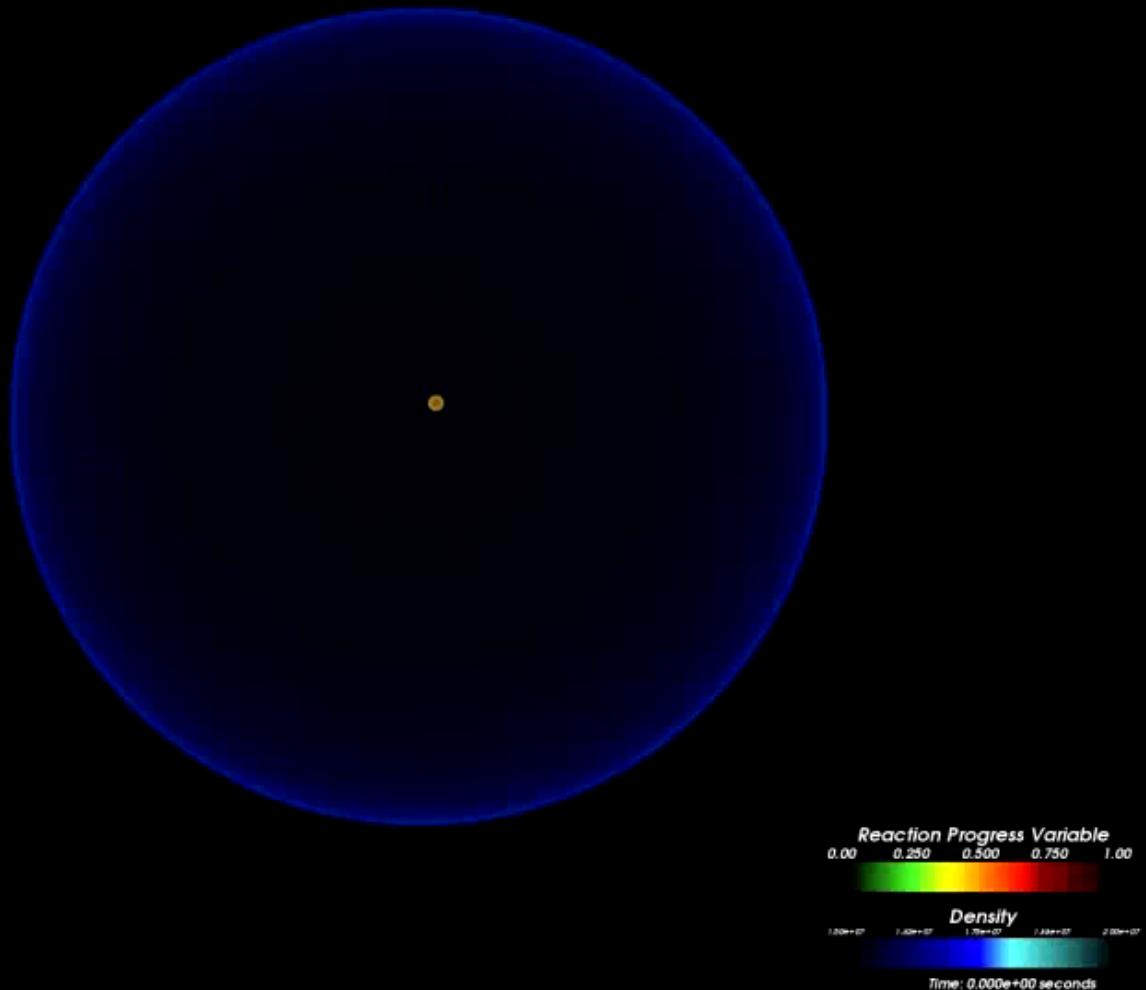
Collision/merger of  
two white dwarfs

White dwarf gains mass  
from companion star  
("accretion")

Most white dwarfs: Composed of Carbon & Oxygen.

Merger/Accretion: Ignite carbon/oxygen fusion reactions!

# White Dwarf Explosion



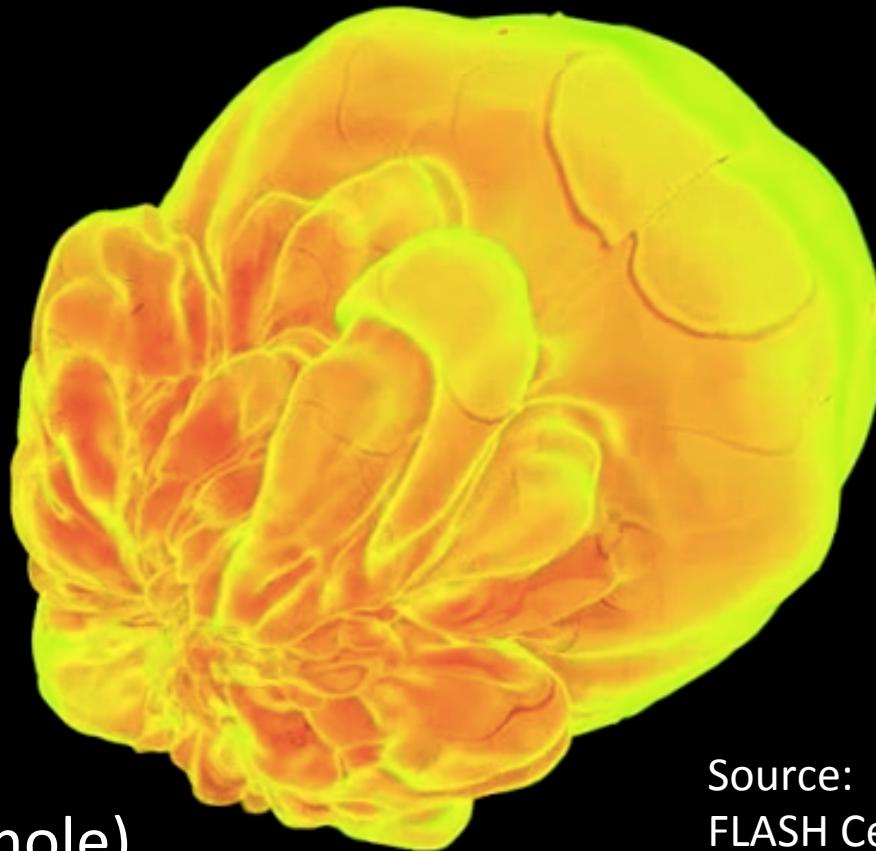
Simulation on a  
supercomputer  
Source:  
FLASH Center  
U. of Chicago

# White Dwarf Explosion

Explosion powered by  
fusion of carbon & oxygen  
to nickel.

Visible supernova light  
is powered by  
radioactive decay:  
Nickel->Cobalt->Iron

Nothing remains!  
(No neutron star or black hole)



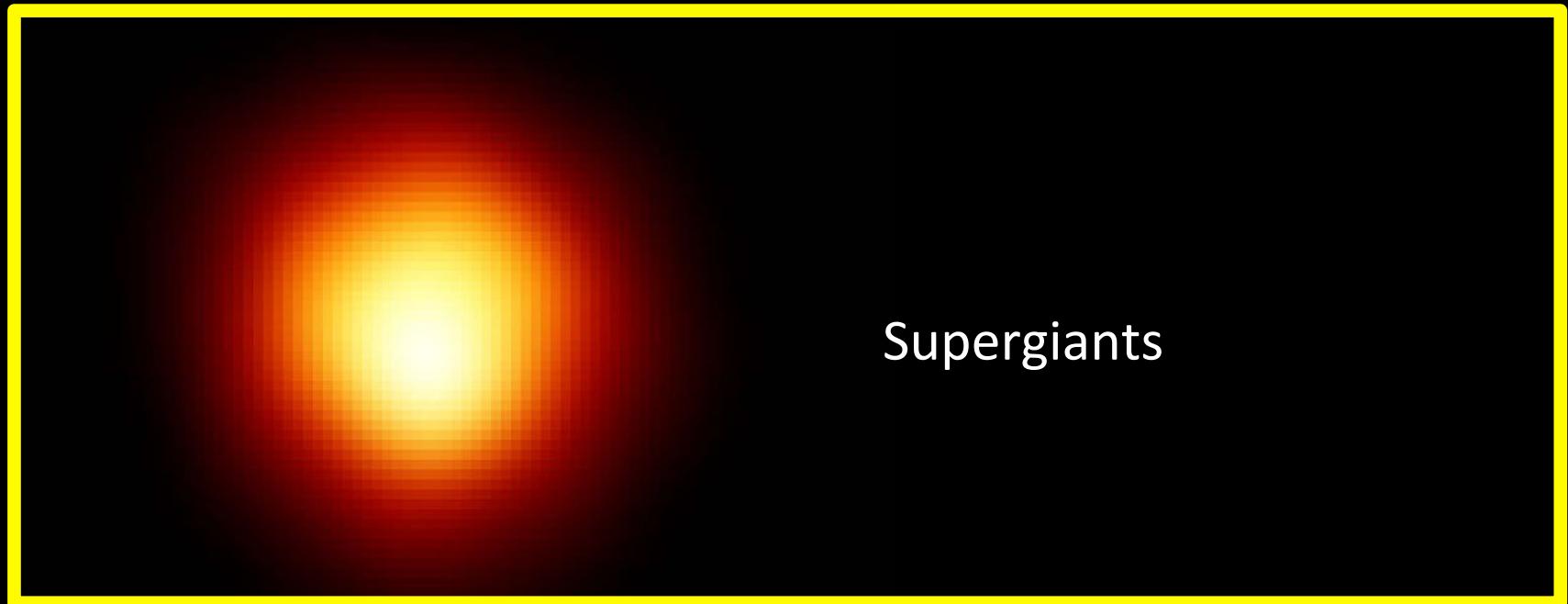
Source:  
FLASH Center  
U. of Chicago

Technical name in Astronomy: **Type Ia Supernova**

# Back to Supernova Explosions:



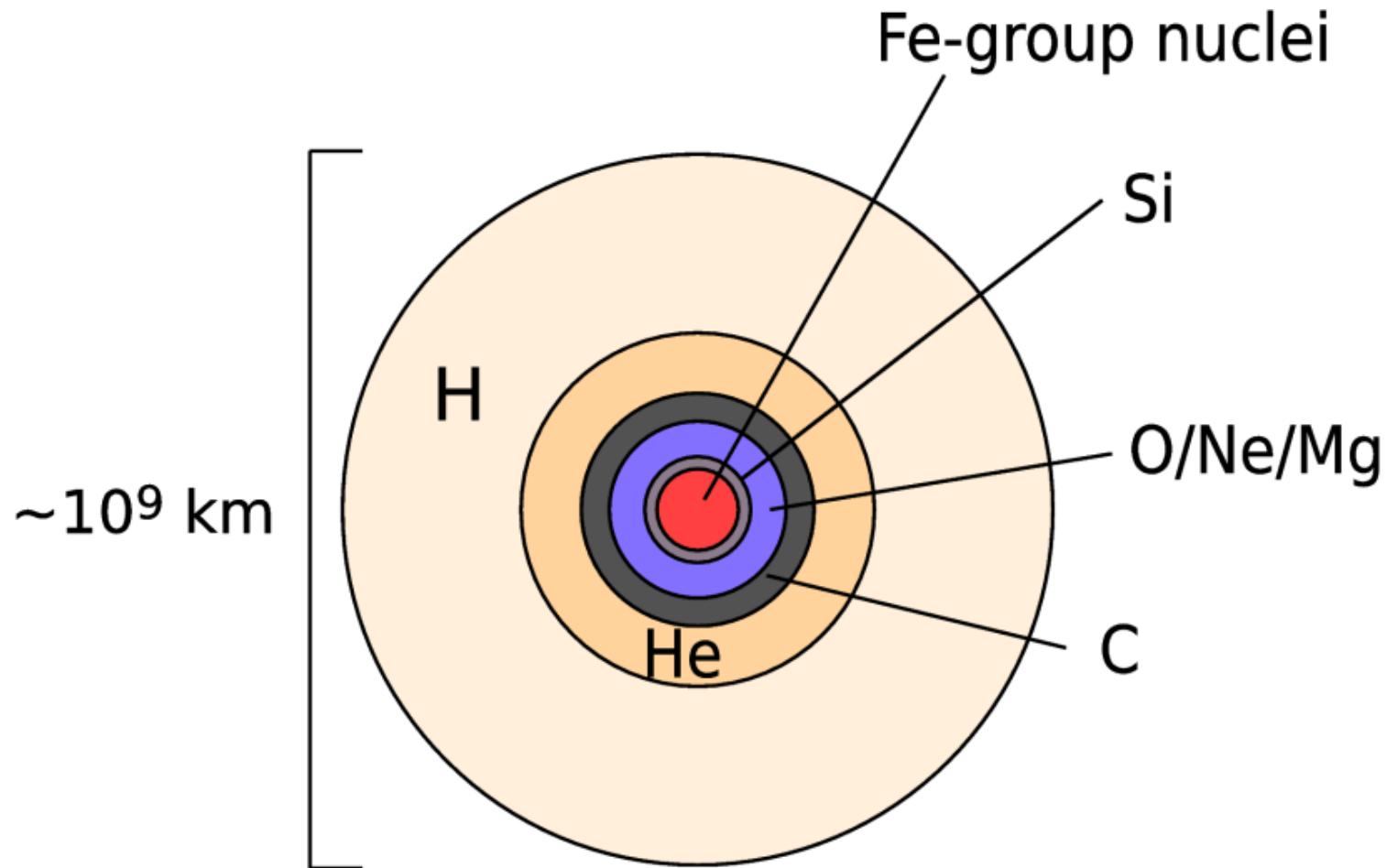
White Dwarfs: Type Ia SNe



Supergiants

How do we get them to blow up?

