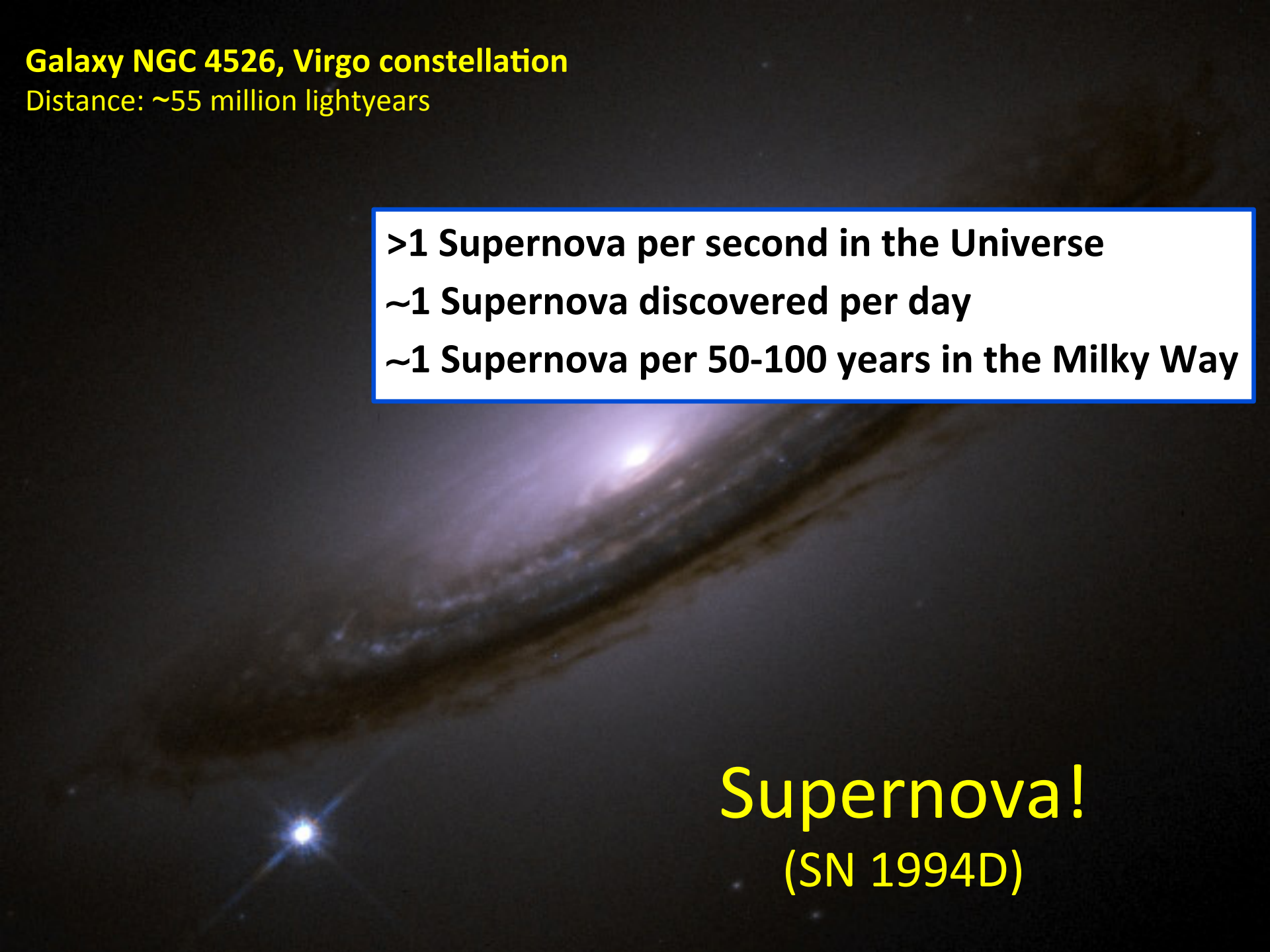
The Explosive Death of Stars & The Birth of a New Astronomy

The 2013 Squire Lecture

Christian D. Ott
California Institute of Technology


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,
Samarkant, Usbekistan

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

Arabic/Persian: SNe 1006, 1054

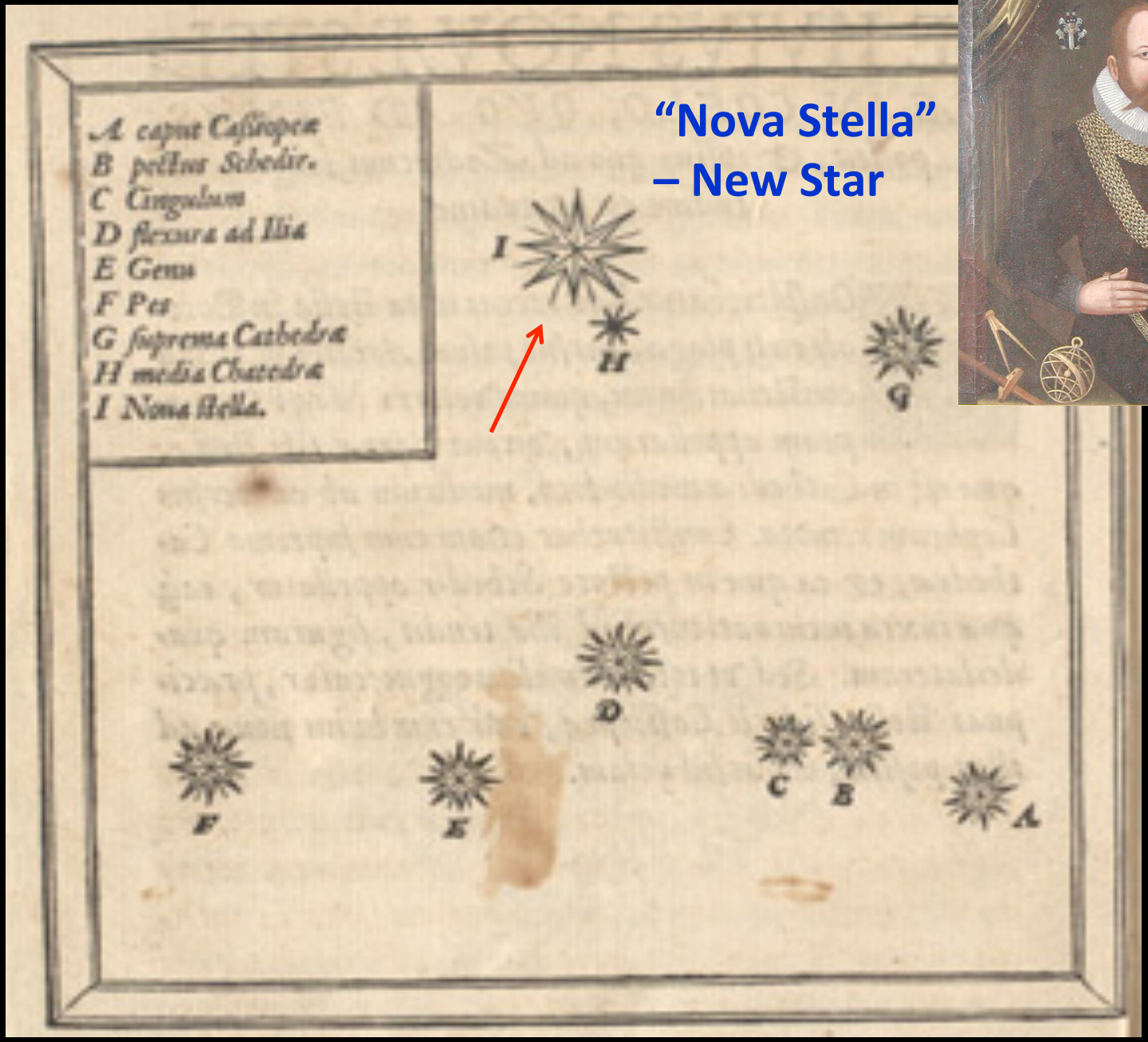
Japan: SNe 1006, 1054, 1181

Europe: SNe 1006, 1054

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

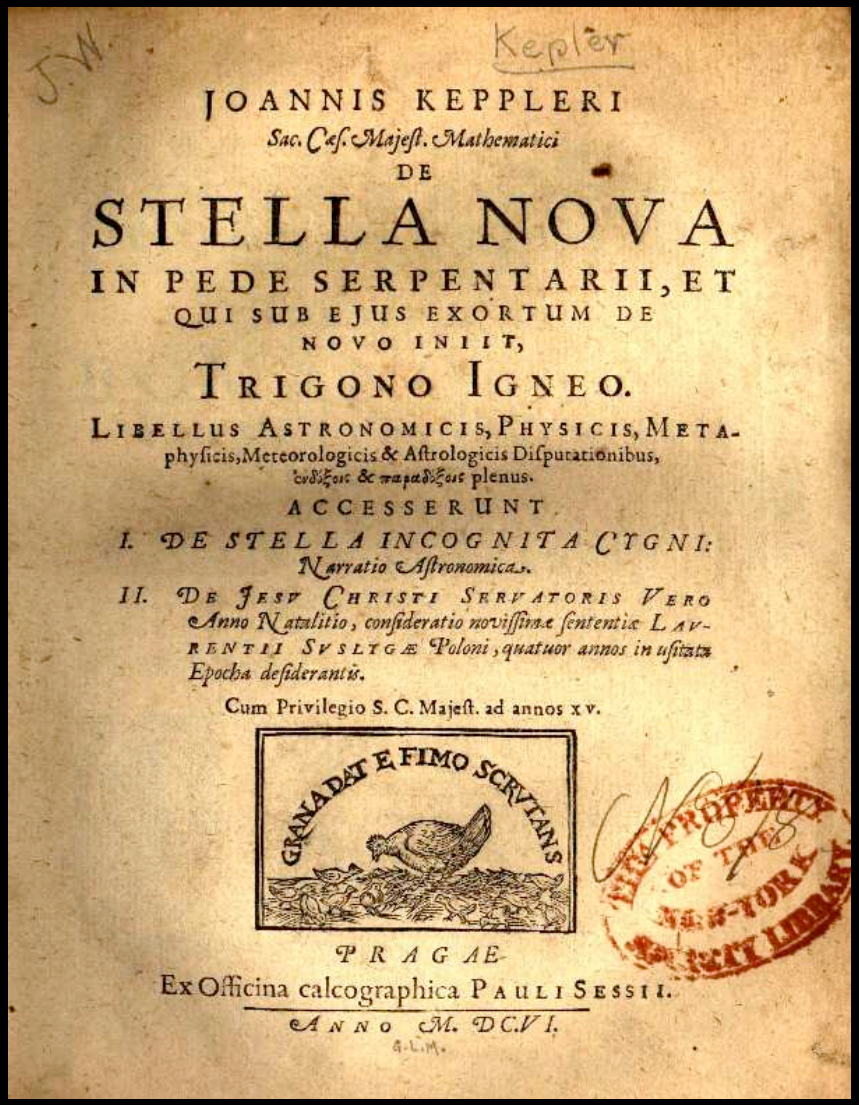
Possible record of SN 1006 (?),
Hohokam tribe, White Tank Mountains, Arizona

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



“Nova Stella” – New Star

Tycho Brahe (1572): „De Nova Stella“



JOANNIS KEPPLERI
Sac. Cæs. Majest. Mathematici
DE
STELLA NOVA
IN PEDE SERPENTARII, ET QUI SUB EJUS EXORTUM DE NOVO INIIT,
TRIGONO IGNEO.

LIBELLUS ASTRONOMICIS, PHYSICIS, METAphysicis, Meteorologicis & Astrologicis Disputationibus, ἐνδείξεσι & παραδείξεσι plenus.