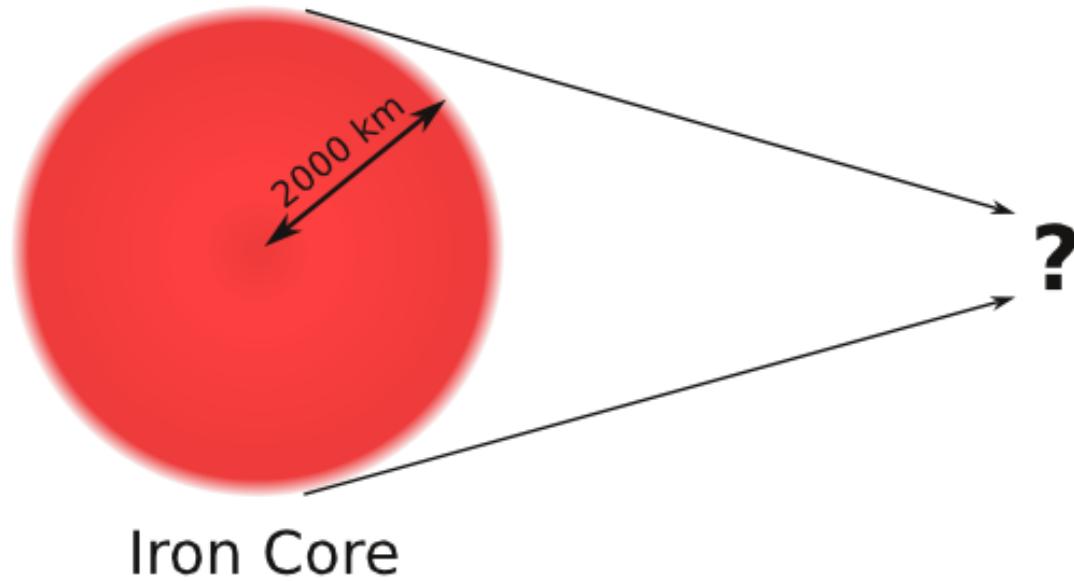
# Massive Stars: Supergiant Stars



Recall: No more fusion after Iron (Fe)

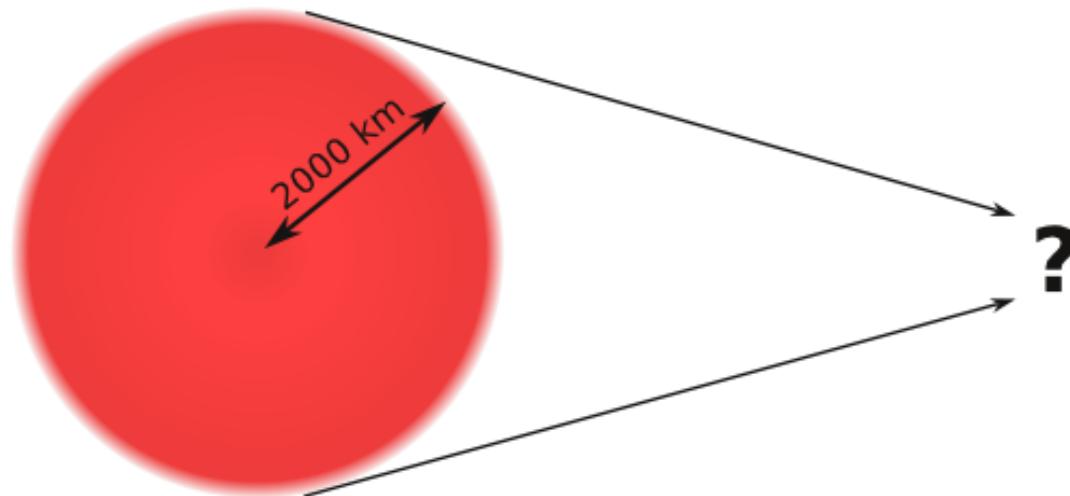
# Iron Core Collapse

No more energy input: core collapses under its own weight!



# Iron Core Collapse

No more energy input: core collapses under its own weight!



Iron Core

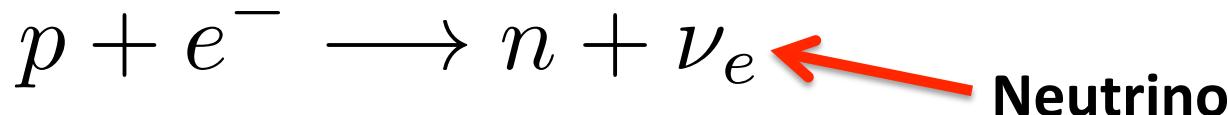
Density  $\approx 10^{10}$  g/cm<sup>3</sup>

Collapse: Core is compressed!  
Within  $\sim 0.5$ s:

Density  $> 10^{14}$  g/cm<sup>3</sup>

# Two Important Things:

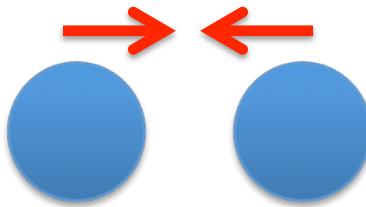
(1) At high density: Electrons “captured” on protons



Matter becomes “neutron rich” (-> neutron star!)

(2) **Strong Nuclear Force**: Holds atomic nuclei together.

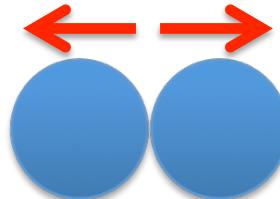
Normally:  
Force is “attractive”



2 nucleons:  
protons or neutrons

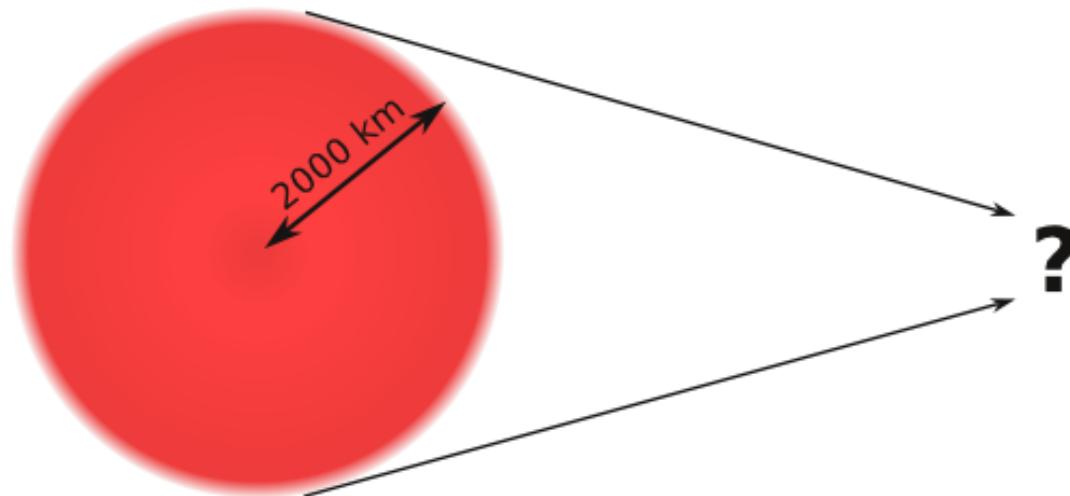
In the strongly compressed core at density  $> 10^{14} \text{ g/cm}^3$ .

Nuclear force become  
“repulsive”



# Iron Core Collapse

No more energy input: core collapses under its own weight!



Iron Core

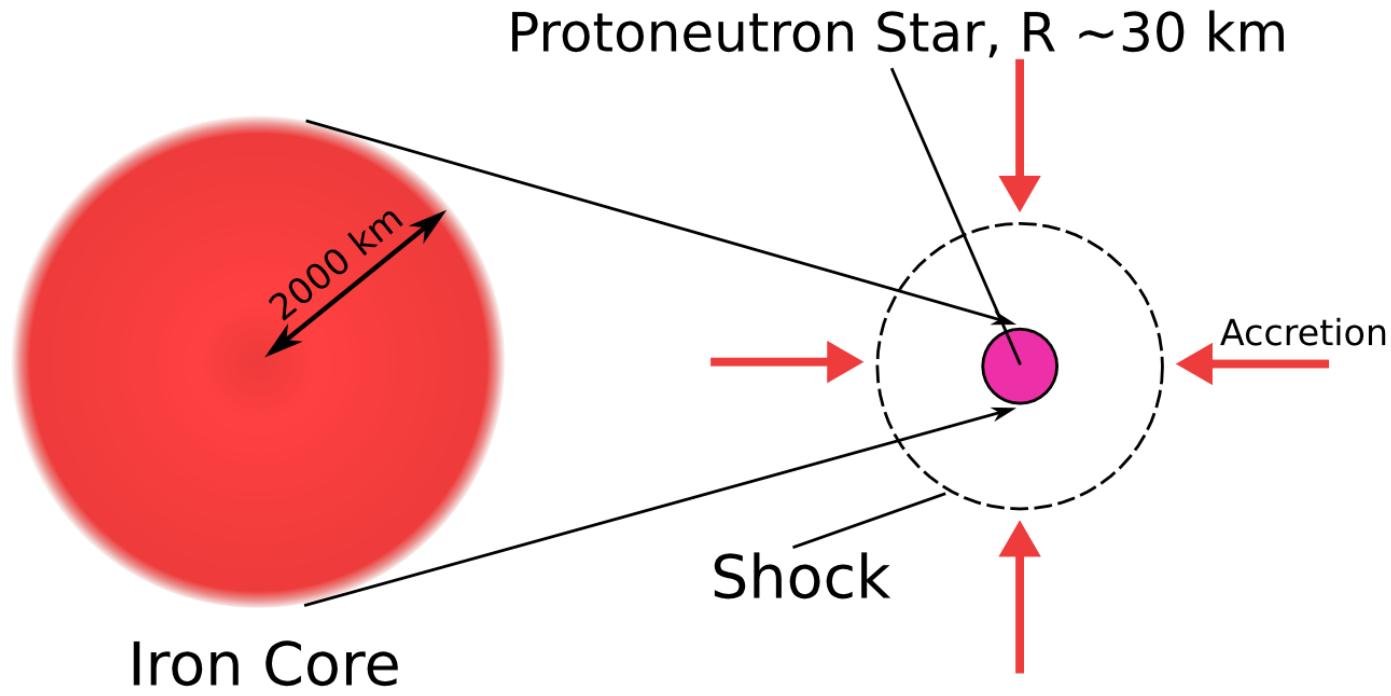
Density  $\approx 10^{10}$  g/cm<sup>3</sup>

Collapse: Core is compressed!  
Within  $\sim 0.5$ s:

Density  $> 10^{14}$  g/cm<sup>3</sup>

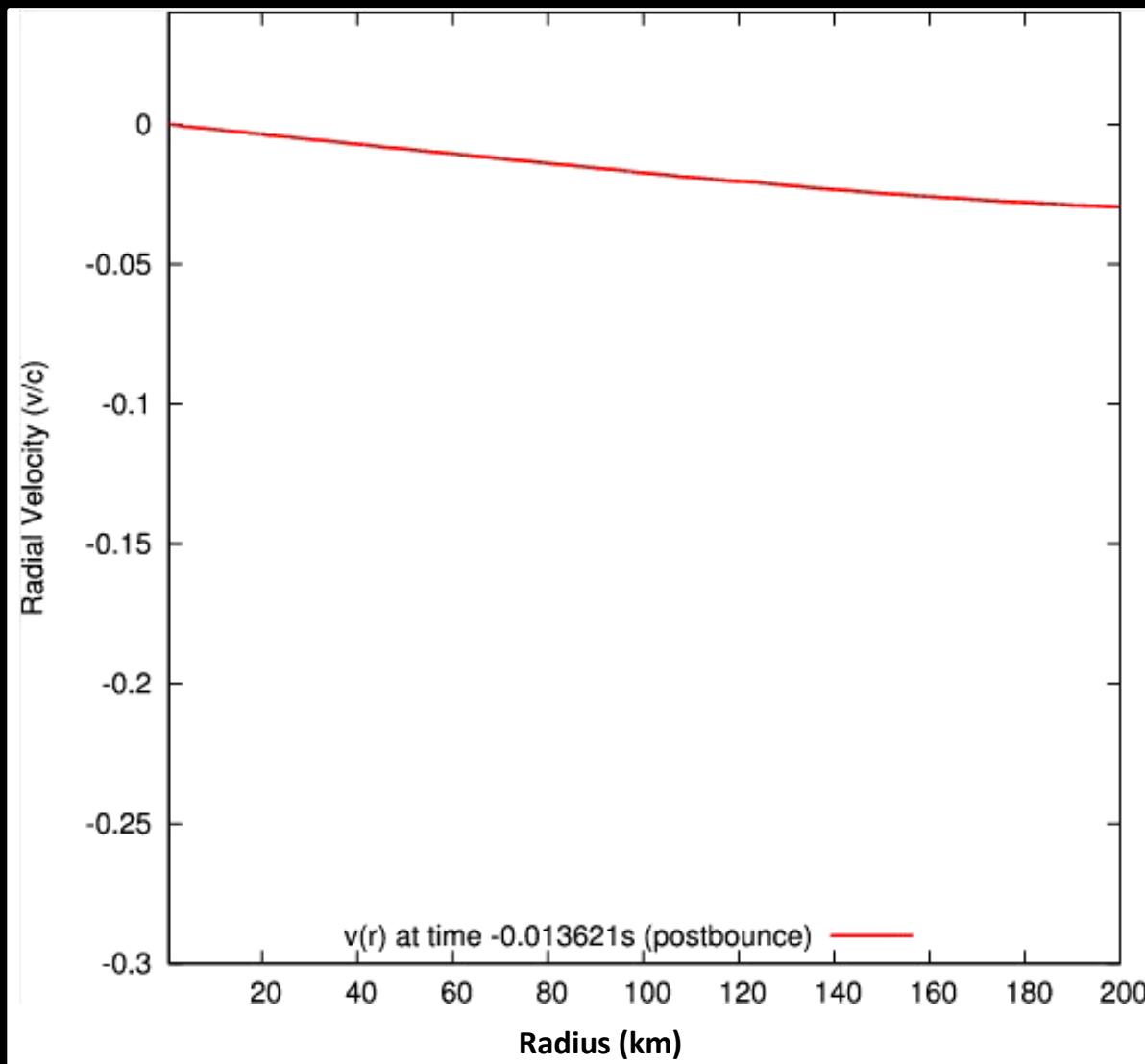
**Nuclear repulsive force kicks in!**

# “Bounce” of the Inner Core

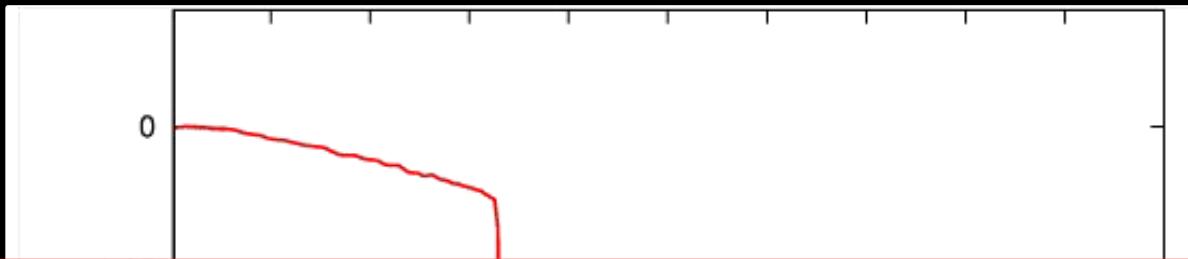


Nuclear force stabilizes inner core in **protoneutron star**.  
Outer core and outer layers still collapsing, pushing down  
on the supernova shock!

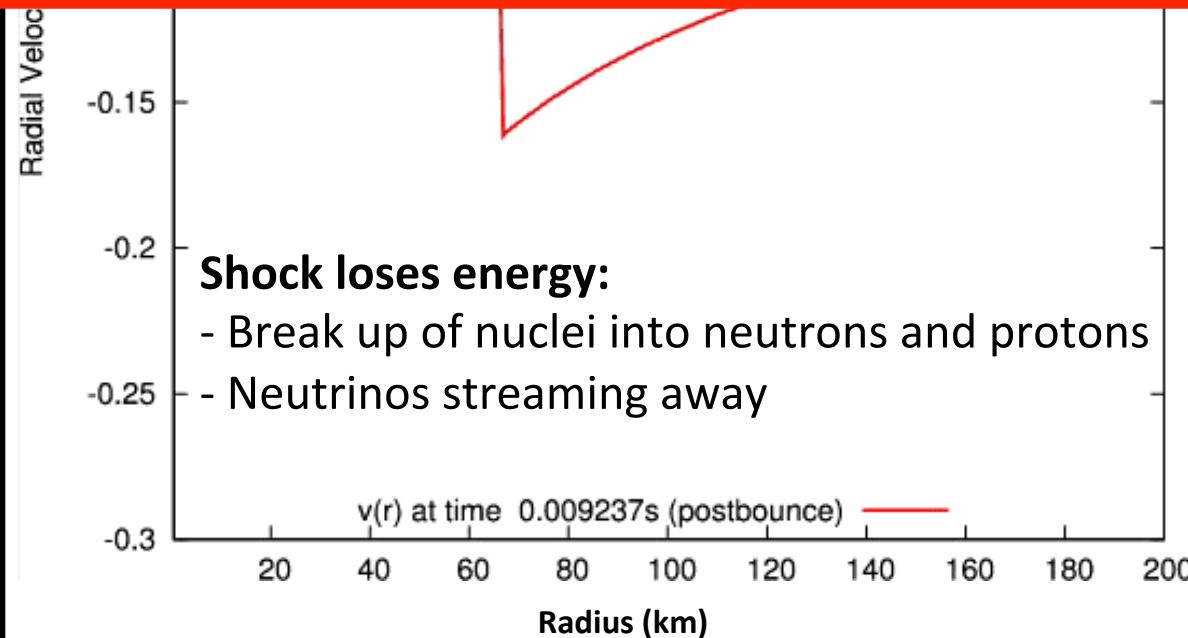
# The Supernova Problem



# The Supernova Problem

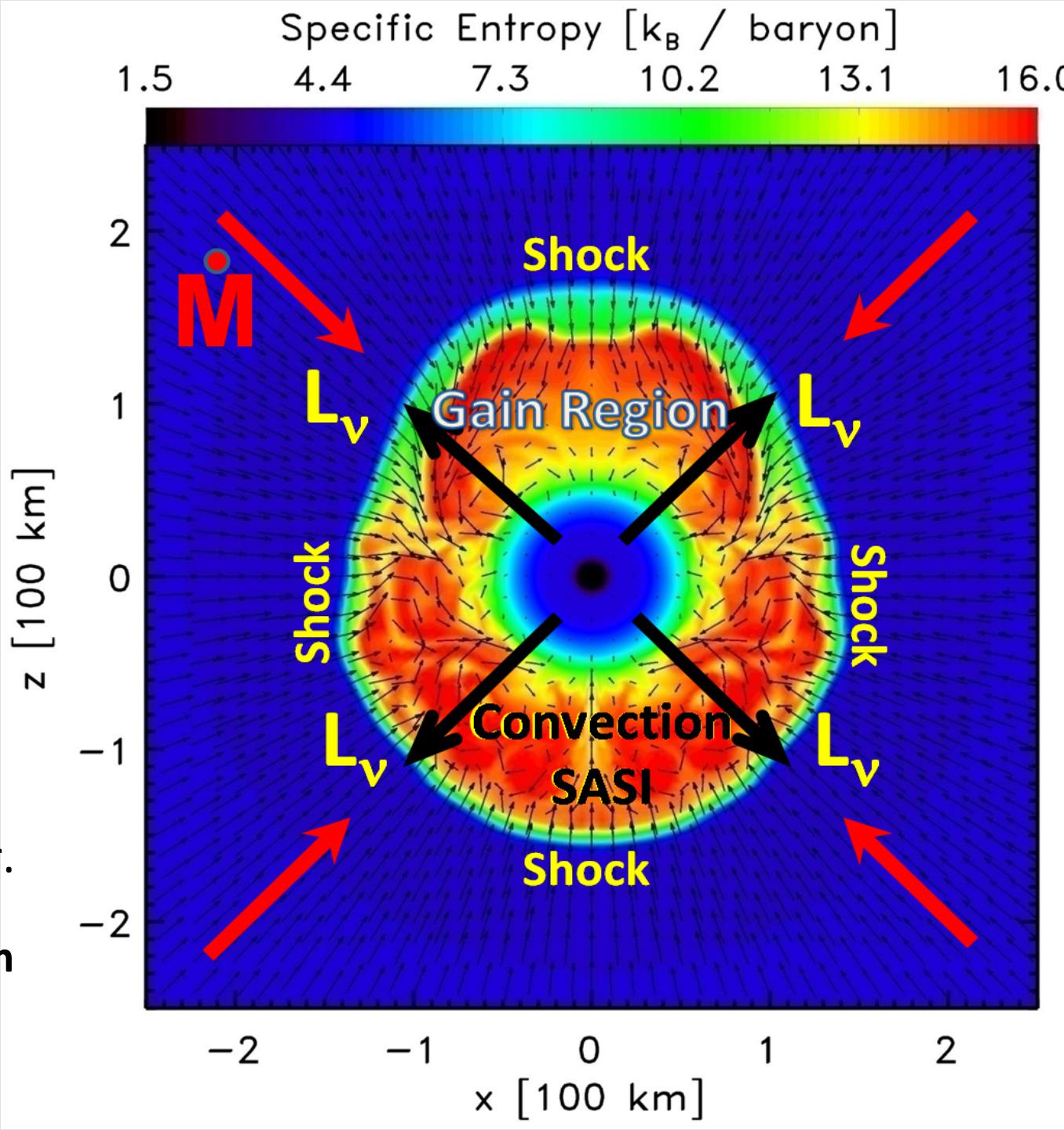


**Shock “stalls” and must be revived:  
What is the mechanism that revives the shock?**

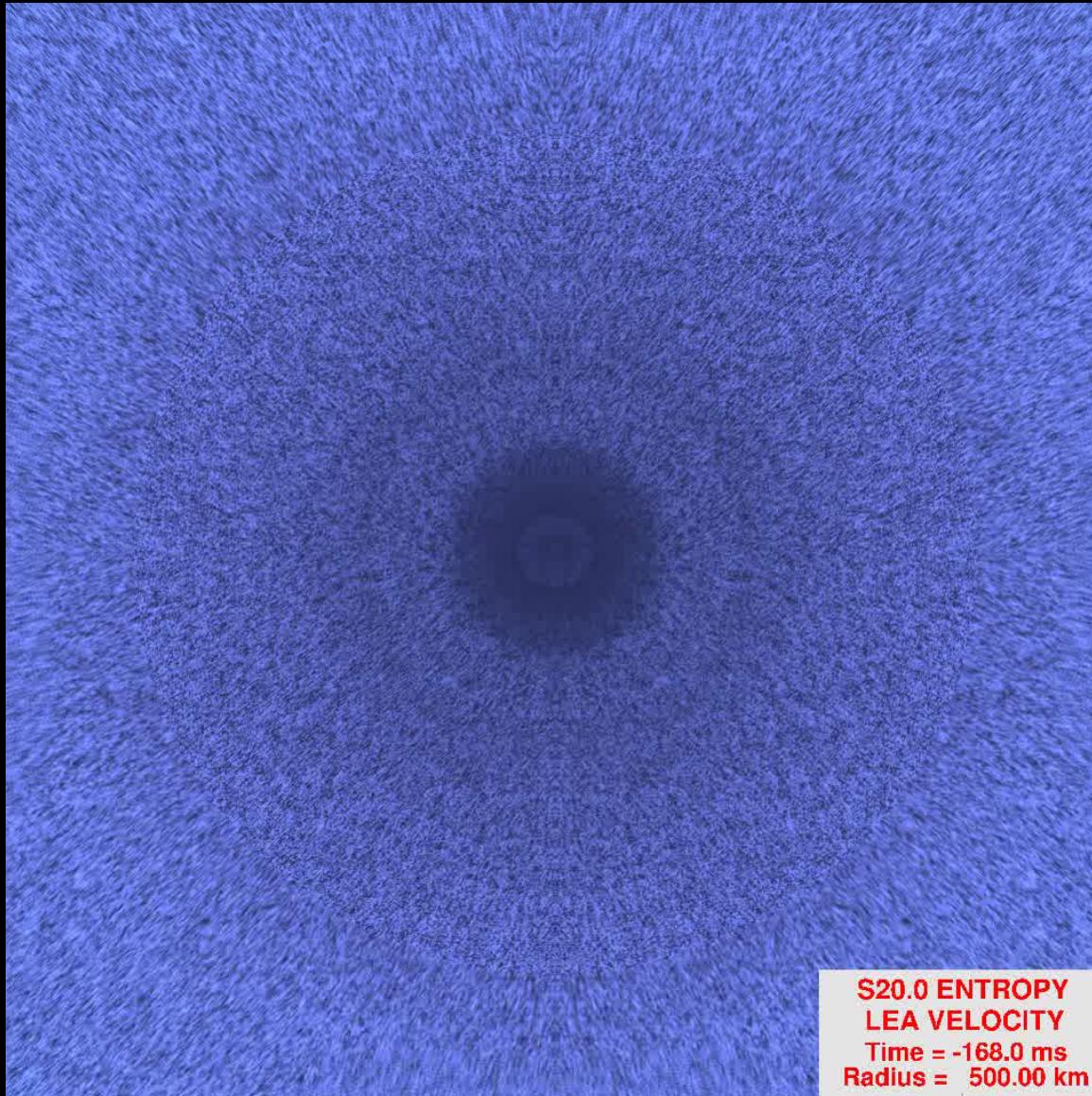


- Neutrinos emitted near protoneutron star.
- Idea: Some neutrinos could be re-absorbed near the shock.
- This mechanism could provide sufficient energy to explode the star.

## Neutrino Mechanism



# Standing Accretion Shock Instability



-6.18 ms

Movie  
by Steve Drasco  
(Grinnell)

# Core-Collapse Supernovae!

Explosion powered by  
the release of collapse energy  
(in neutrinos).

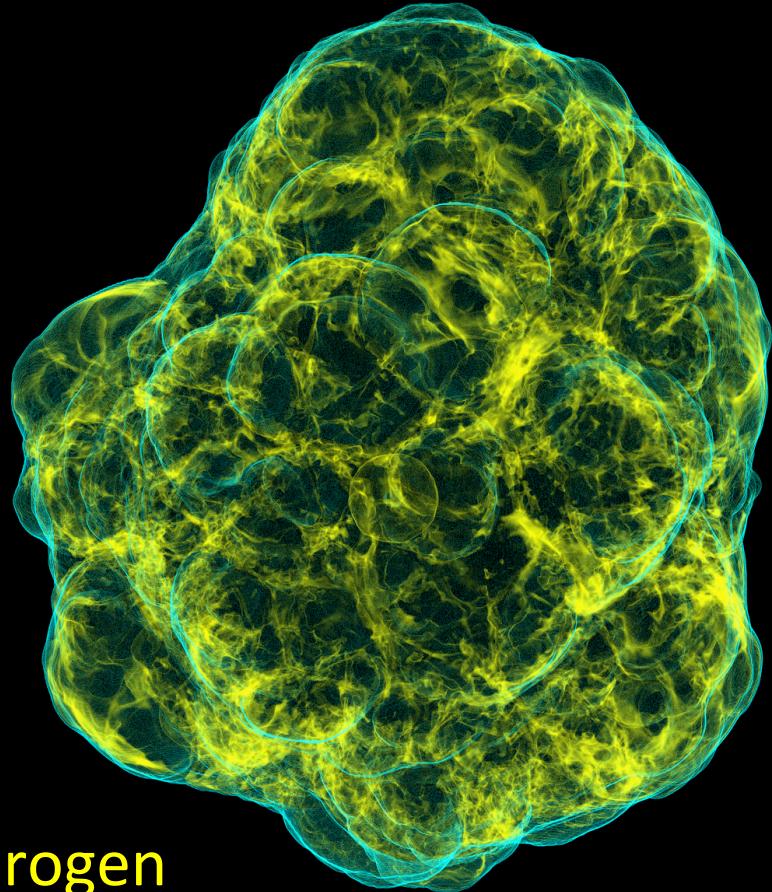
**But details still uncertain!**

Very complex physics involved:  
neutrinos, nuclear physics,  
fluid dynamics.