ACCESSERUNT

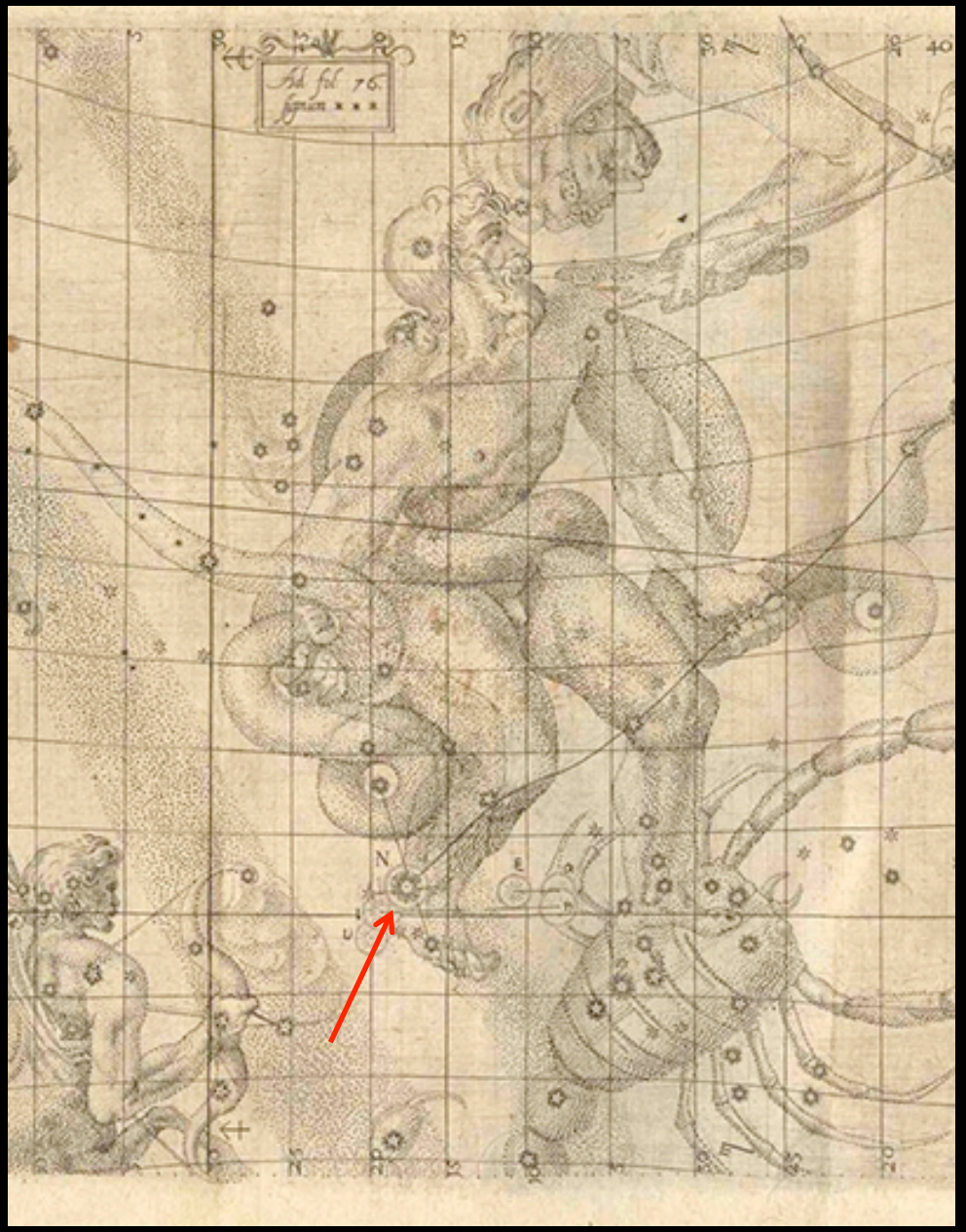
I. DE STELLA INCOGNITA CYGNI: Narratio Astronomica.

II. DE JESU CHRISTI SERVATORIS VERO Anno Natalitio, consideratio novissimæ sententiæ LAURENTII SUSLYGÆ Poloni, quatuor annos in usitata Epocha desiderantis.

Cum Privilegio S. C. Majest. ad annos XV.

GRANA DAT E FIMO SCRUTANS

PRAGAE
Ex Officina calcographica PAULI SESSII.
ANNO M. DC. VI.

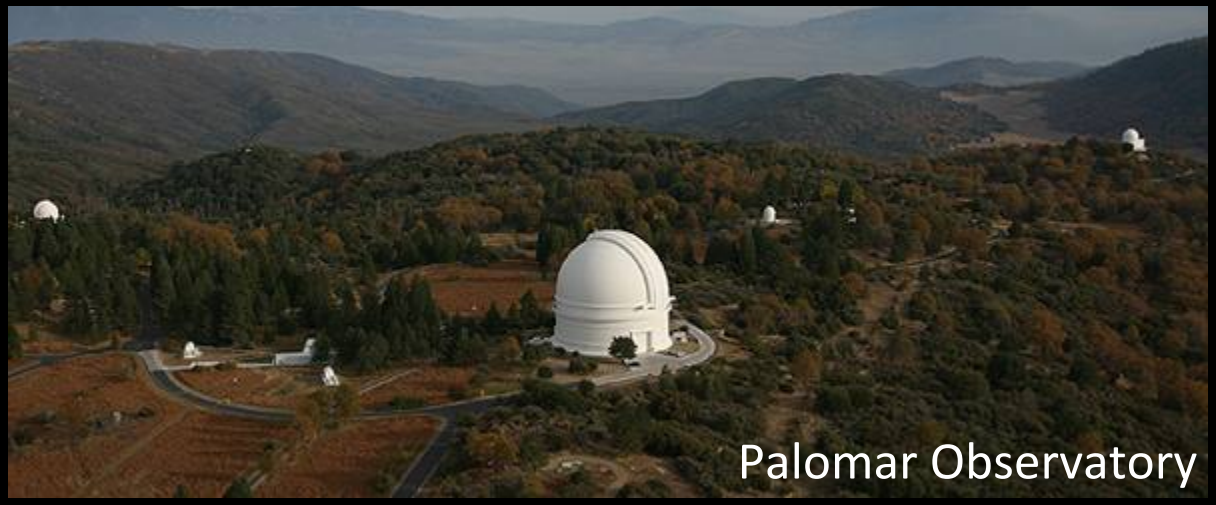


Johannes Kepler (1604): „De Stella Nova“

Mt. Wilson Observatory

Fritz Zwicky
1898-1974

Walter Baade
1893-1960



Palomar Observatory

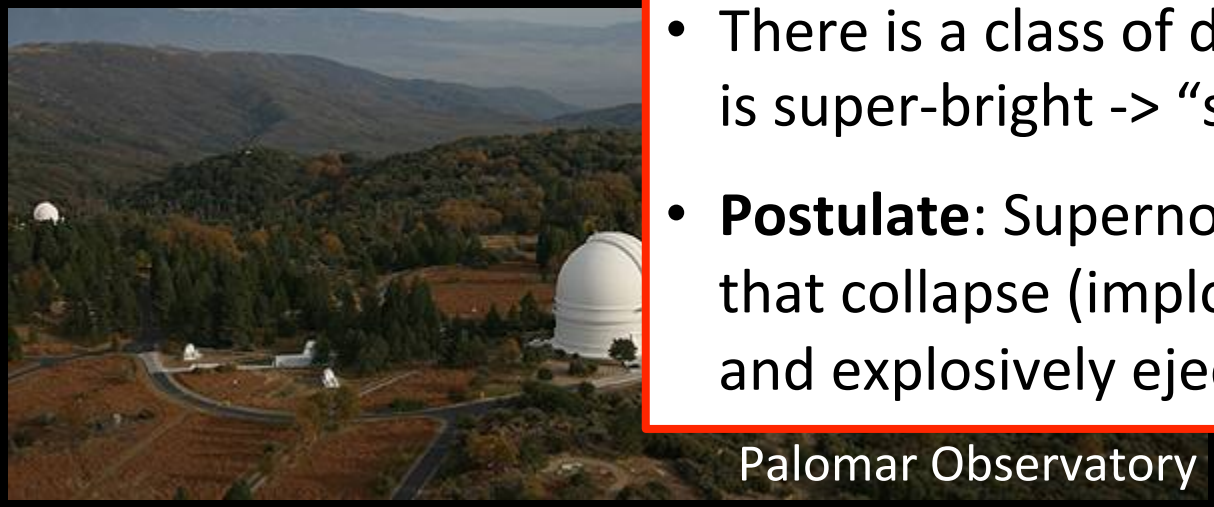
Mt. Wilson Observatory

Fritz Zwicky
1898-1974

Walter Baade
1893-1960

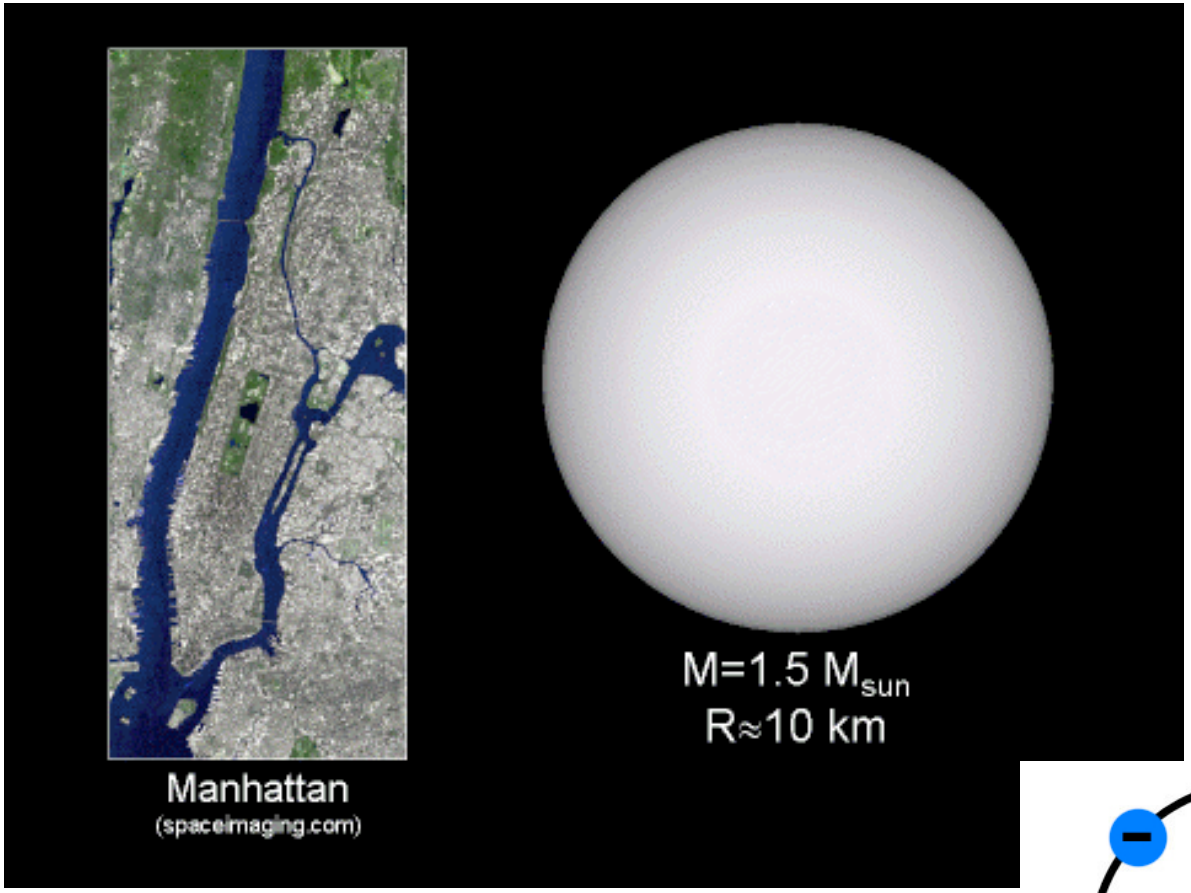
"Supernova" (1934)

- 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

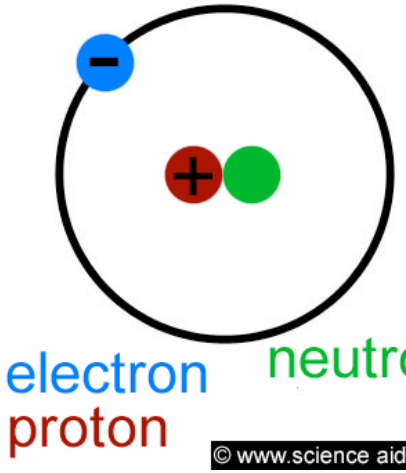


R. Pogge
Ohio State

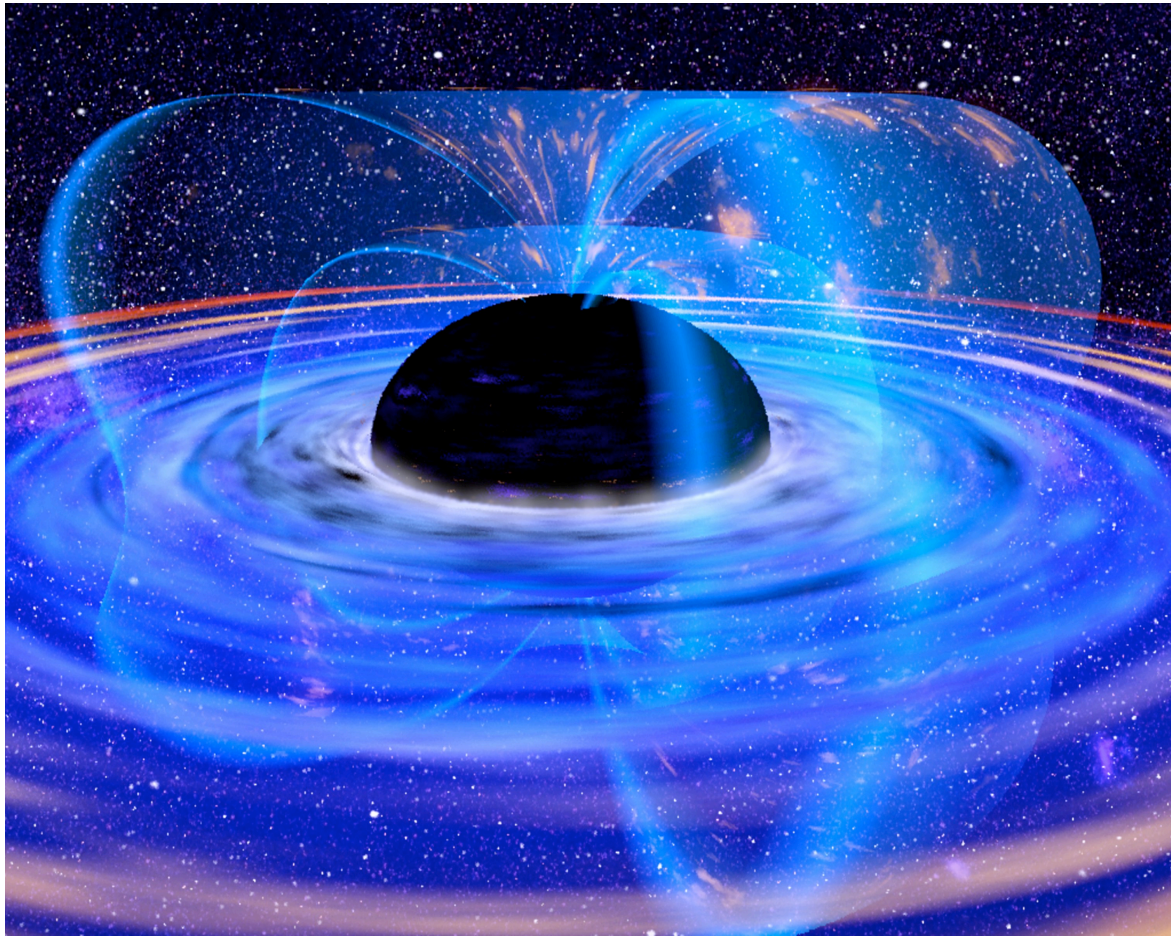
- Density (Mass per volume) in a neutron star is ~10^{15} g/cm^3 (quadrillion times the density of water!)
- Electrons get pushed into protons -> make neutrons

$$p + e^- \longrightarrow n + \nu_e$$ (ν_e = "neutrino")