Visible supernova light  
is powered by two things:

- (1) “Recombination” of ionized hydrogen  
after the explosion;
- (2) Decay: Nickel->Cobalt->Iron

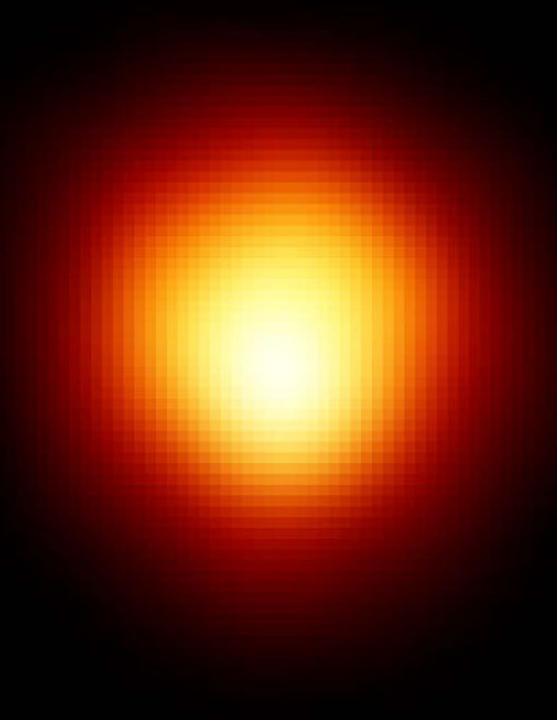
Technical name in Astronomy: **Type II Supernovae**



# Supernova Summary

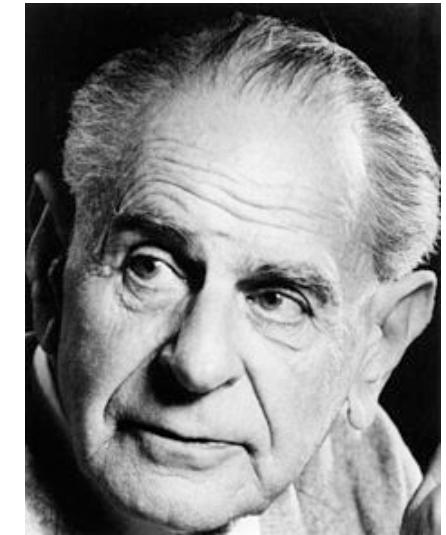
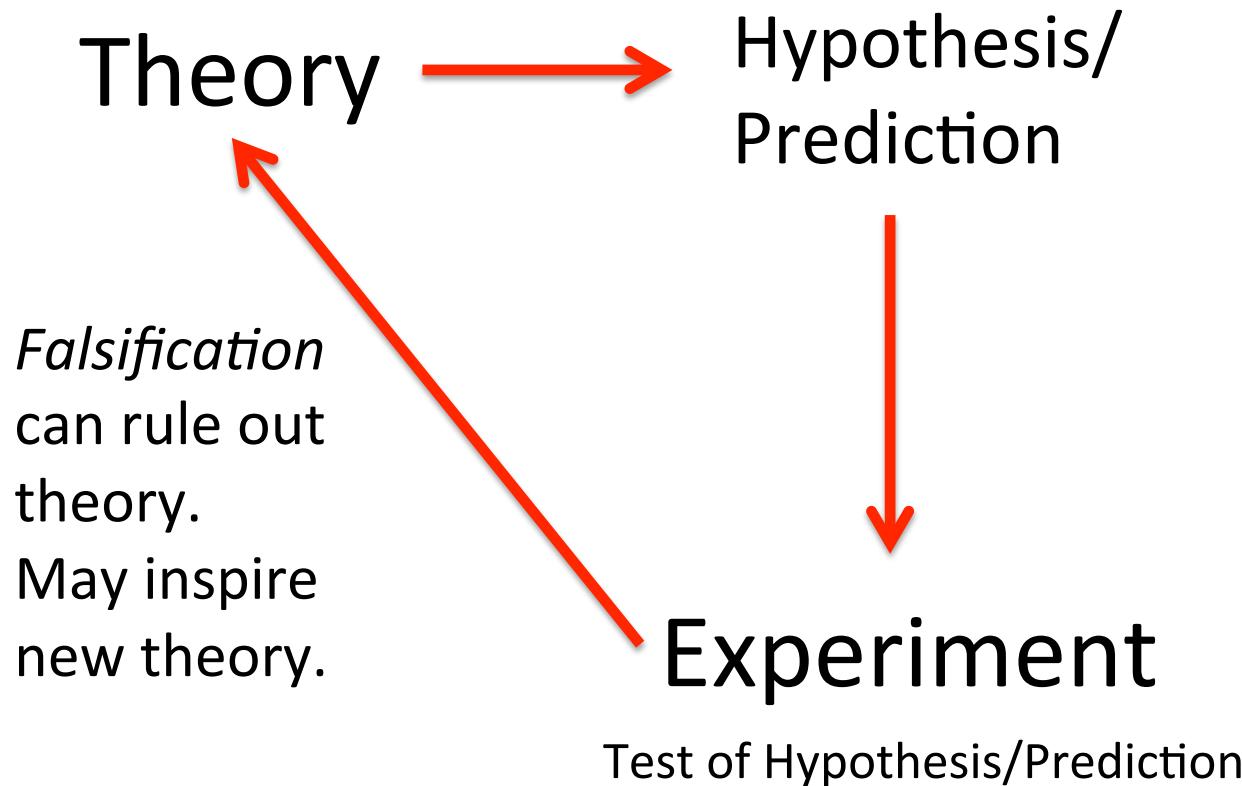


White Dwarfs: Type Ia SNe  
Thermonuclear Explosions



Supergiants (massive stars):  
**Core-Collapse SNe (Type II SNe)**  
Explosion powered by collapse  
energy (via neutrinos?).

# Quick Aside on the Philosophy of Science



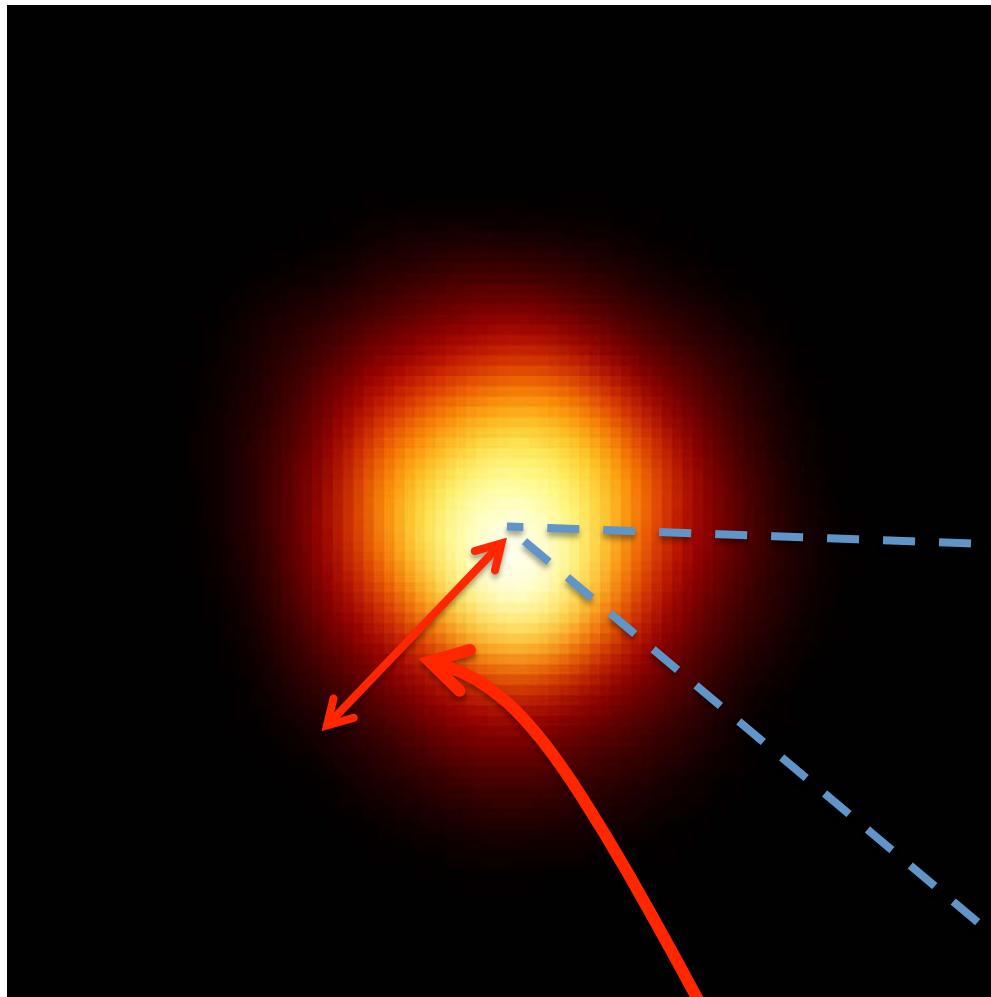
Karl Popper  
1902-1994

**In science, a theory can only be proven to be wrong, never to be right.**

In Astrophysics:

Cannot experiment with stars: Observation replaces Experiment.

# Observing the Core-Collapse Supernova Engine



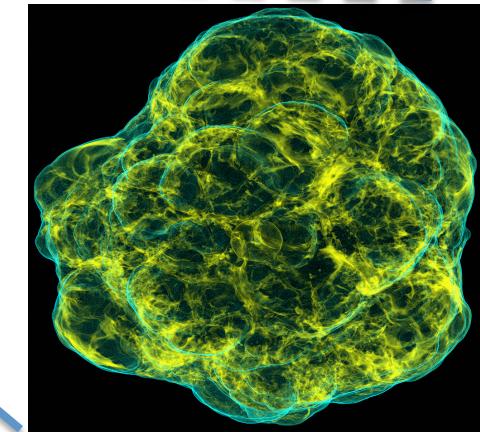
Red Supergiant

Betelgeuse

Distance:

~600 lightyears

Supernova “Central Engine”



HST

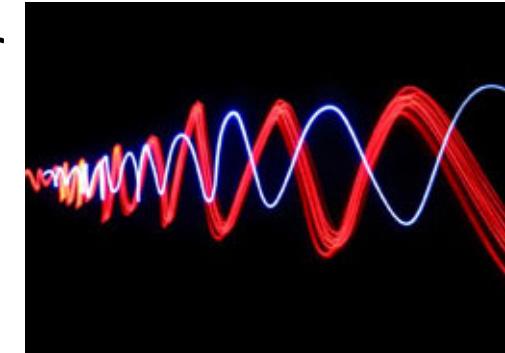
800 million km

300 km

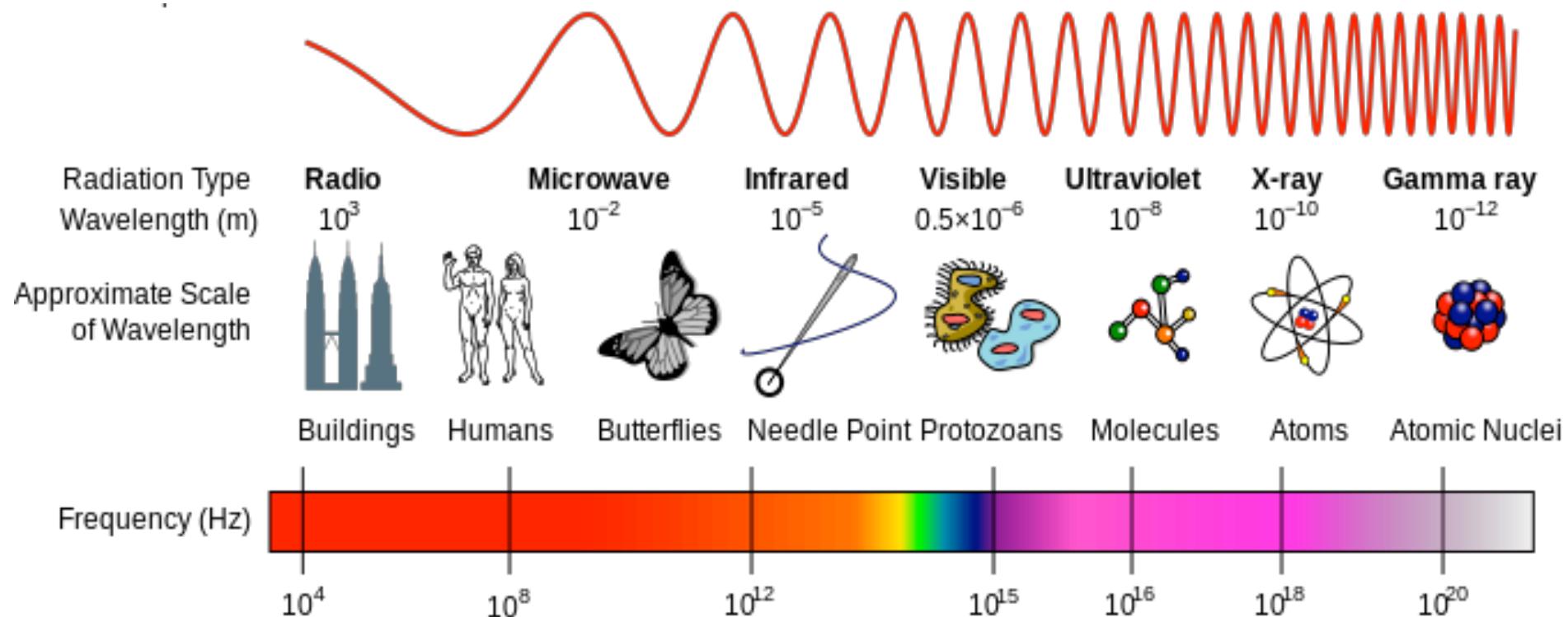
# Instruments of Observational Astronomy



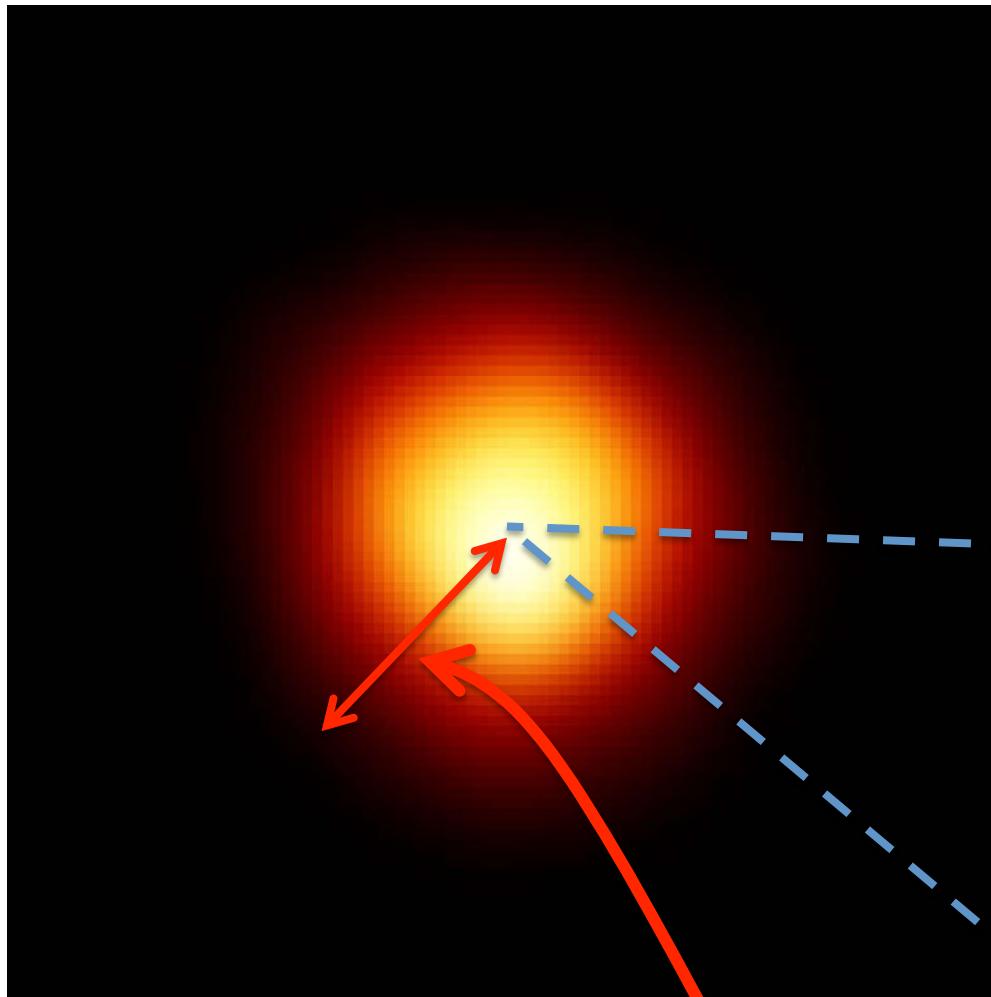
These telescopes all look for  
**electromagnetic waves!**  
(radio, infrared, light, UV,  
X-rays, Gamma rays)



# Spectrum of Electromagnetic Waves:



# Observing the Core-Collapse Supernova Engine



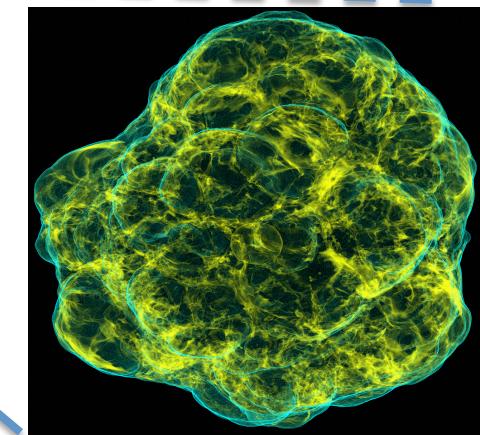
Red Supergiant

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Distance:

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Supernova “Central Engine”



HST

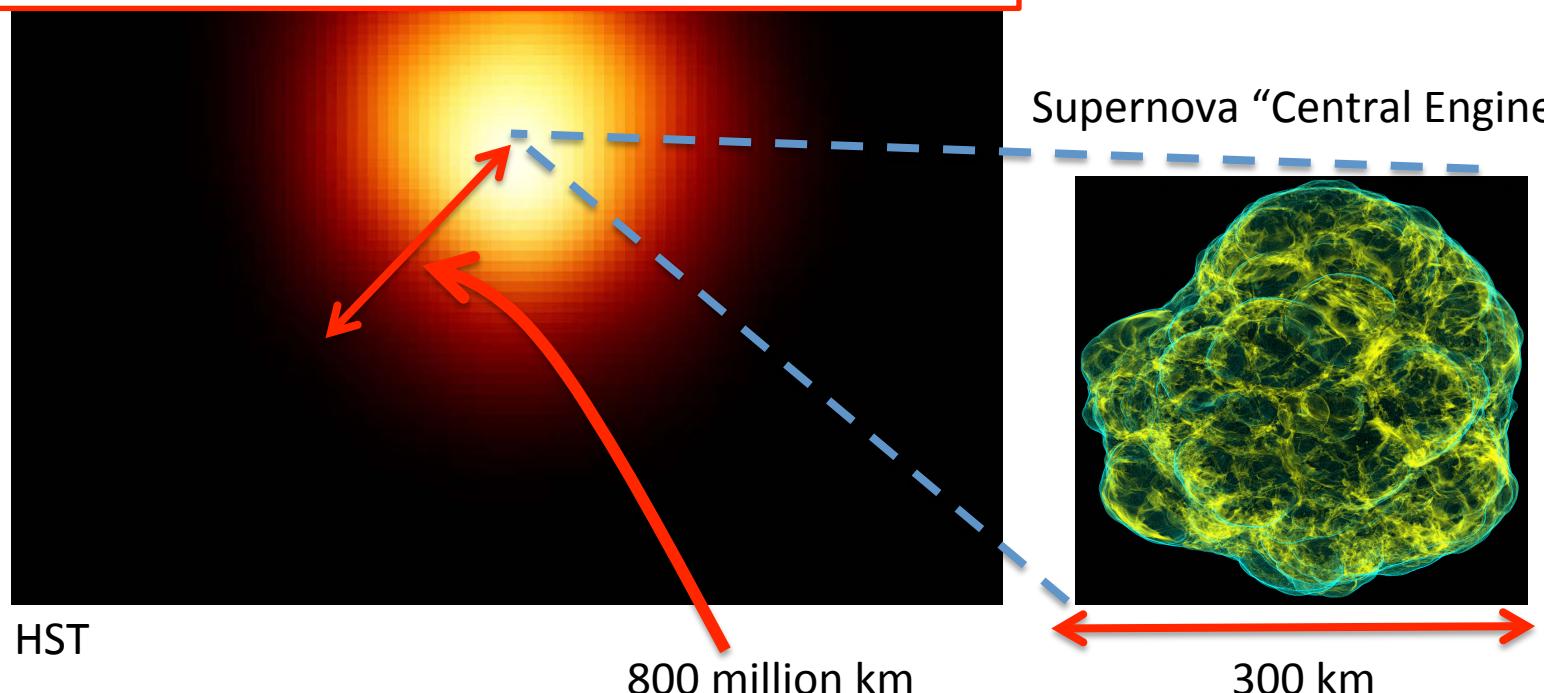
800 million km

300 km

# Observing the Core-Collapse Supernova Engine

Problem: Electromagnetic waves can't tell us what is happening in the supernova!  
We need other “messengers” to observe the core of the supernova:

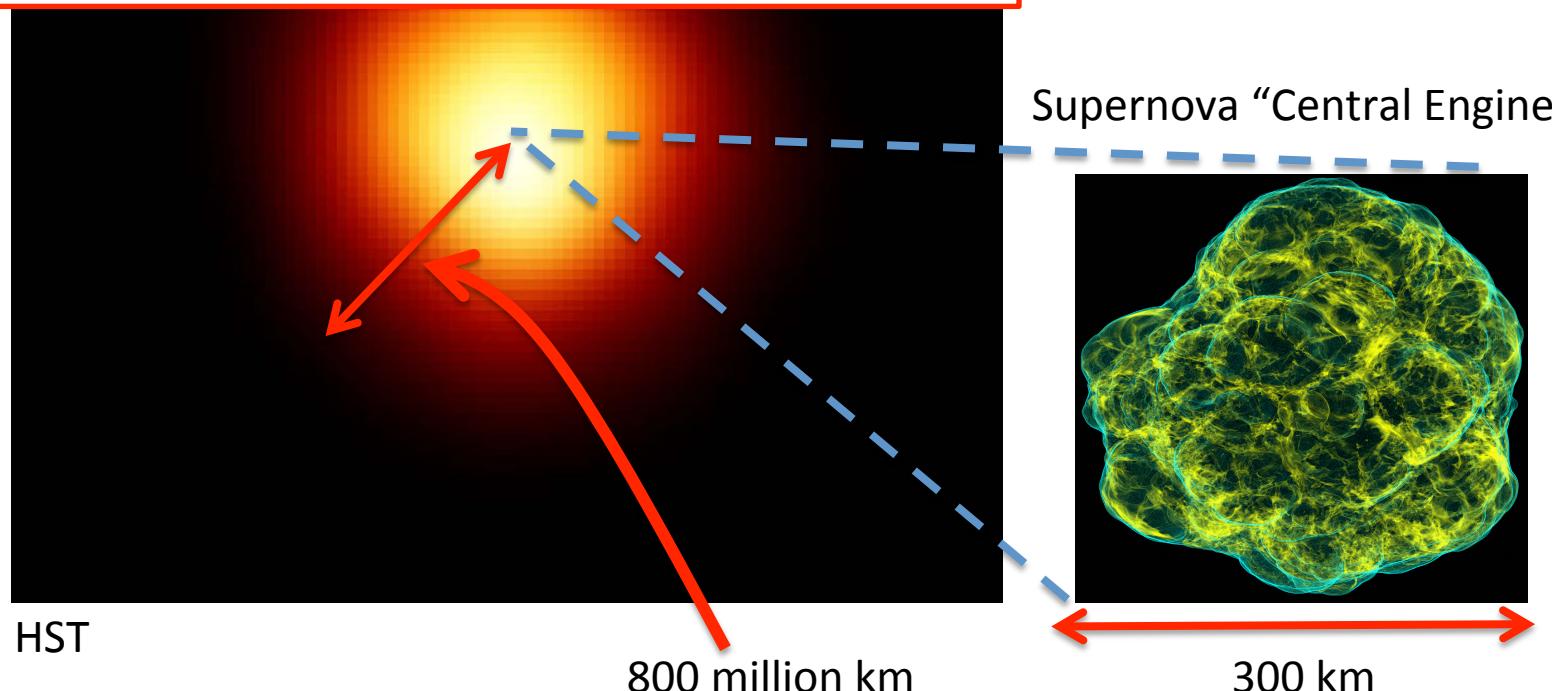
Red Supergiant  
Betelgeuse  
Distance:  
~600 lightyears



# Observing the Core-Collapse Supernova Engine

Problem: Electromagnetic waves can't tell us what is happening in the supernova!  
We need other "messengers" to observe the core of the supernova:  
-> Neutrinos (-> Neutrino Observatories)

Red Supergiant  
Betelgeuse  
Distance:  
~600 lightyears



# Observing the Core-Collapse Supernova Engine

Problem: Electromagnetic waves can't tell us what is happening in the supernova!

We need other “messengers” to observe the core of the supernova:

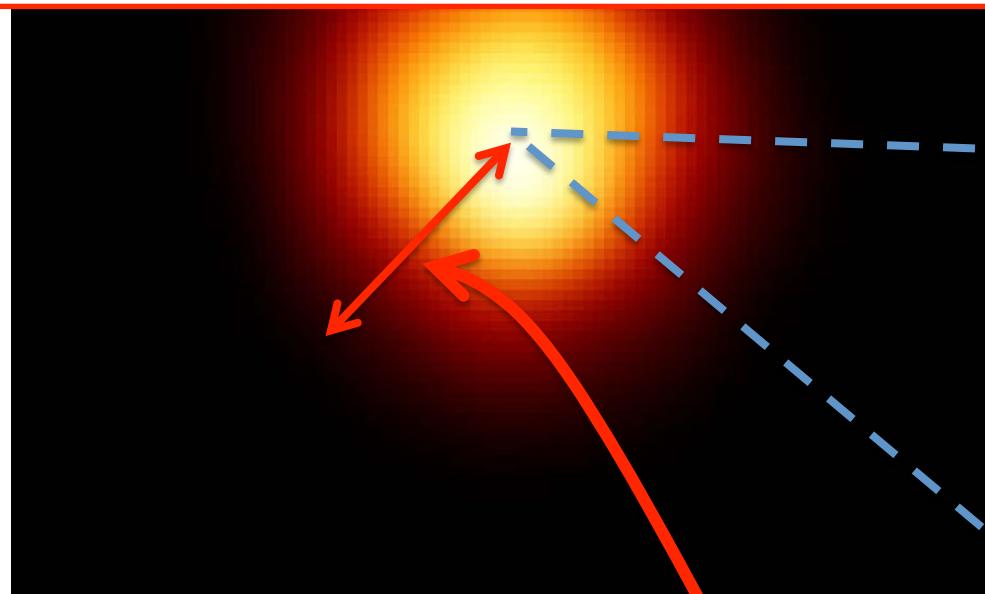
- > Neutrinos (-> Neutrino Observatories)
- > **Gravitational Waves**

Red Supergiant

Betelgeuse

Distance:

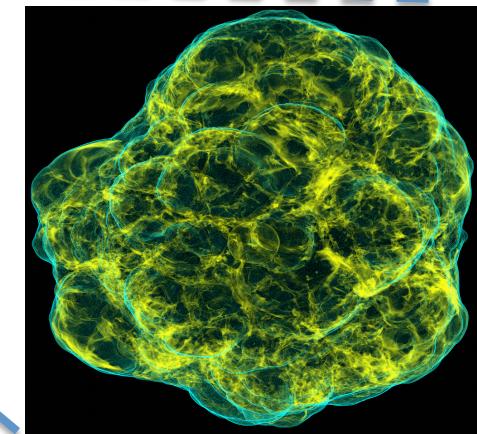
~600 lightyears



HST

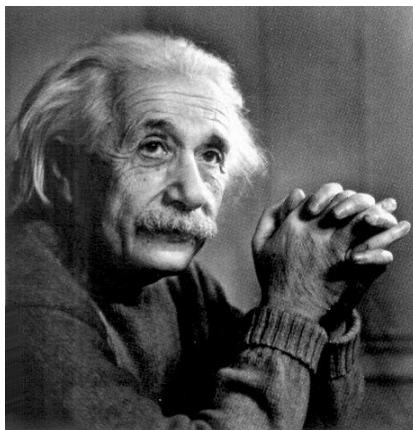
800 million km

Supernova “Central Engine”