Hydrogen Atom:



Black Holes

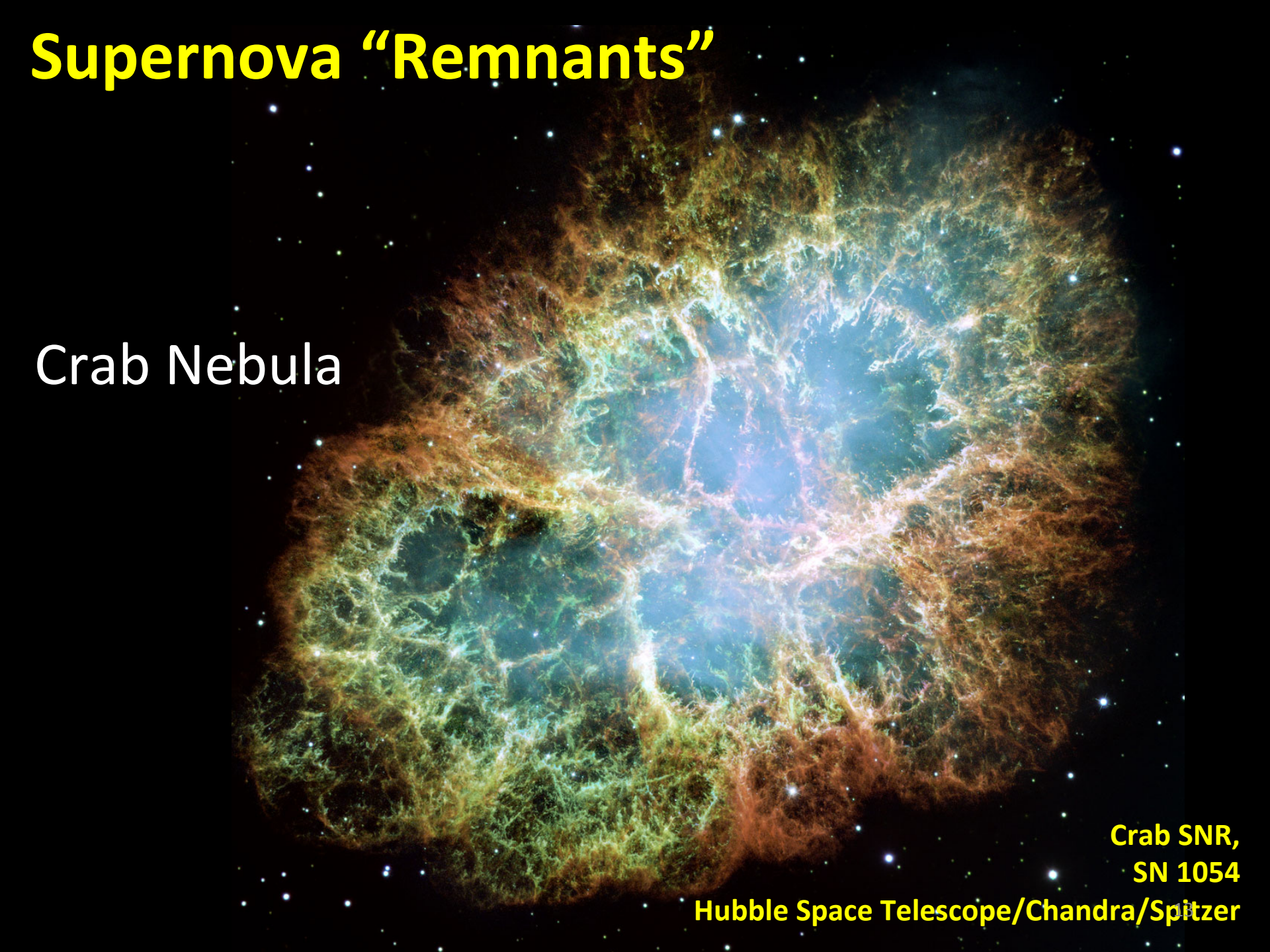


Wikipedia: Artist rendition of a black hole.

- 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”

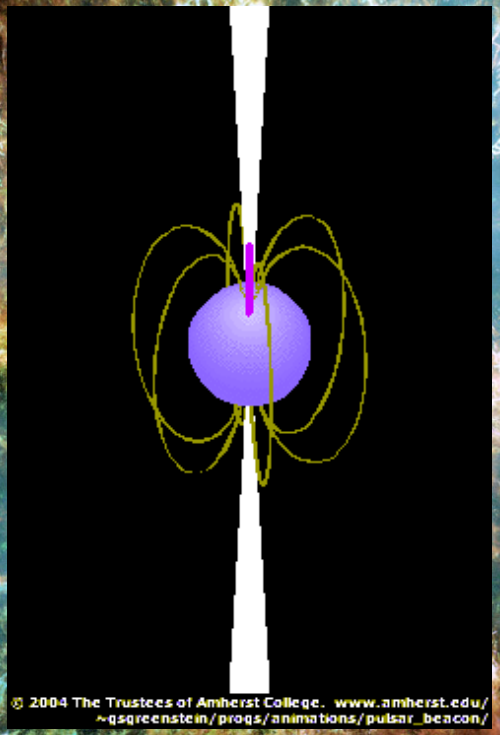
Crab Nebula



Crab SNR,
SN 1054
Hubble Space Telescope/Chandra/Spitzer

Pulsars:

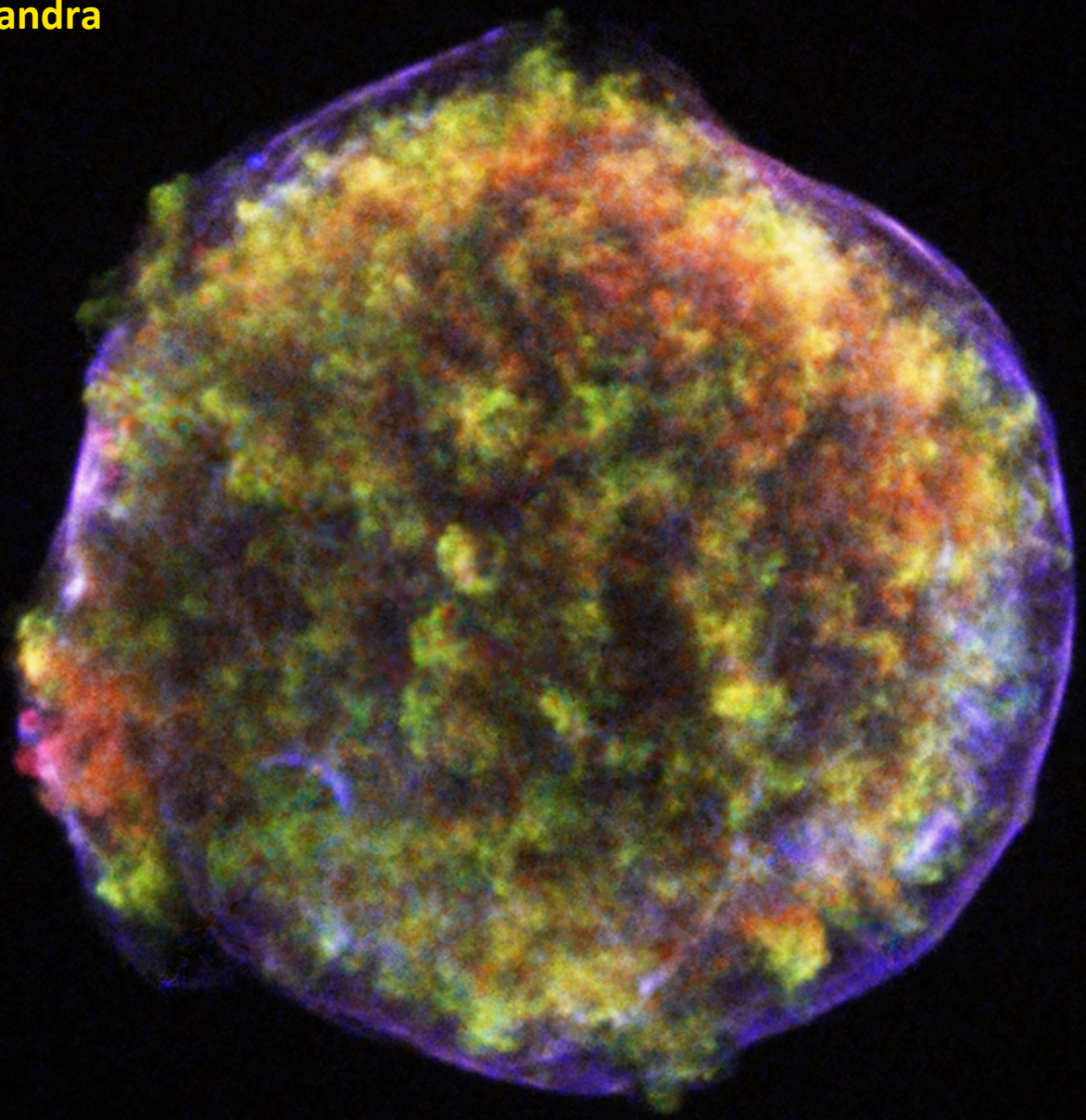
Radio-wave emitting neutron stars



1967: Discovery of Pulsars by Hewish & Bell
Nobel 1974

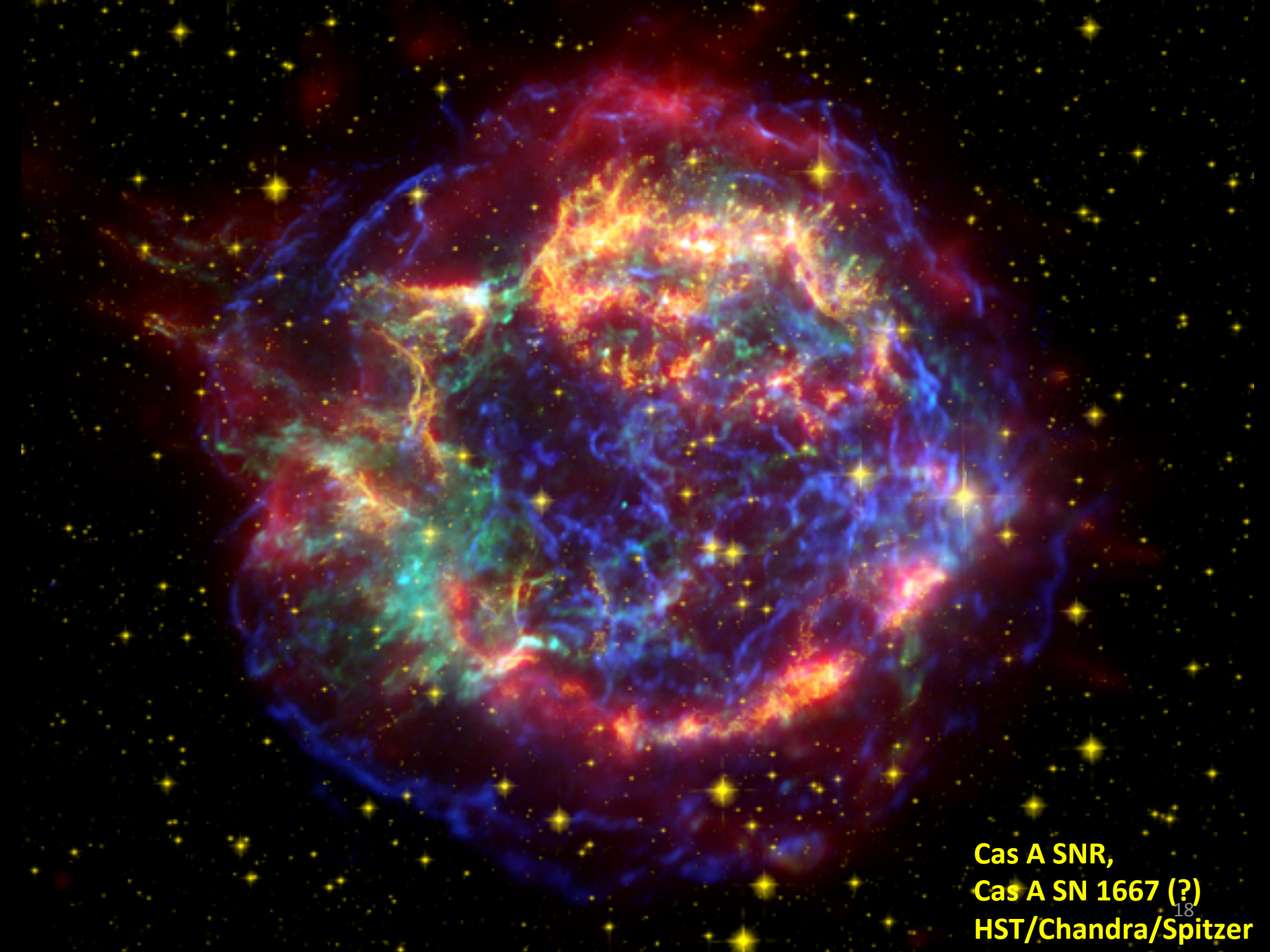
Crab SNR, SN 1054
Hubble Space Telescope/Chandra/Spitzer