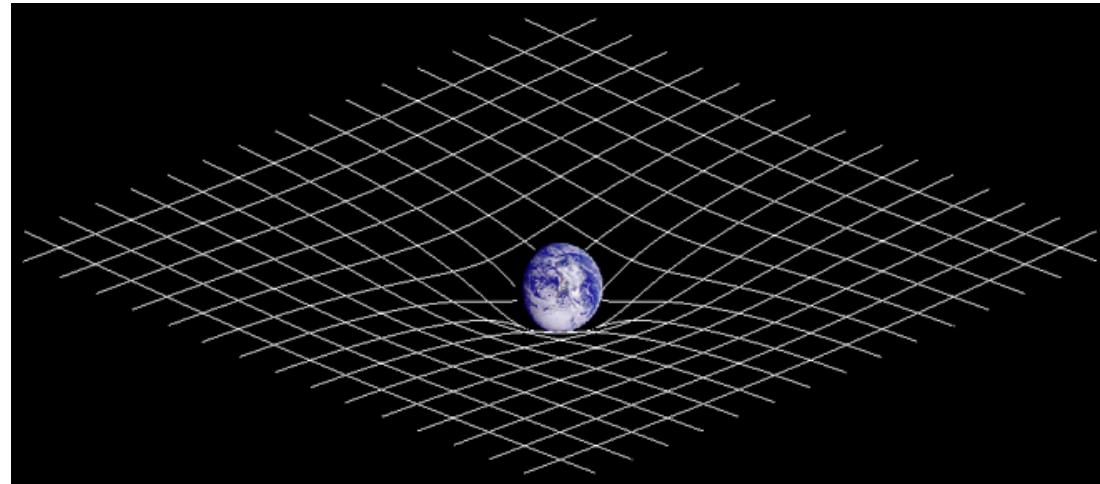
300 km

# Gravitational Wave Astronomy



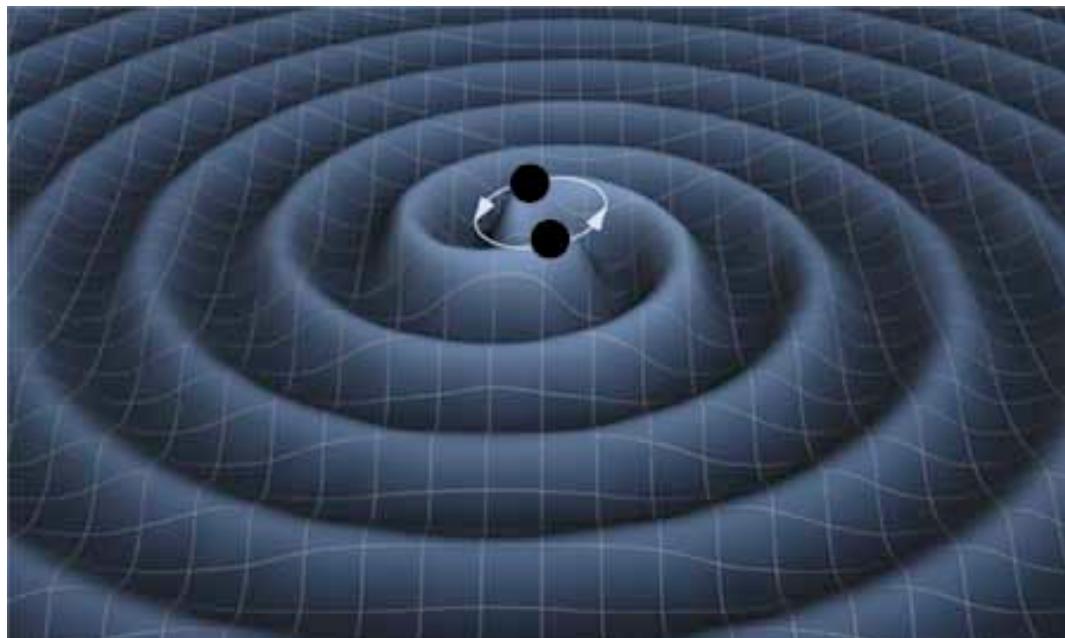
Albert Einstein  
1879-1955

## Einstein's General Theory of Relativity

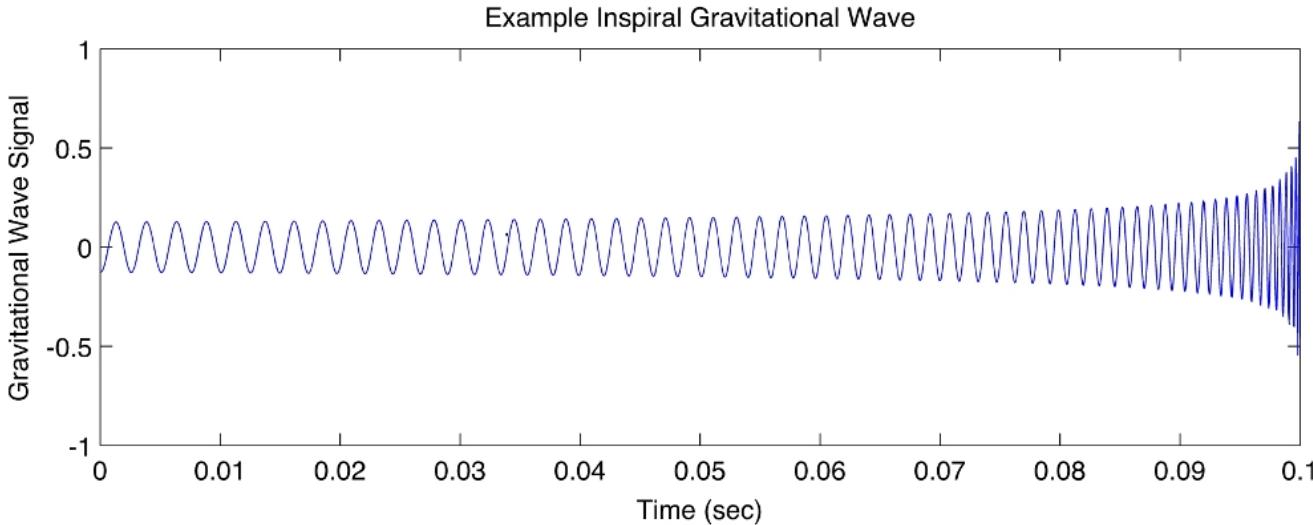


- Matter “curves” spacetime (geometric interpretation of gravity).
- Matter wobbling/moving around: creates **ripples in spacetime**  
-> **Gravitational Waves**
- Gravitational waves cannot be used to make an image of their source. Instead, they encode their source’s dynamics.
- Gravitational waves have not yet been observed directly.

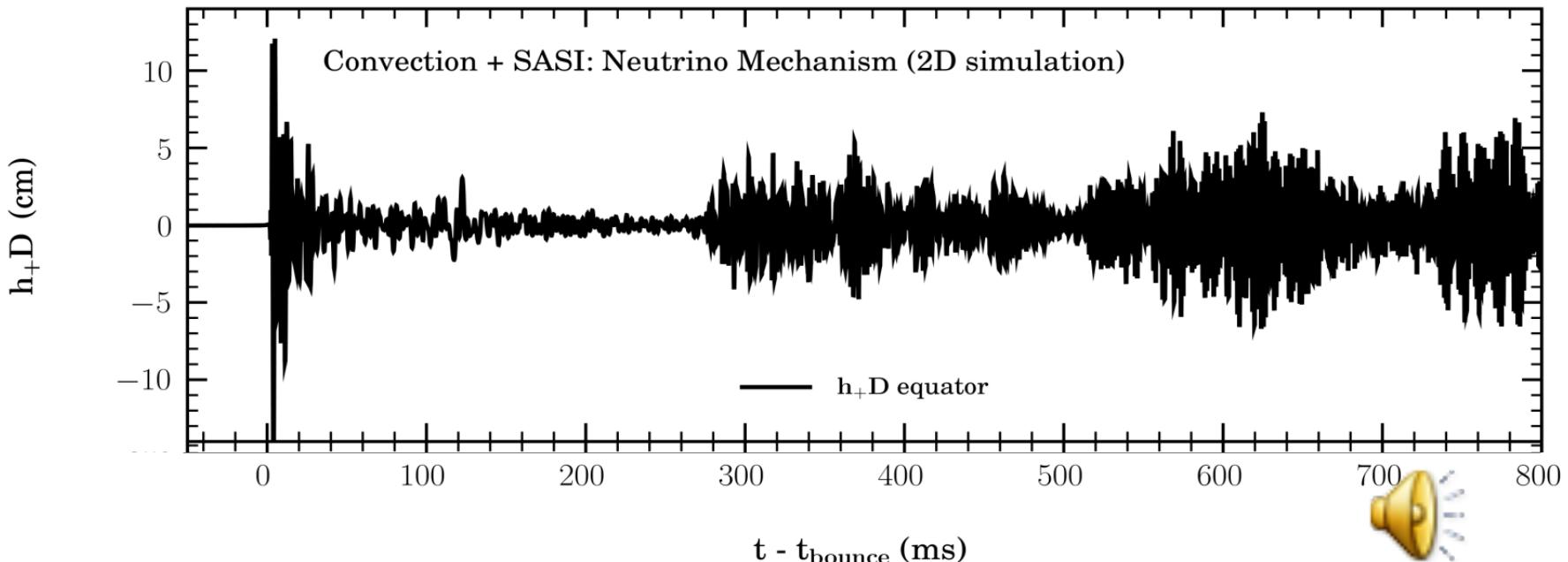
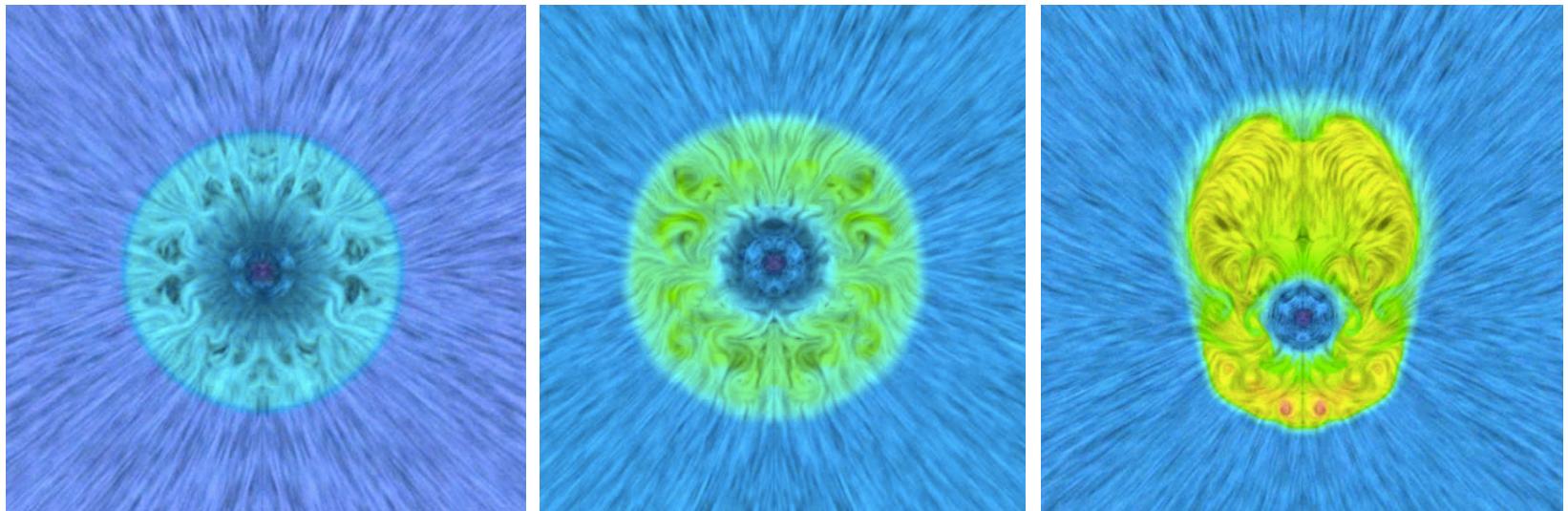
# Example: Merging Double Neutron Stars



- Gravitational waves carry away energy from the orbit.  
-> Orbit shrinks
- Eventually the two stars merge.
- Emitted waves are in the audible band!

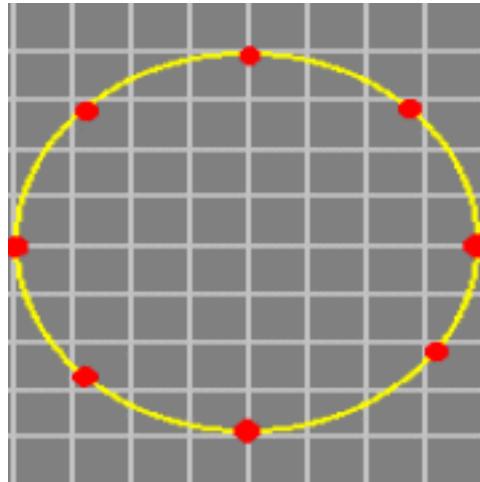


# Example: Core-Collapse Supernova

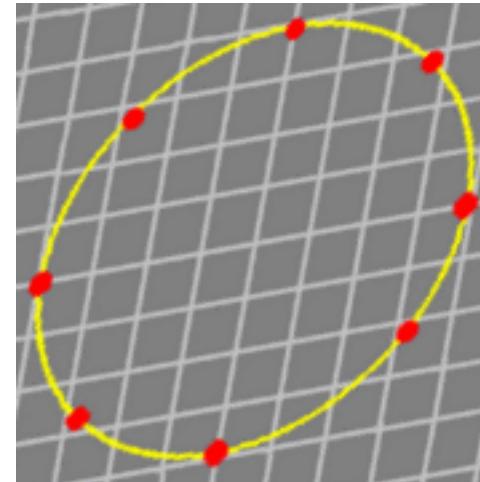


# Gravitational Wave Observation

Effect of GWs on rings of test masses is a bit strange:



“+ Polarization”



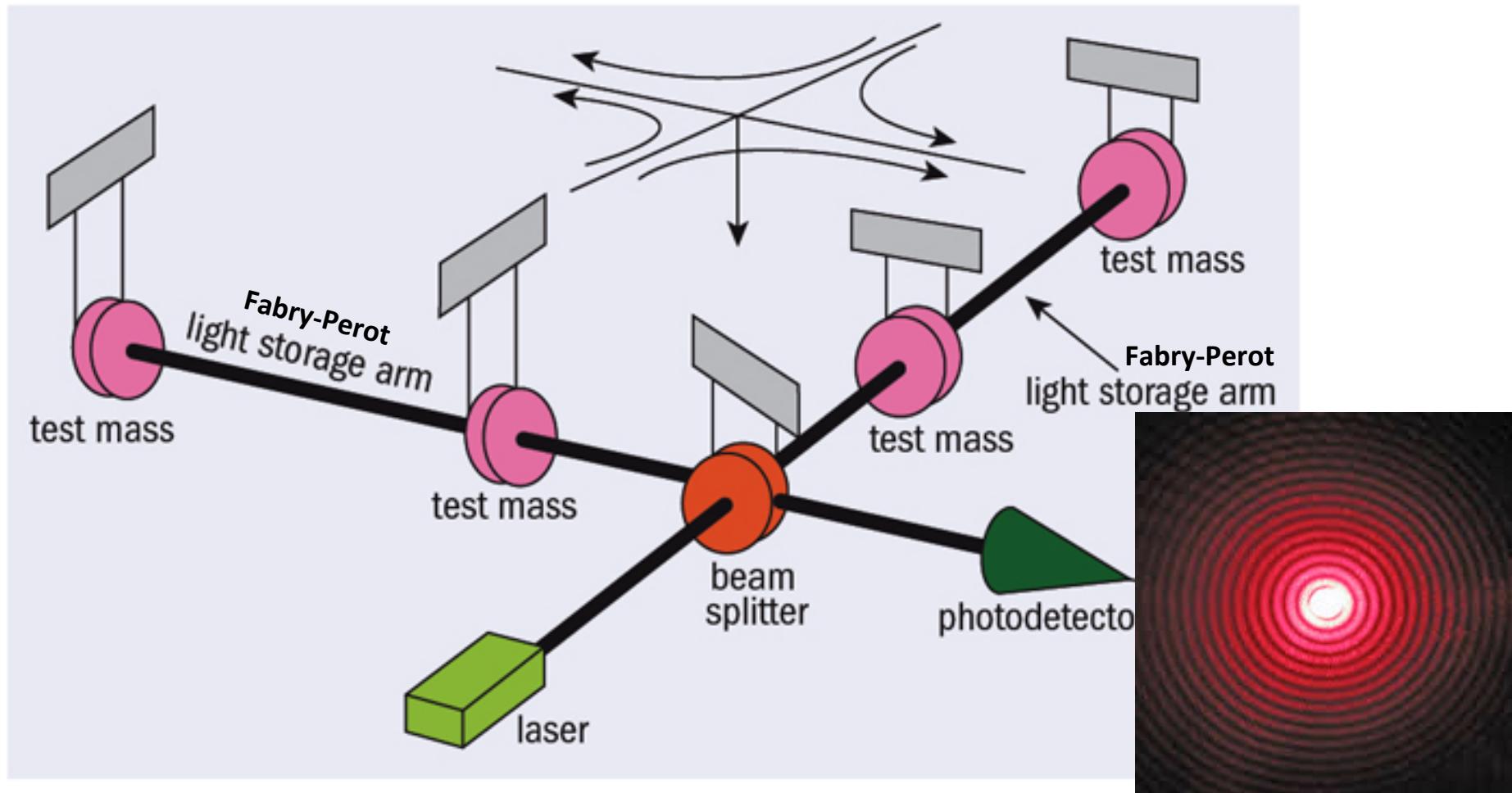
“x Polarization”

Stretching & Squeezing:

**Distance changes between test masses!**

-> Need an instrument that is really good at measuring displacements!