Tycho's SN 1572
NASA: Spitzer/Chandra



Kepler‘s SN 1604
NASA: Chandra Telescope

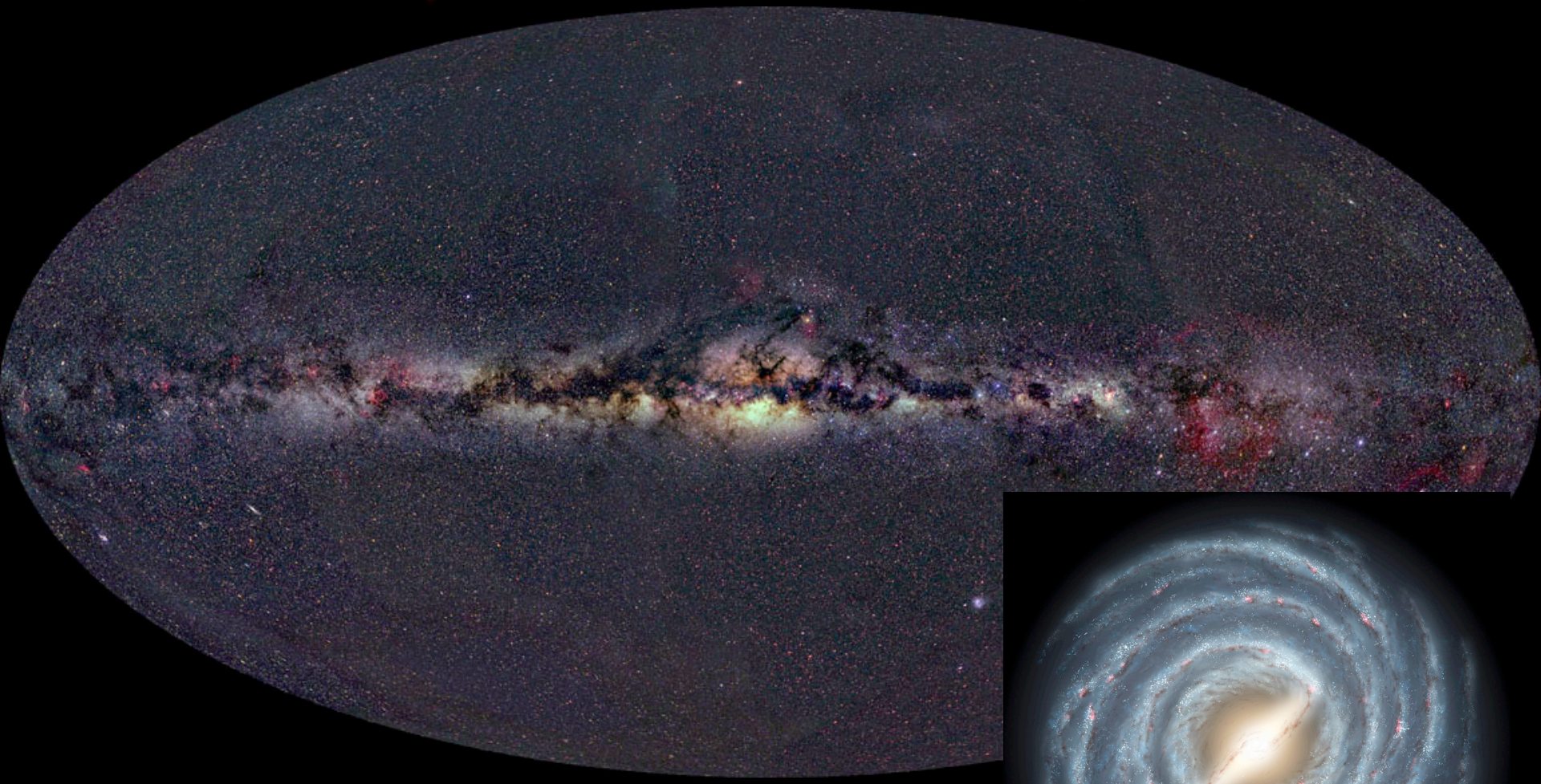
SN 1006


Cas A SNR,
Cas A SN 1667 (?)
HST/Chandra/Spitzer

Chandra X-Ray Observatory

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 ≈ 800 ly

SN1987A, Large Magellanic Cloud
Progenitor star: Blue Supergiant star Sanduleak -69° 220a, 18 M_{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 H Hydrogen 1.00794																	2 He Helium 4.002602
2 3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3 11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4 19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5 37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6 55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7 87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

Atomic # / Symbol / Name / Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

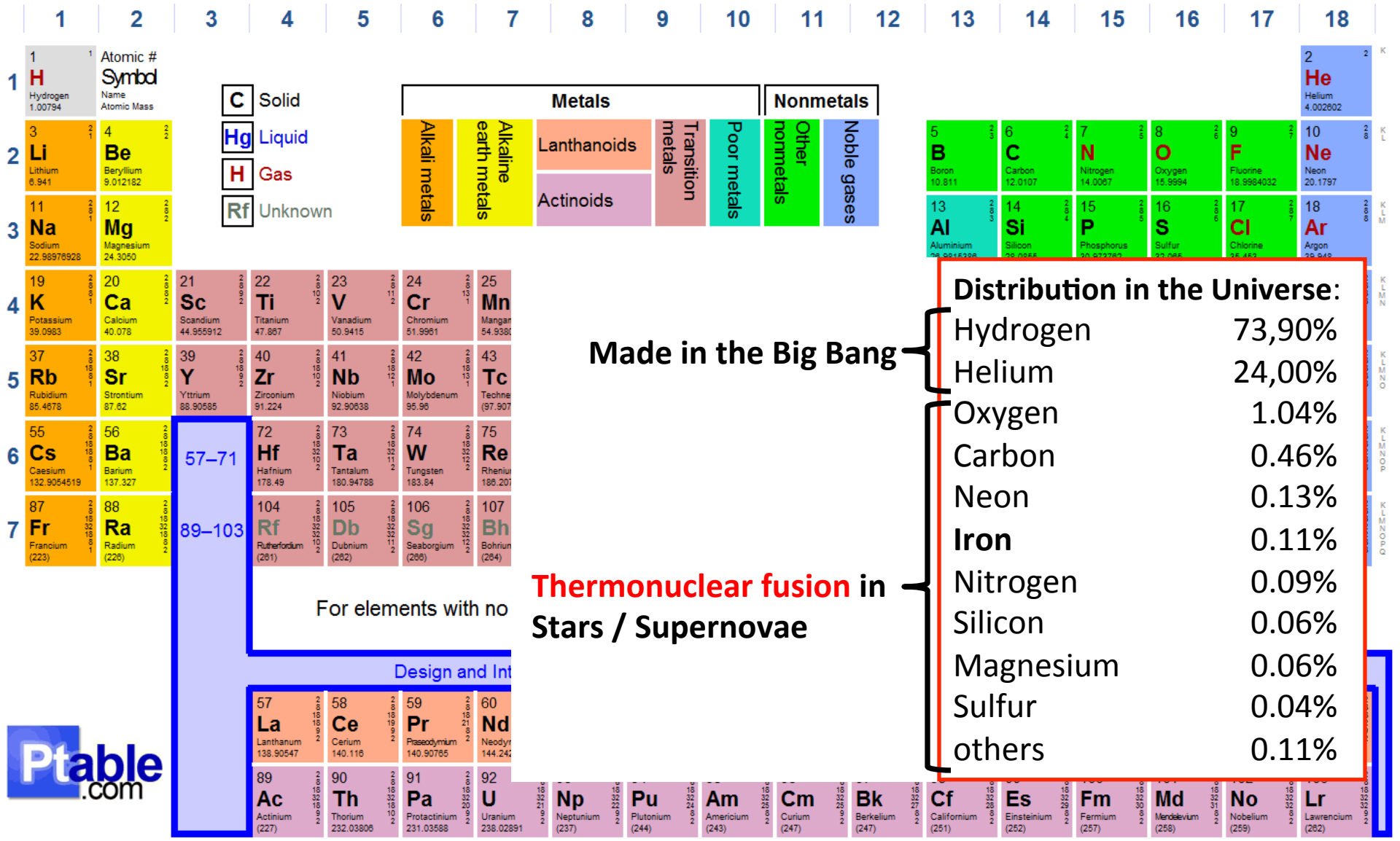
Metals: Alkali metals; Alkaline earth metals; Lanthanoids; Actinoids; Transition metals; Poor metals
Nonmetals: Other nonmetals; Noble gases

			57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
			89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Ptable.com

Periodic Table of Elements



Distribution in the Universe:

Made in the Big Bang

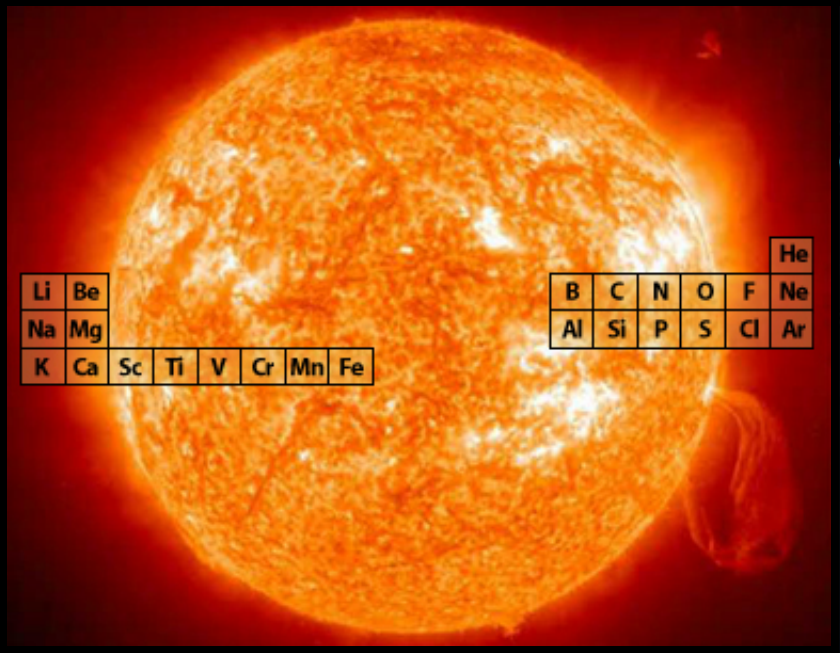
Hydrogen	73,90%
Helium	24,00%

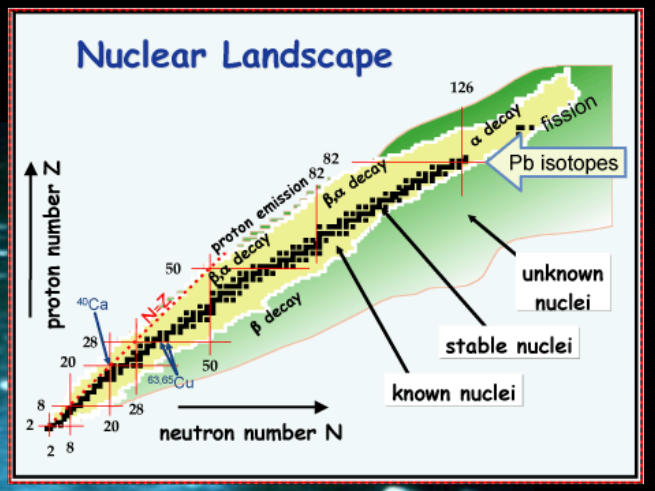
Thermonuclear fusion in Stars / Supernovae

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%

Why do we care about Supernovae?

- SNe are the main cosmic polluters.





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

Source: NASA

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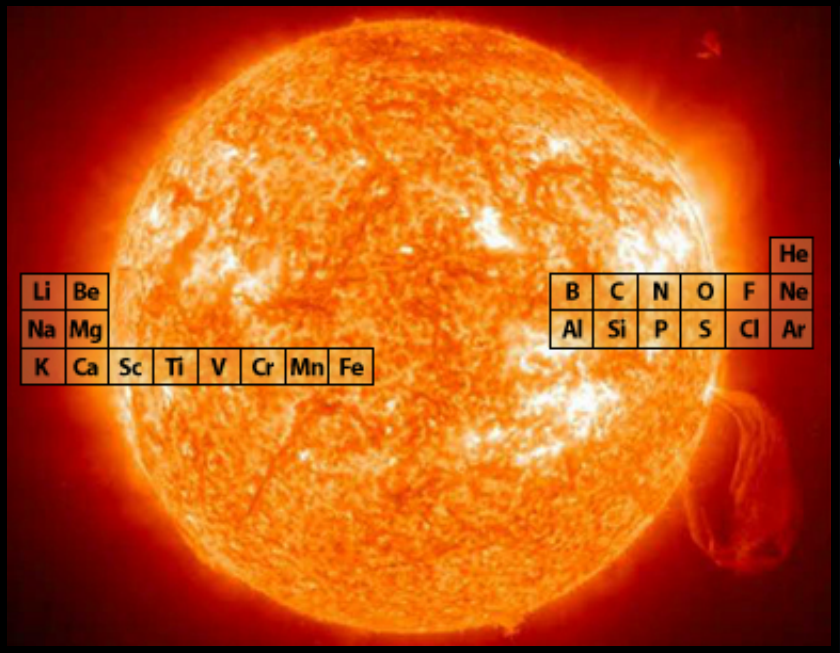

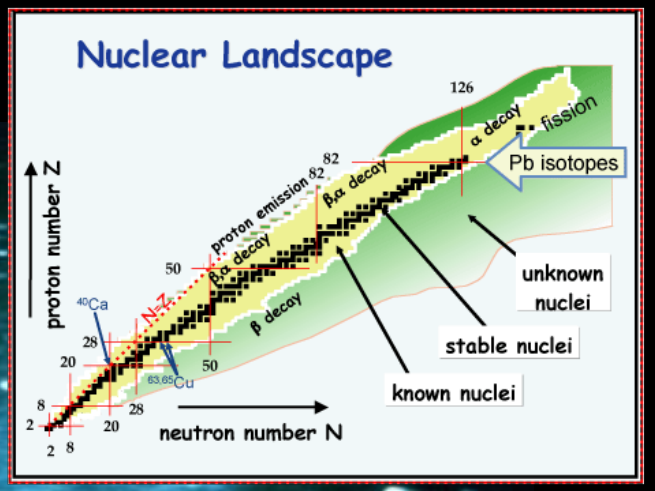

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Source: NASA

- Dynamical impact on galaxy evolution.

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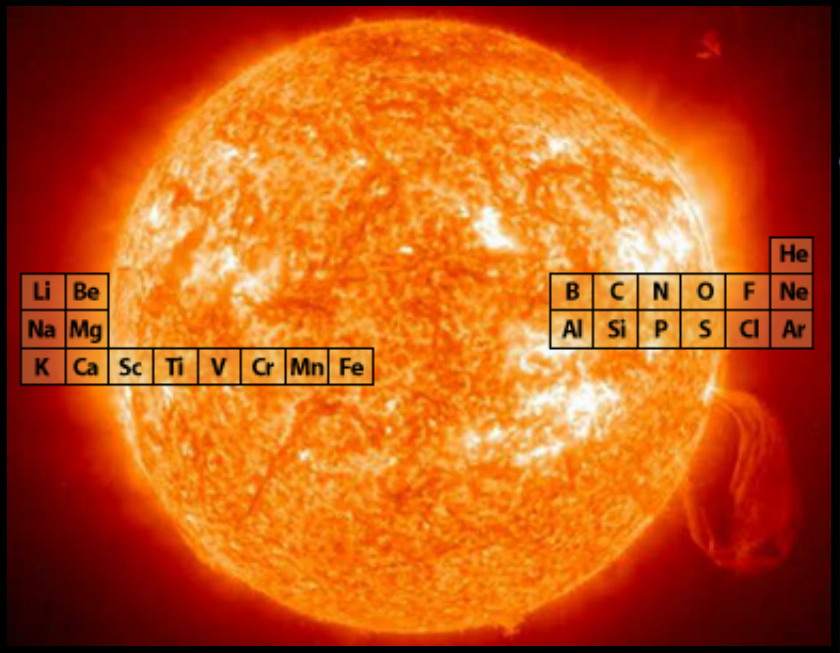

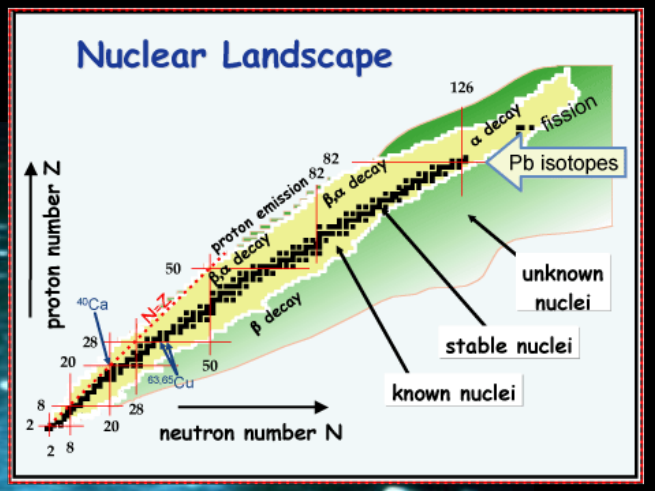

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Source: NASA

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- At least for some supernovae:
  Birth sites of neutron stars and black holes.

Why do we care about Supernovae?

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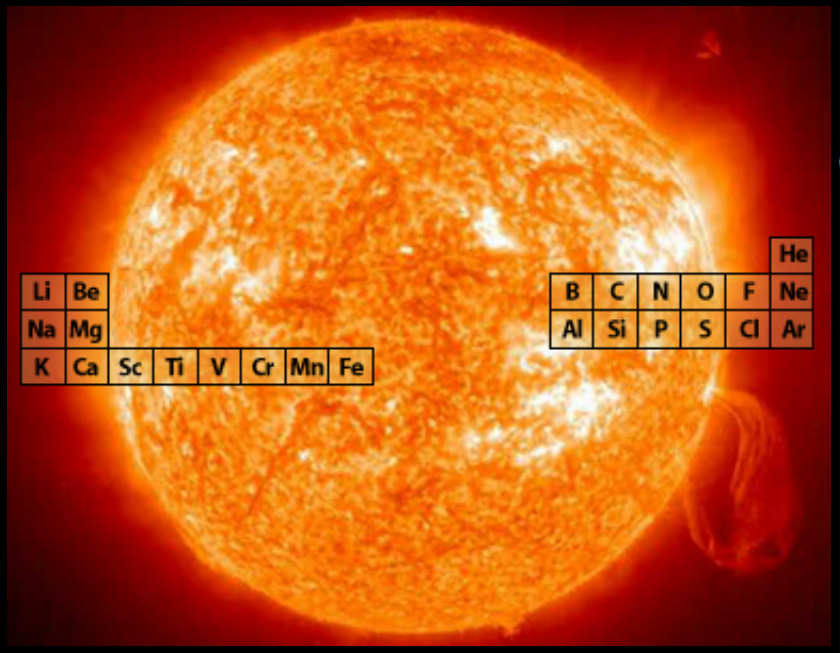

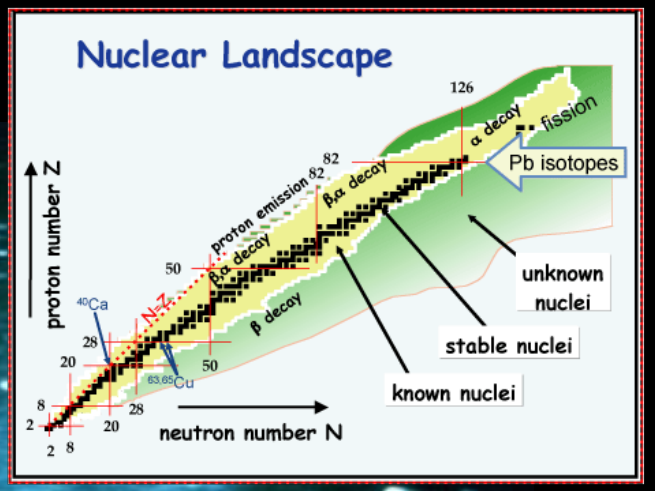

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- At least for some supernovae:
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- Gigantic cosmic laboratories for fundamental physics.

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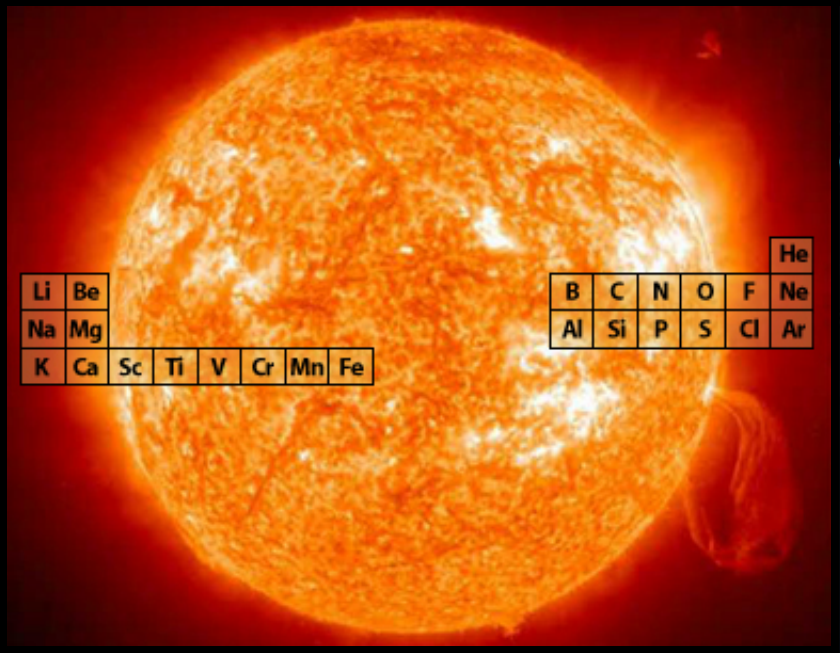