# Gravitational Wave Interferometer



**Michelson-type light interferometer.**

Concept for gravitational wave detection invented by Rai Weiss (MIT)

Laser light “interferes” with itself -> interference pattern.  
Change of arm-length -> change of pattern.

# Laser Interferometer Gravitational-Wave Observatory



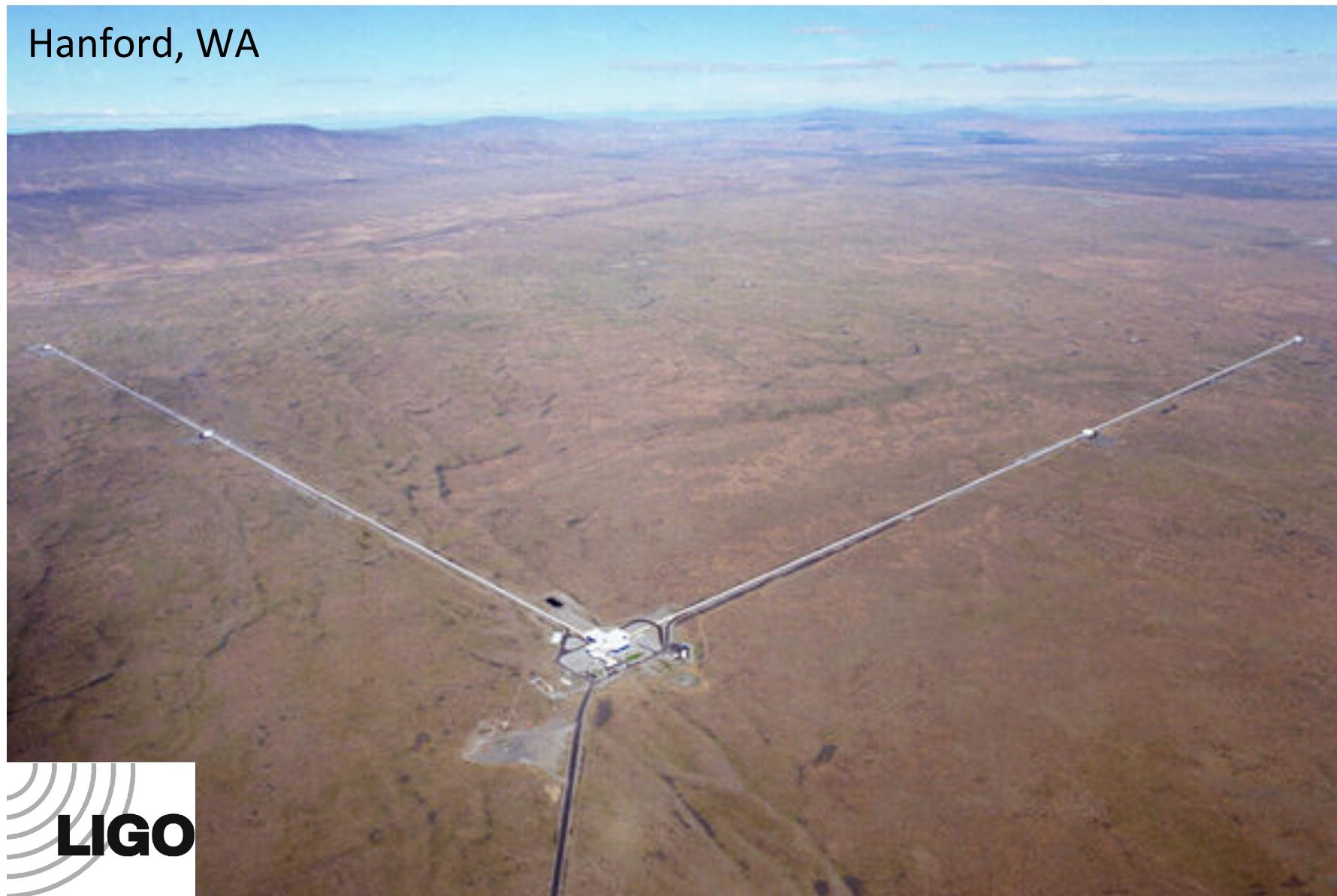
- GWs change the distance between test masses very slightly.  
Distance change:  $\Delta L$     Distance:  $L$
- Strength of a GW from a Milky Way supernova:  
$$\Delta L/L \sim 10^{-22} = \frac{1}{1000000000000000000000000}$$
- Want to have a large  $L$  so that  $\Delta L$  is not too tiny.



Kip Thorne, Rai Weiss, Ron Drever

# Laser Interferometer Gravitational-Wave Observatory

Hanford, WA





mid station

# Laser Interferometer Gravitational-Wave Observatory

Livingston, LA



**Initial LIGO: 2000-2010**  
currently being upgraded  
**to Advanced LIGO**



**Advanced LIGO  
will be 10 x more  
sensitive!**

# The Advanced GW Detector Network: 2020+

Advanced LIGO  
Hanford 2015+

GEO 600 (**operating**)

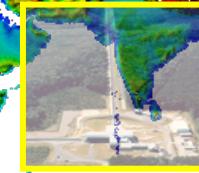


Advanced LIGO  
Livingston  
2015+

Advanced  
Virgo 2015+

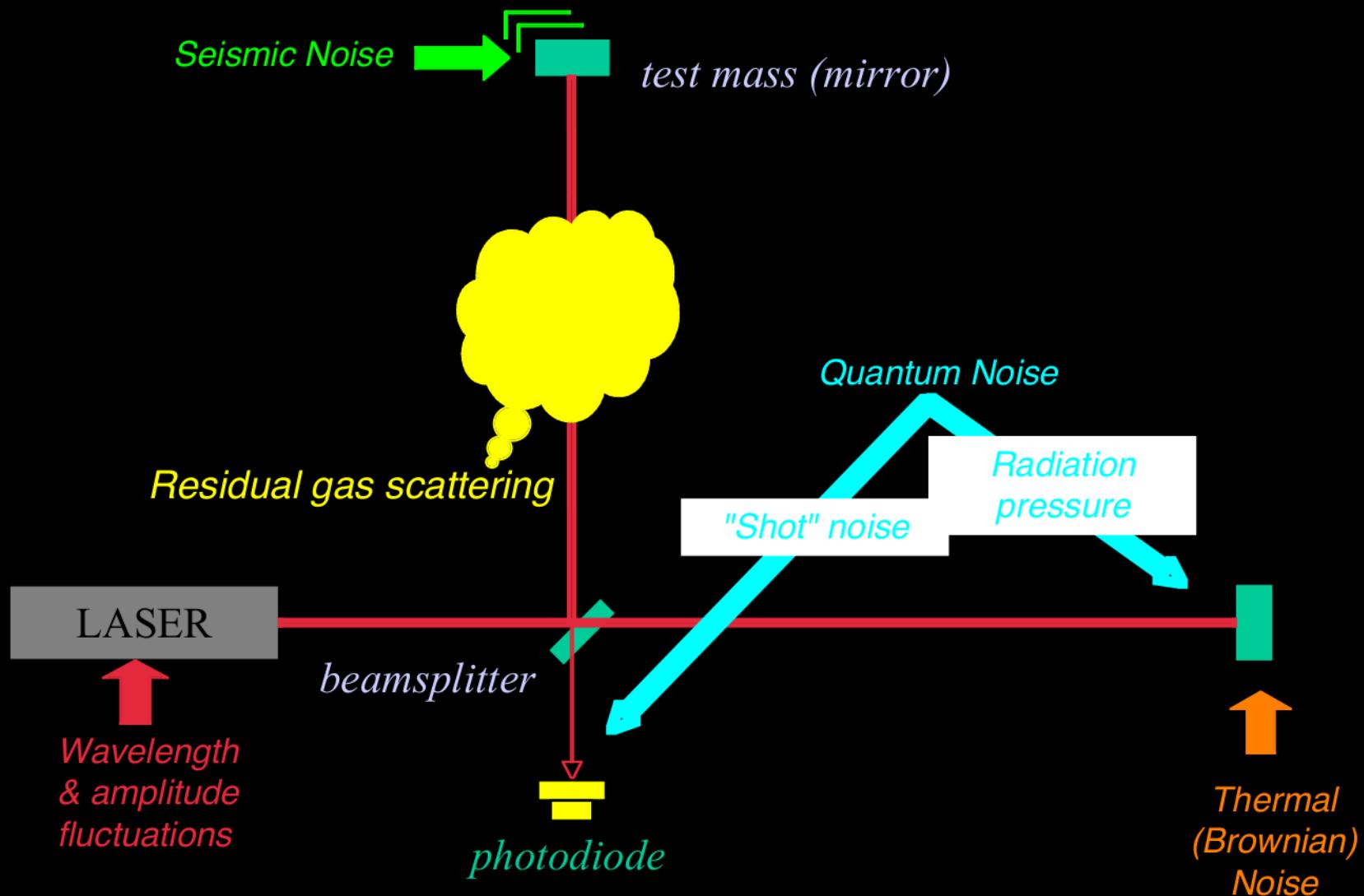


**LIGO India  
2020+**



KAGRA  
2017+

# Major Problem: Background Noise!



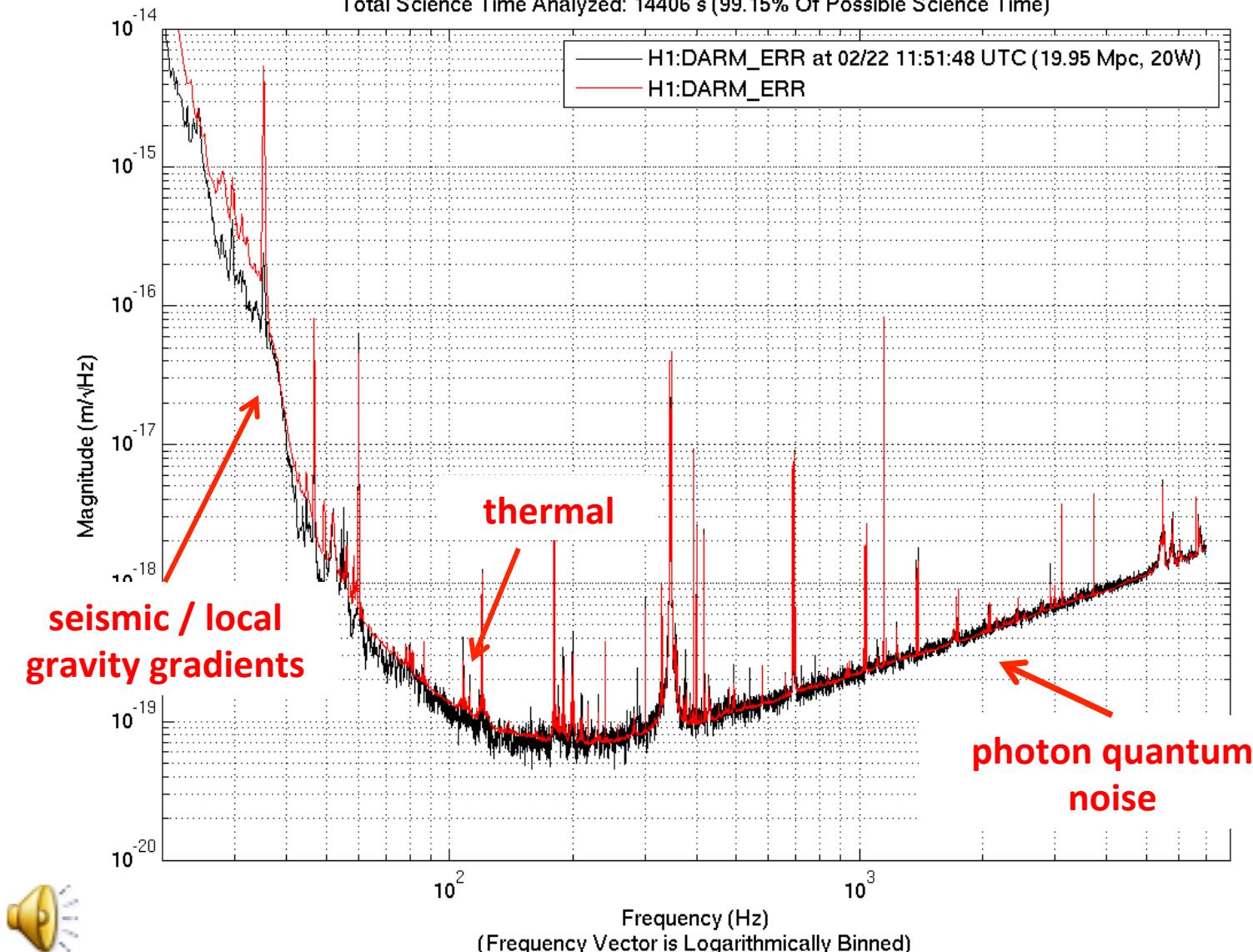
(by R. Adhikari)

# Gravitational Wave Detection

H1:DARM\_ERR at 20W (05/13 22:43:33 UTC - 05/14 06:43:33 UTC)

Range Of Calibrated Spectrum: 18.04 Mpc

Total Science Time Analyzed: 14406 s (99.15% Of Possible Science Time)



# Anthropogenic Noise...

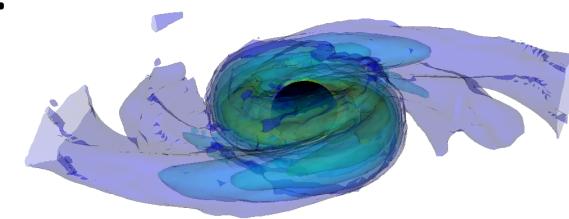


+ trucks, trains, tree cutting, rush hour on highways...

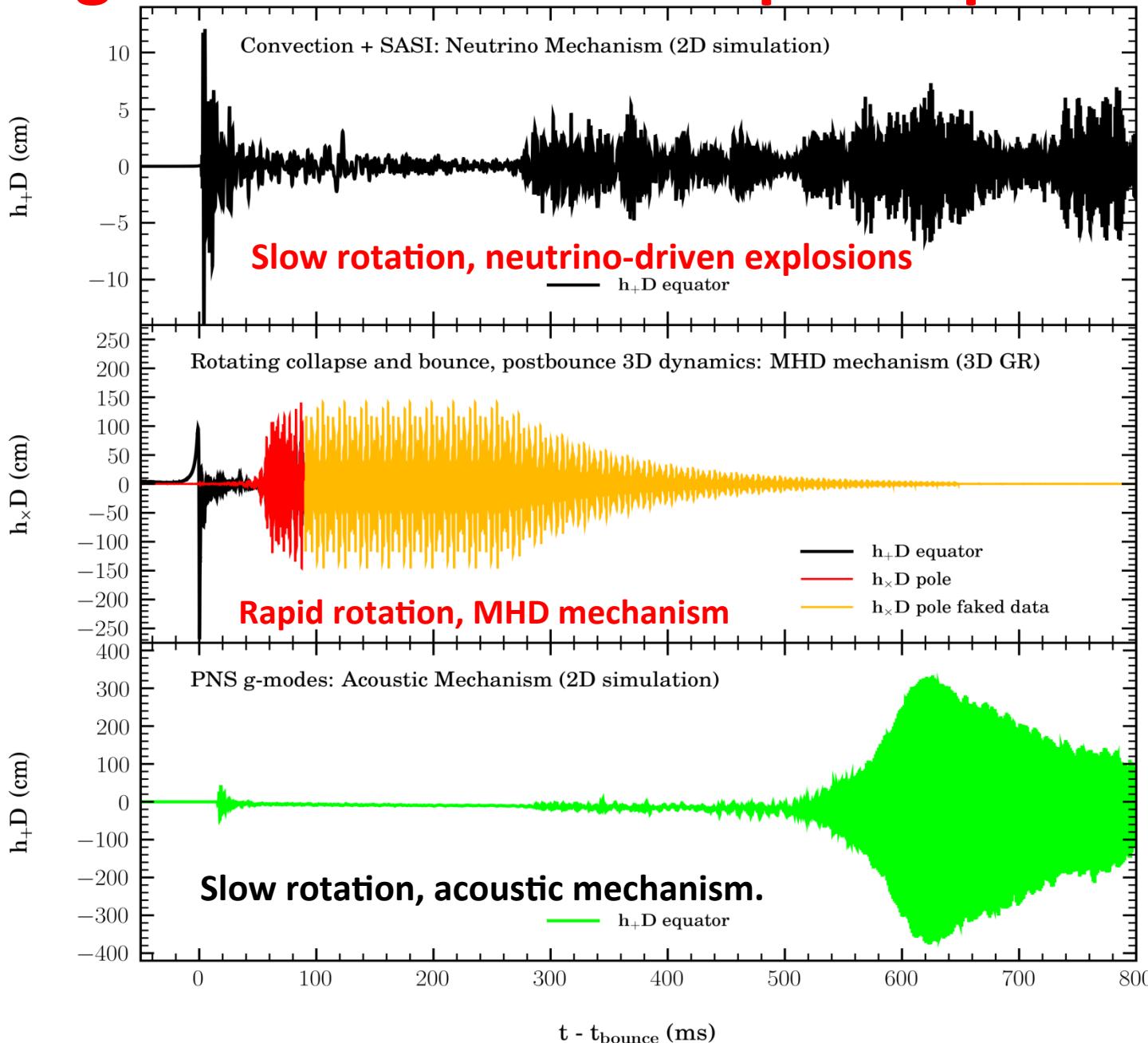


# What Advanced LIGO will do:

- First direct detection of gravitational waves ~2015-2017:  
Inauguration of **Gravitational Wave Astronomy**!
- First detection: Most likely a merging double neutron star system millions of lightyears away!
- Detections are expected to be frequent; more than a few per year.
- Network of Advanced LIGO will be able to point normal telescopes for follow-up observations!
- Will detect gravitational waves from the next galactic core-collapse supernova! -> test theoretical supernova models!
- + much more additional exciting astrophysics!



# GW Signals from Core-Collapse Supernovae



Now:

Wait for the next  
galactic supernova!



**Betelgeuse**  
(Hubble Space Telescope)

# Help us at LIGO next Summer!

## LIGO Research Experience for Undergrads: Summer Undergraduate Research Fellowship (**SURF**) Program

A summer full of exciting research at LIGO Laboratory at Caltech or at the Observatories in Hanford, WA & Livingston, LA.

<http://www.ligo.caltech.edu/REU>



Interested?  
**E-mail Prof. Steve Drasco**  
**drascost@grinnell.edu**



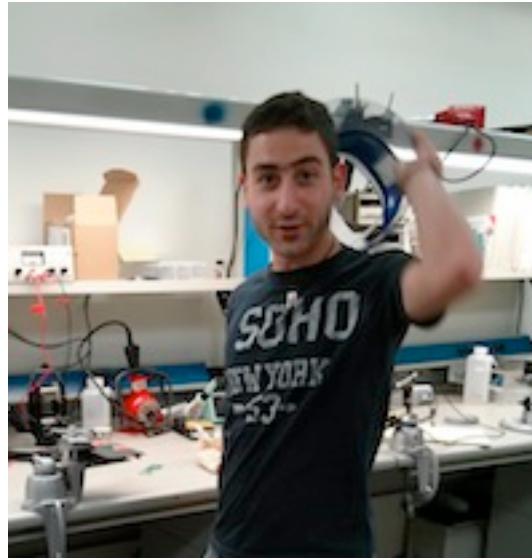
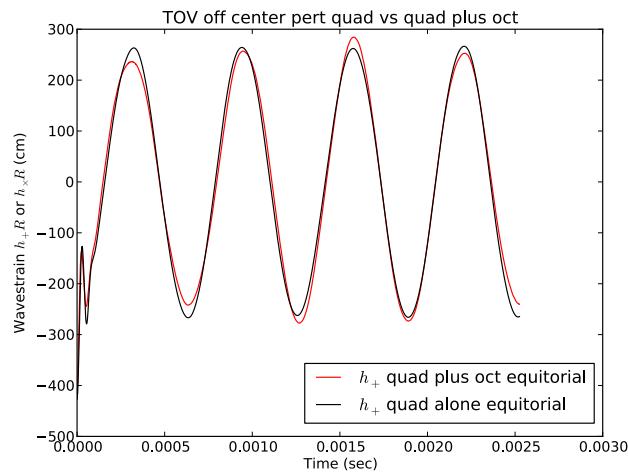


# Grinnell Students @ Caltech/LIGO

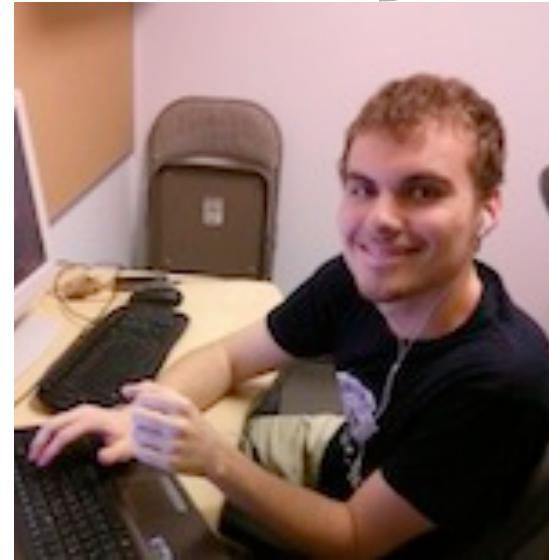
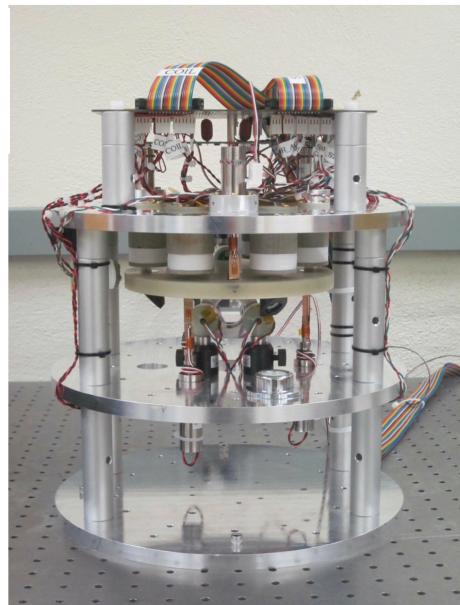


James St. Germain-Fuller

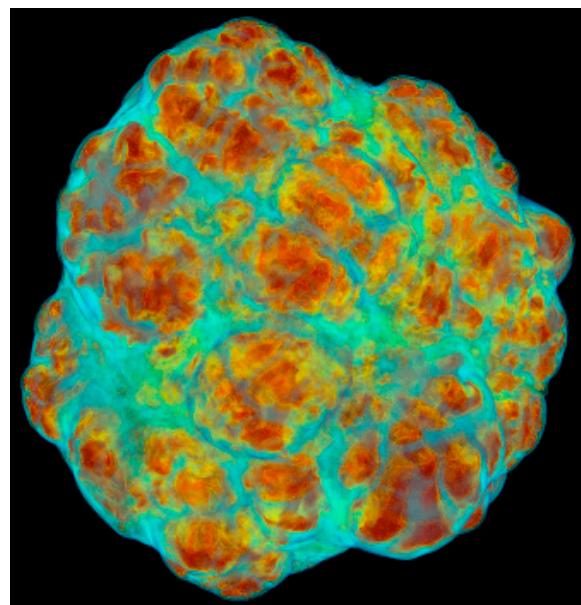
$$h_{TT}^{ij} = \frac{4}{x} \left[ \partial_t \int d^3 x' (-g) T^{0j} x'^i + n_k \frac{1}{2} \partial_t^2 \int d^3 x' (-g) (T^{0i} x'^j x'^k + T^{0j} x'^i x'^k - T^{0k} x'^i x'^j) \right]_{t-x}^{TT}.$$

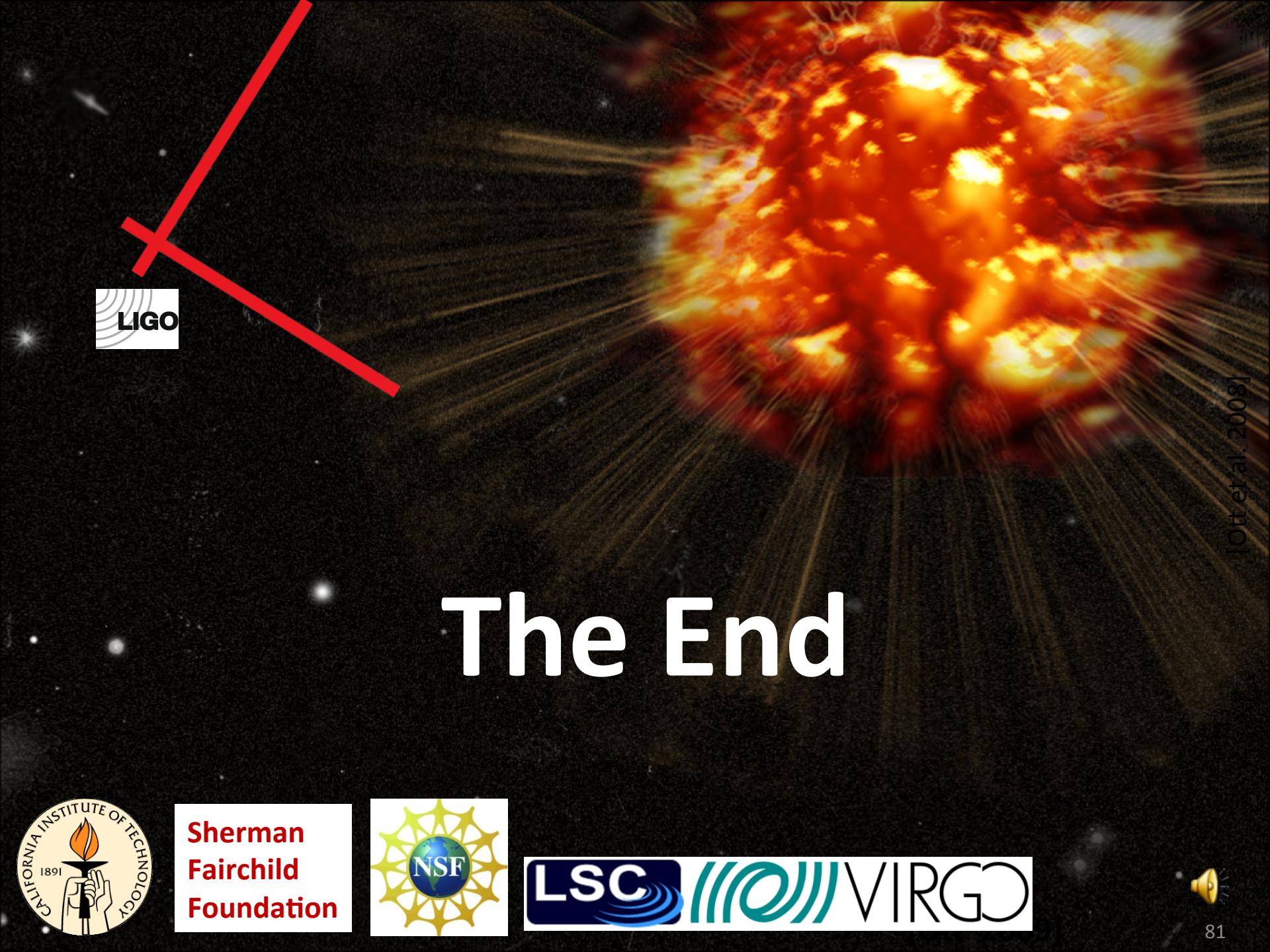


Giorgos Mamakoukas



Marios Tsekitsidis



A dramatic image of a supernova explosion, with intense orange and yellow light rays radiating outwards against a dark background.

The End

[Ott et al. 2008]



**Sherman  
Fairchild  
Foundation**



**LSC**  **VIRGO**