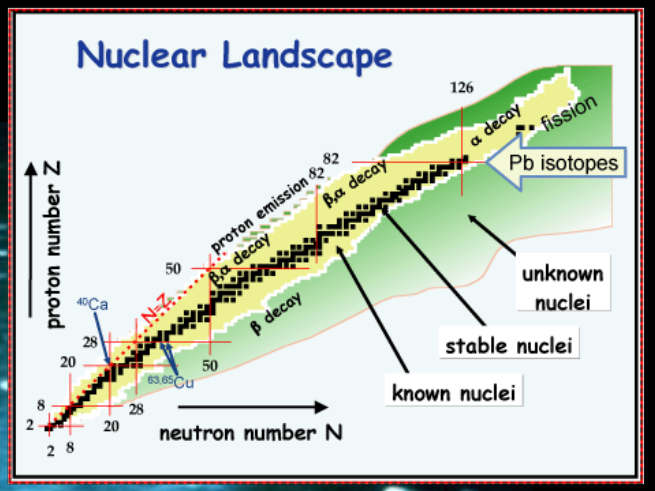

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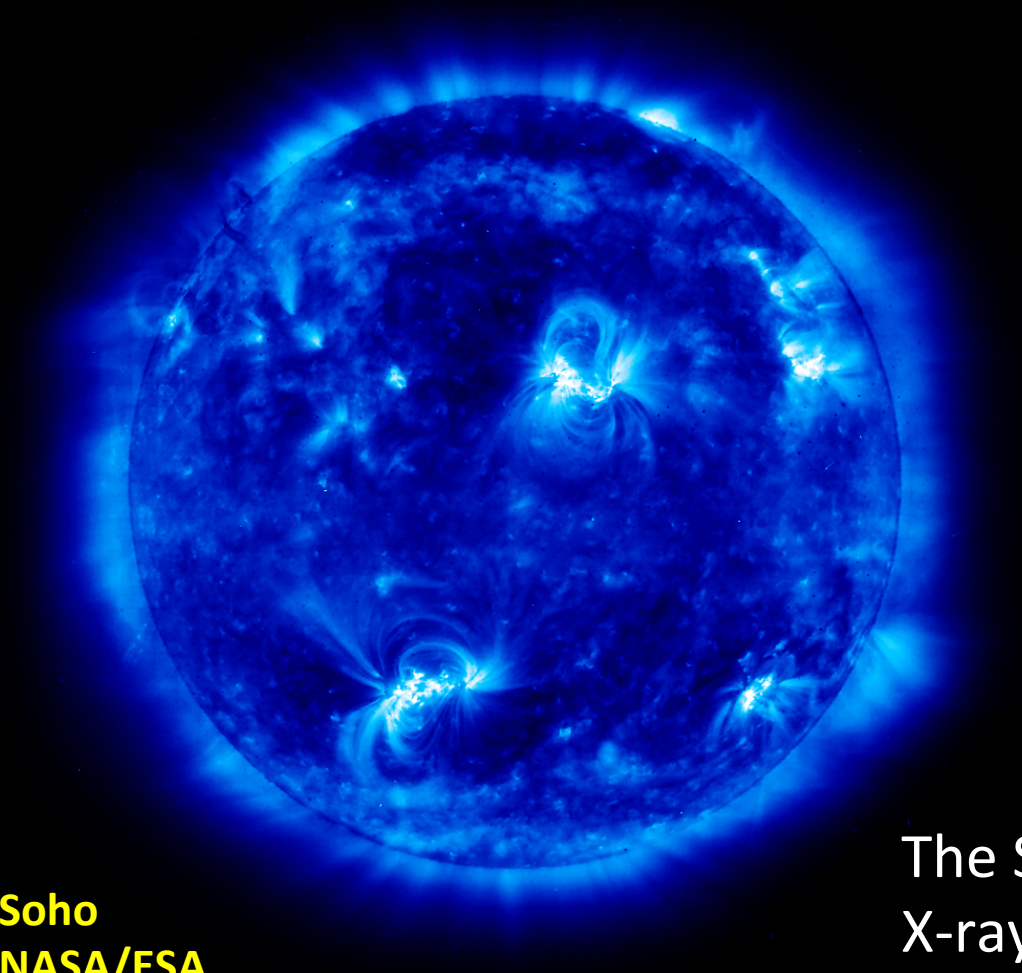
Source: NASA

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

Understanding Supernovae

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



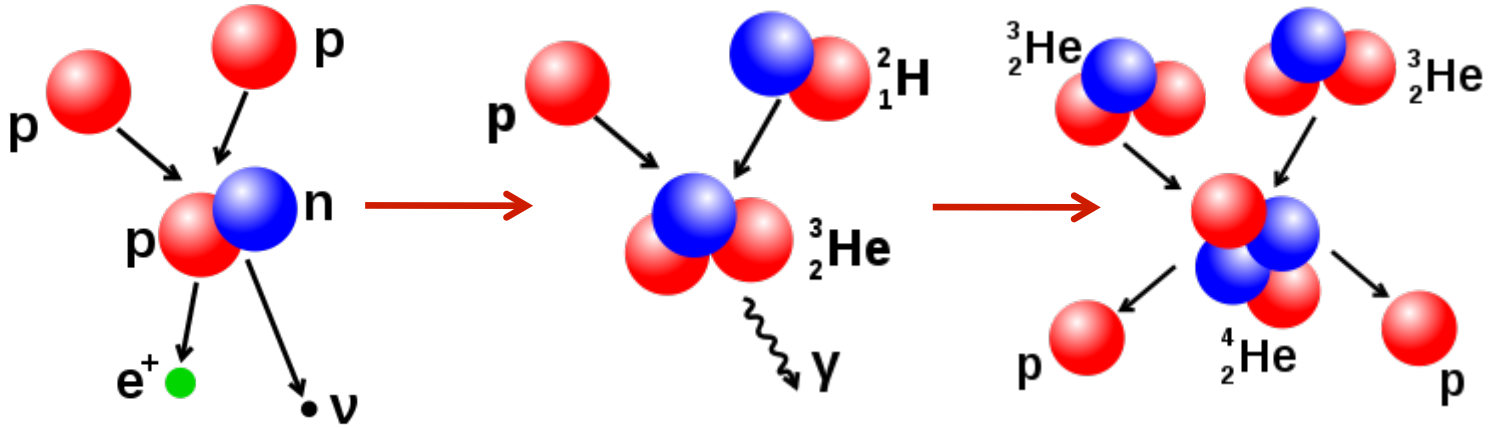
Soho
NASA/ESA

The Sun in
X-rays

171Å *SOHO*/EIT image of the EUV corona (NASA/ESA)

Stellar Evolution

- Stars are power 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!**

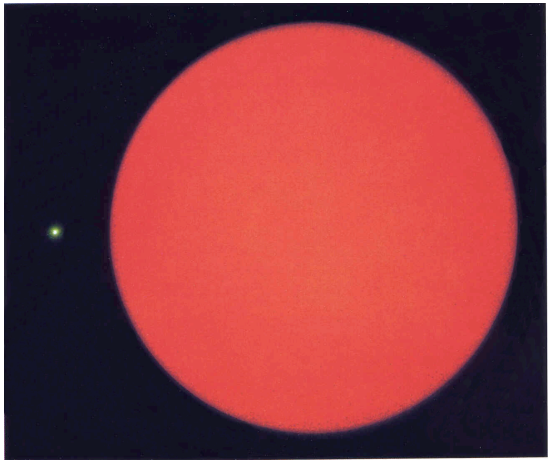
Stellar Evolution

- Stellar Mass M: ~0.5 M_{Sun} – 6 M_{Sun}

  Hydrogen->Helium->Carbon/Oxygen.

- Stellar Mass M: ~6 M_{Sun} – 9 M_{Sun} (exact range uncertain)

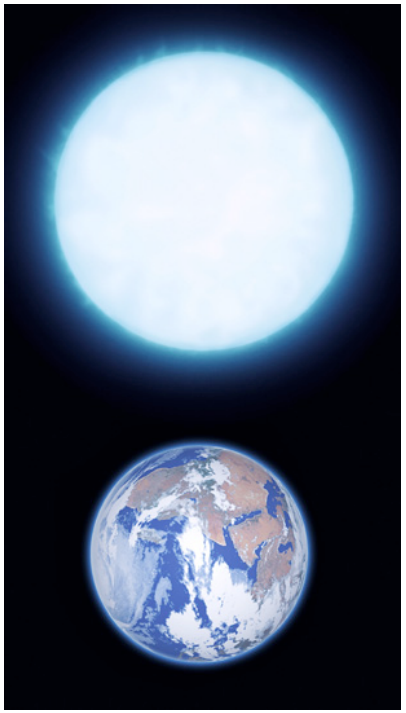
  Hydrogen->Helium->Carbon/Oxygen->Oxygen/Neon



"Red giant" star

Outer stellar envelope ejected.

(takes thousands of years)



"White dwarf" star

Eskimo Nebula
NASA/Hubble Space Telescope

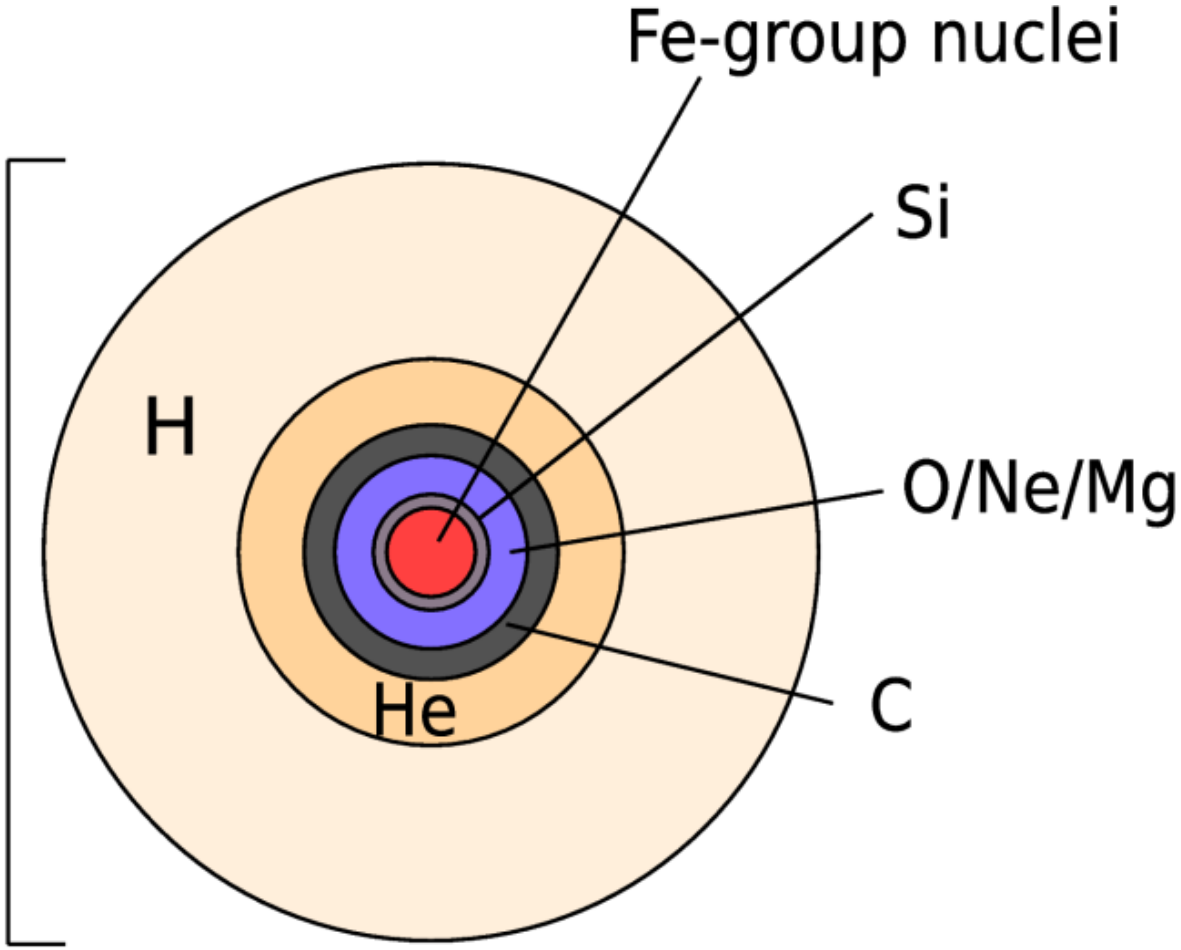
Red giant star ejecting its envelope: a White Dwarf star remains.

Stellar Evolution

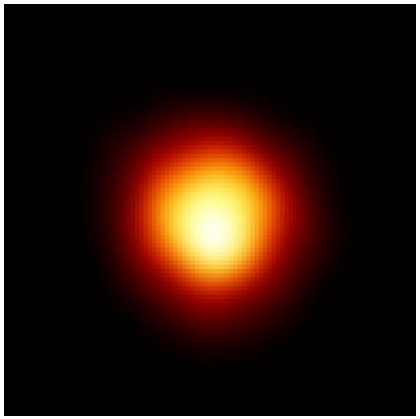
- Stellar Mass M > 9-10 M_{Sun}

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

"Red Supergiant" star



Betelgeuse: ~10^9 km



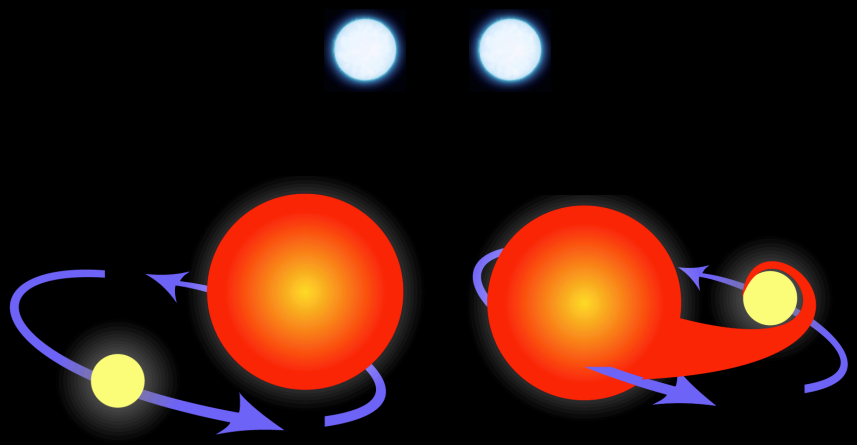
Back to Supernova Explosions:

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

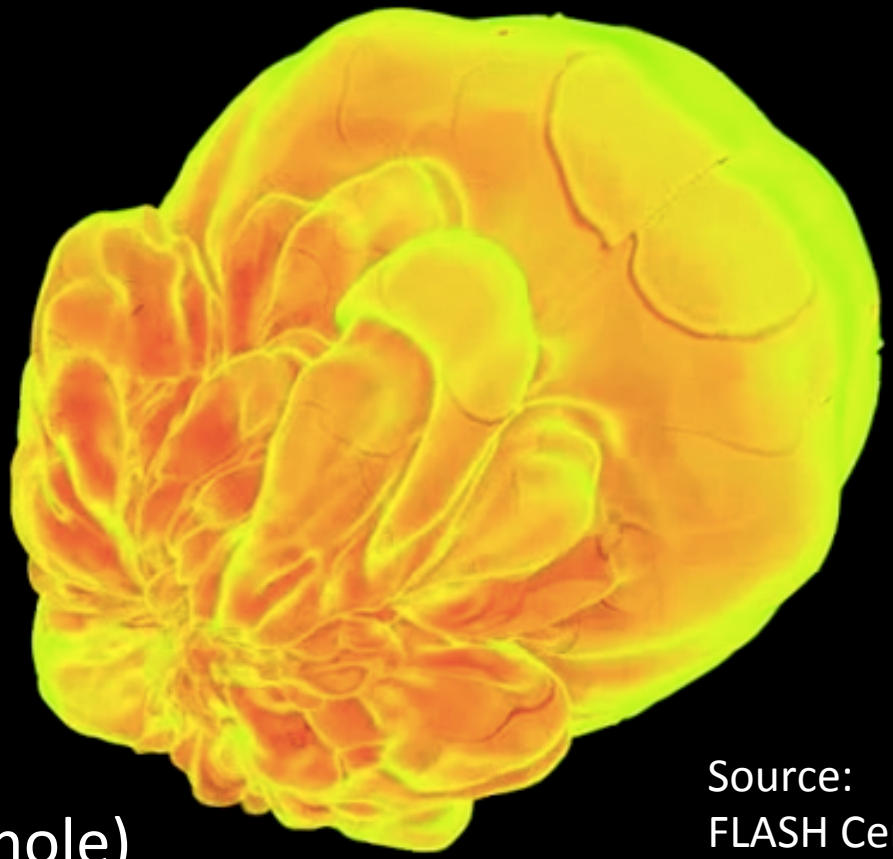
Simulation on a supercomputer
Source:
FLASH Center
U. of Chicago

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)

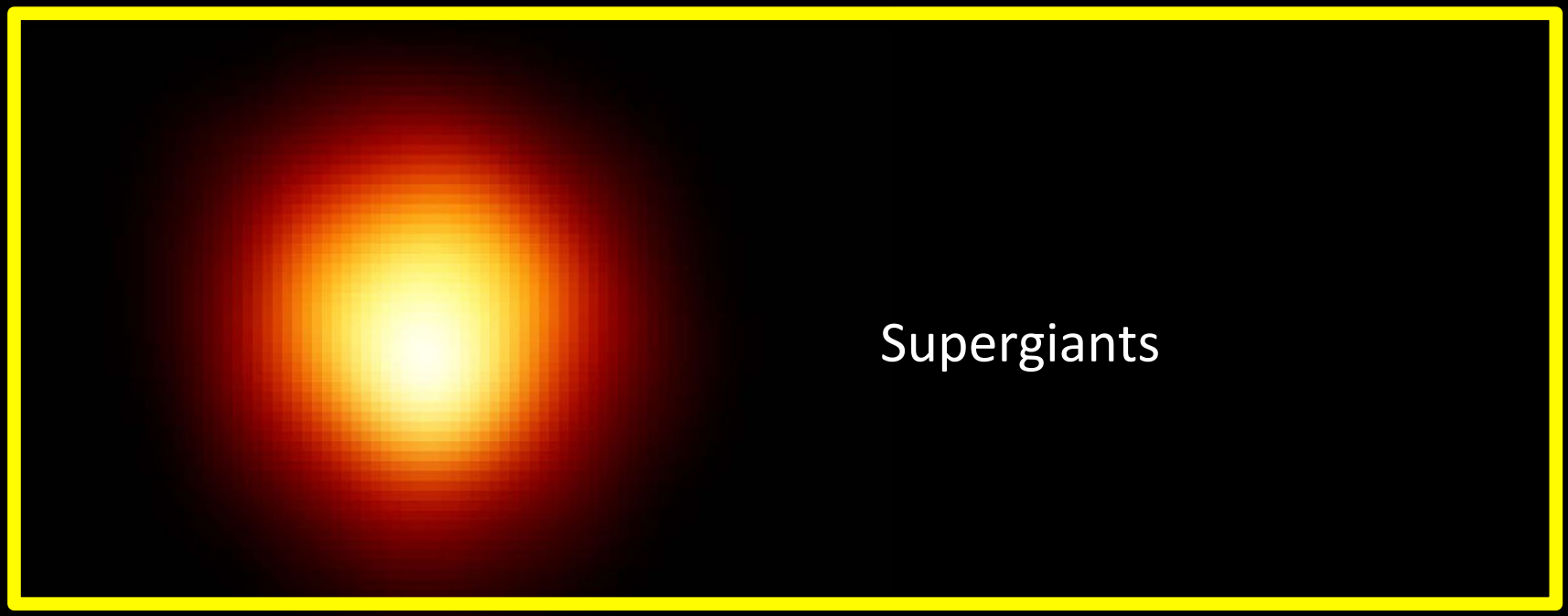


Source:
FLASH Center
U. of Chicago

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

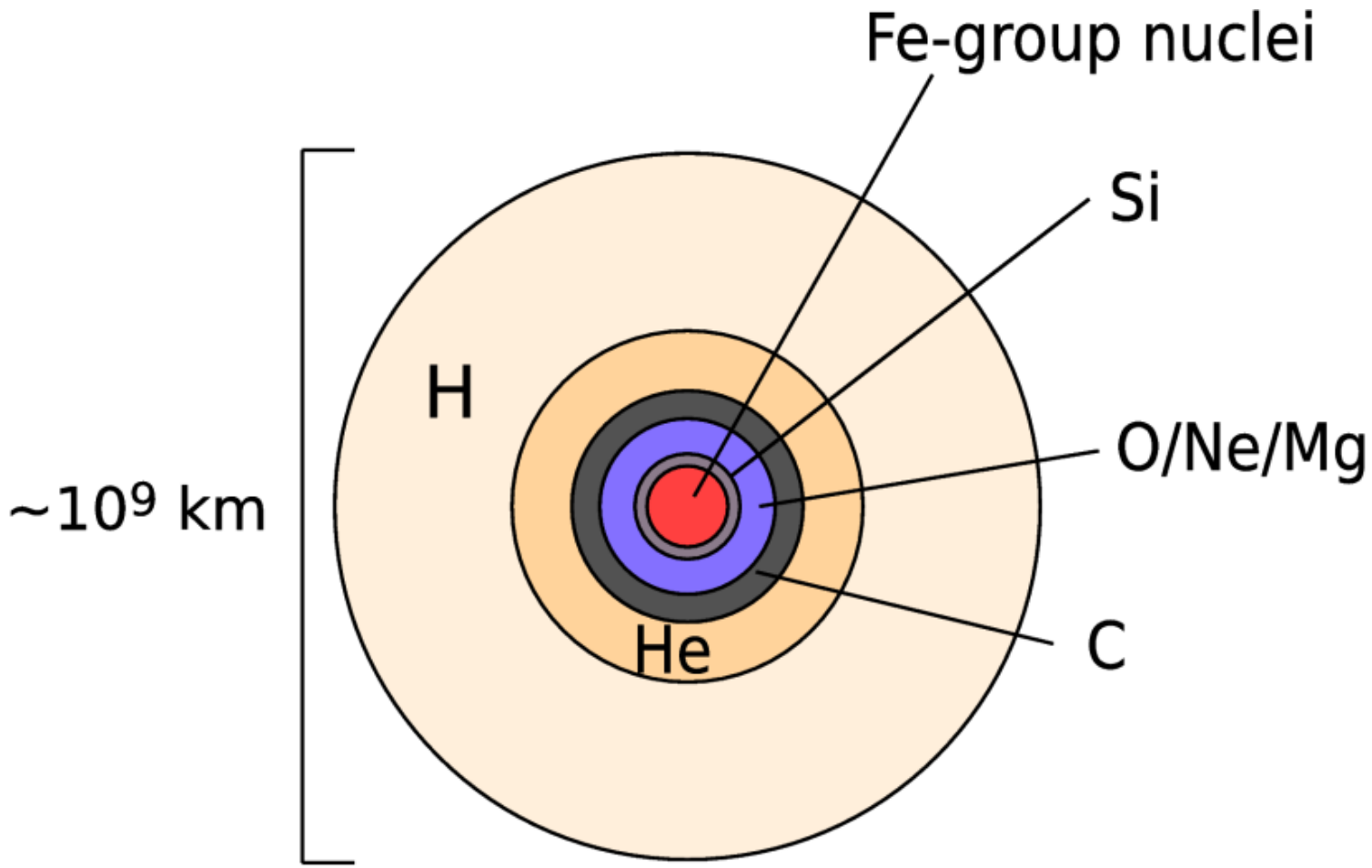
Back to Supernova Explosions:

White Dwarfs: Type Ia SNe



How do we get them to blow up?

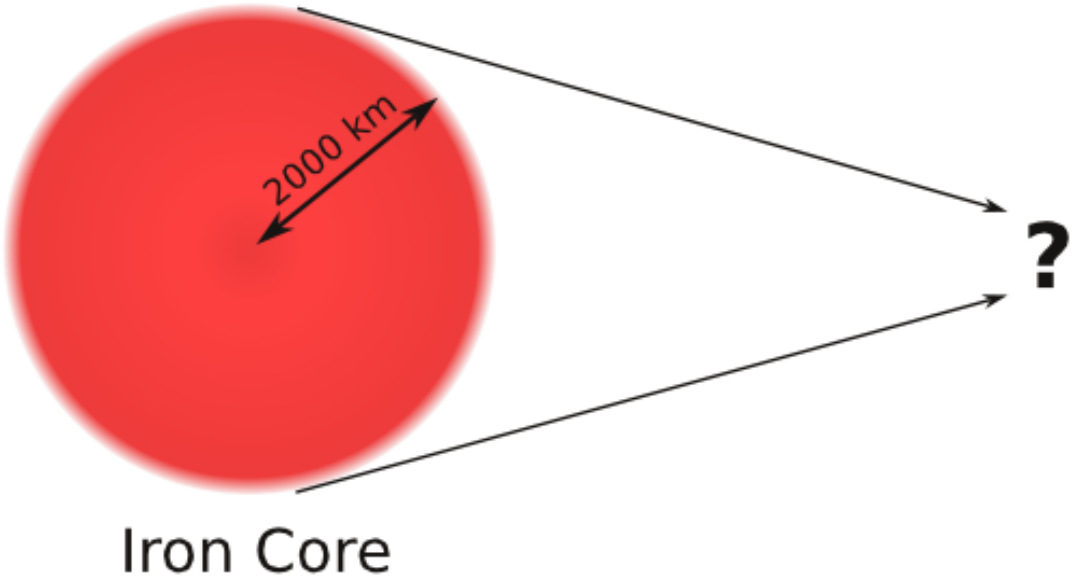
Massive Stars: Supergiant Stars



Recall: No more fusion after Iron (Fe)

Iron Core Collapse

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



Iron Core Collapse

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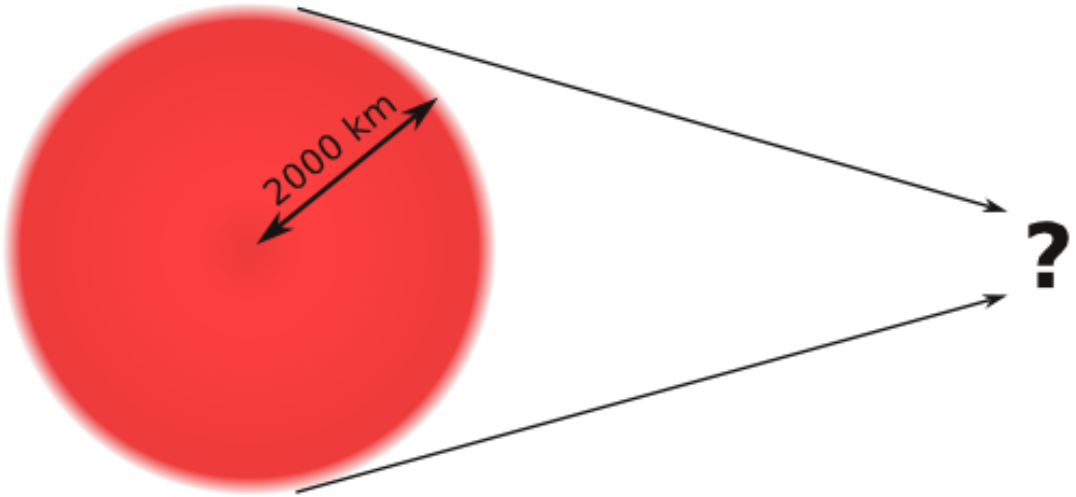


Collapse: Core is compressed!
Within ~0.5s:

Density ≈ 10^{10} g/cm^3

Density > 10^{14} g/cm^3

Two Important Things:

(1) At high density: Electrons "captured" on protons

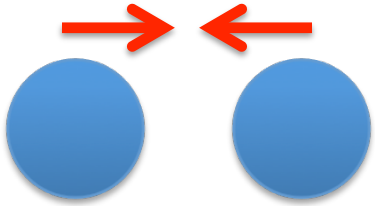
$$p + e^- \longrightarrow n + \nu_e$$

Neutrino

Matter becomes "neutron rich" (-> neutron star!)

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

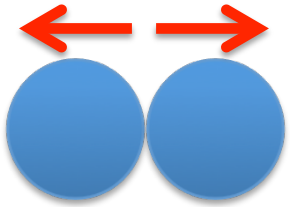
Normally:
Force is "attractive"



2 nucleons:
protons or neutrons

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

Nuclear force become "repulsive"



Iron Core Collapse

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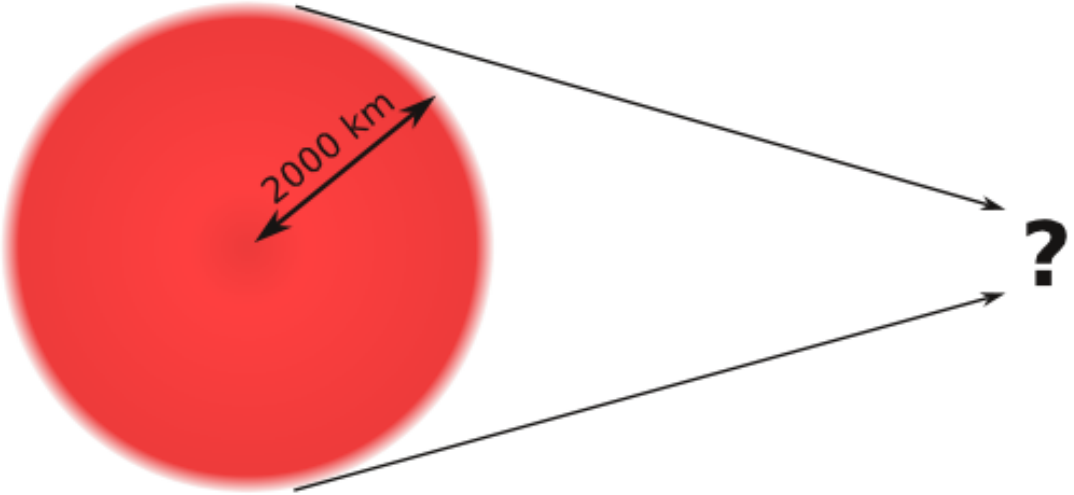


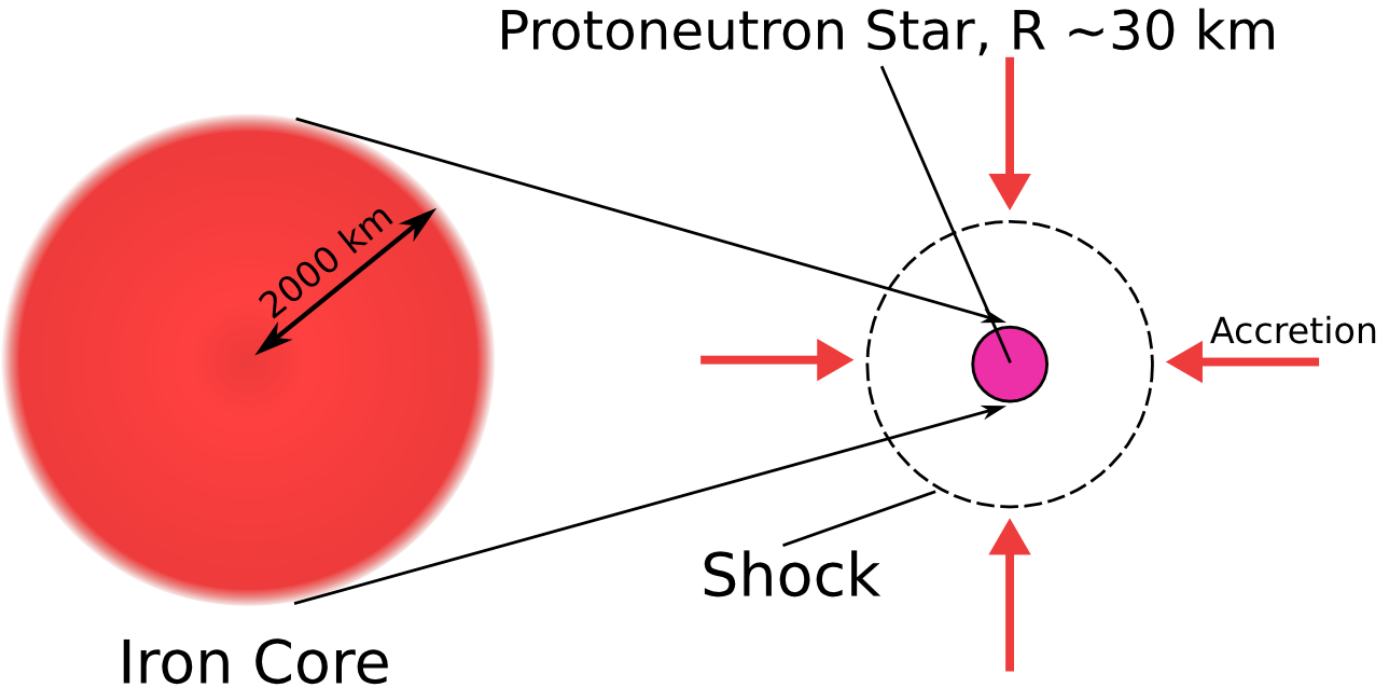
Density ≈ 10^{10} g/cm^3

Collapse: Core is compressed!
Within ~0.5s:

Density > 10^{14} g/cm^3

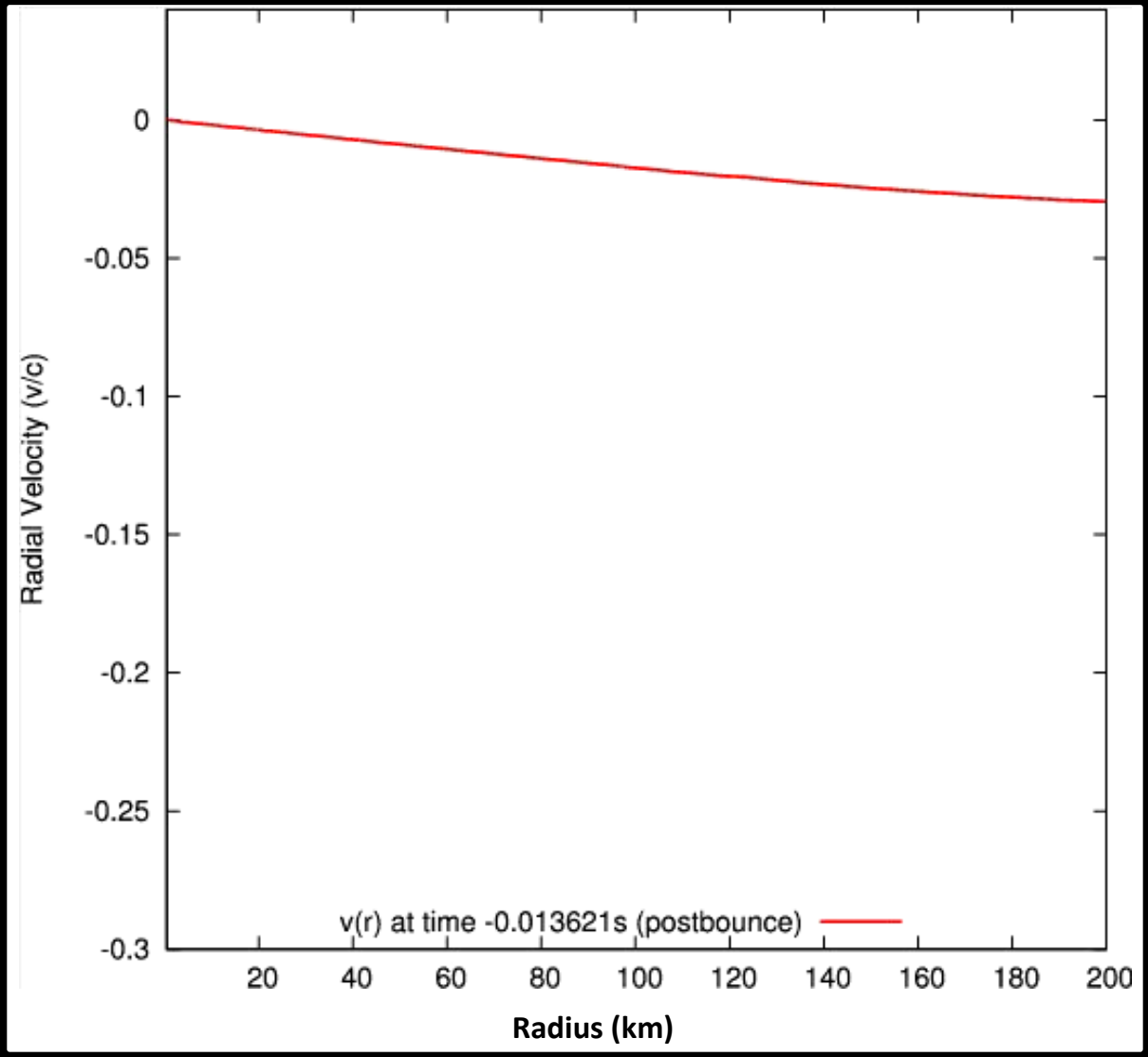
Nuclear repulsive force kicks in!

“Bounce” of the Inner Core

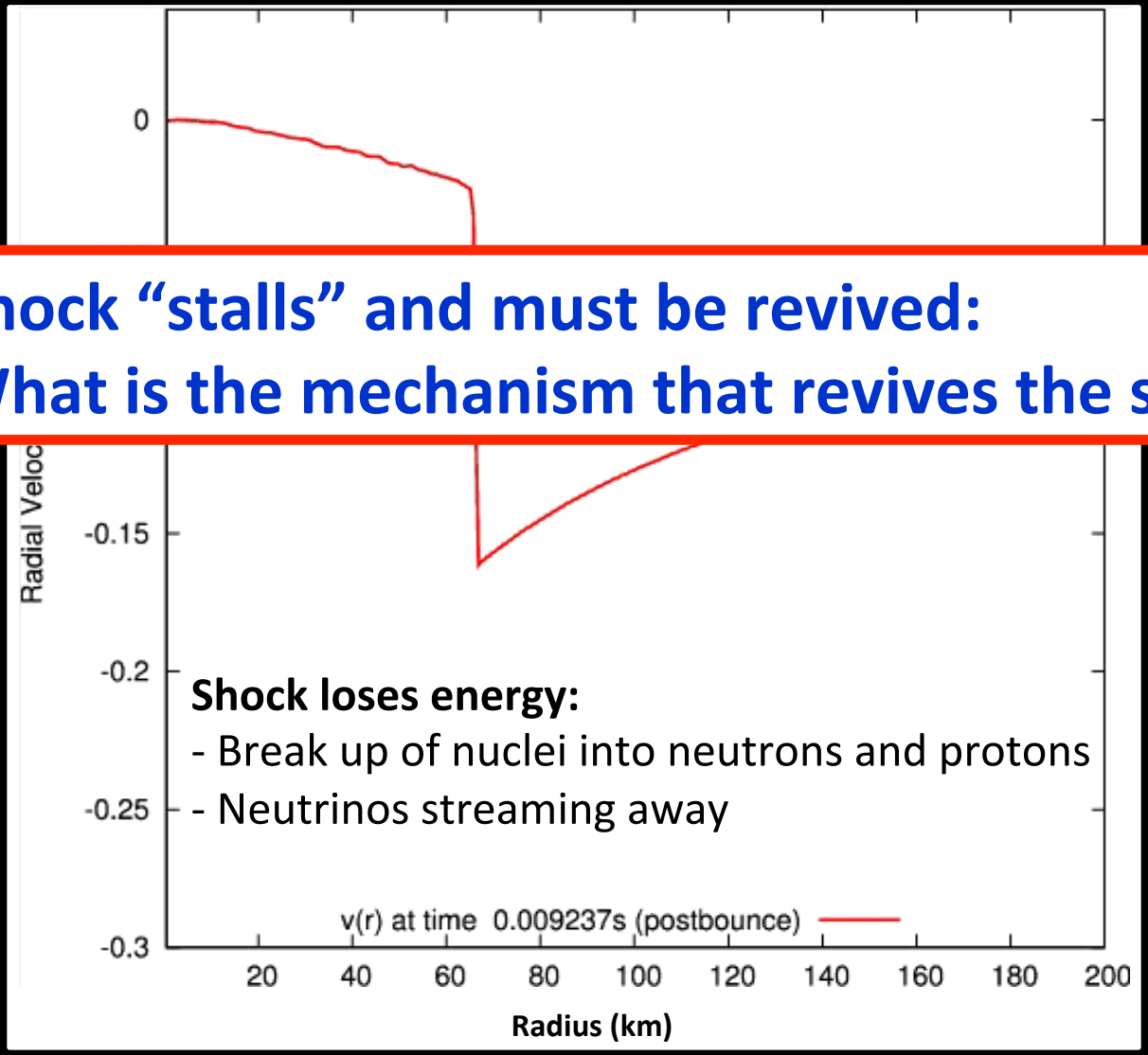


Nuclear force stabilizes inner core in **protoneutron star**.
Outer core and outer layers still collapsing, pushing down on the supernova shock!

The Supernova Problem



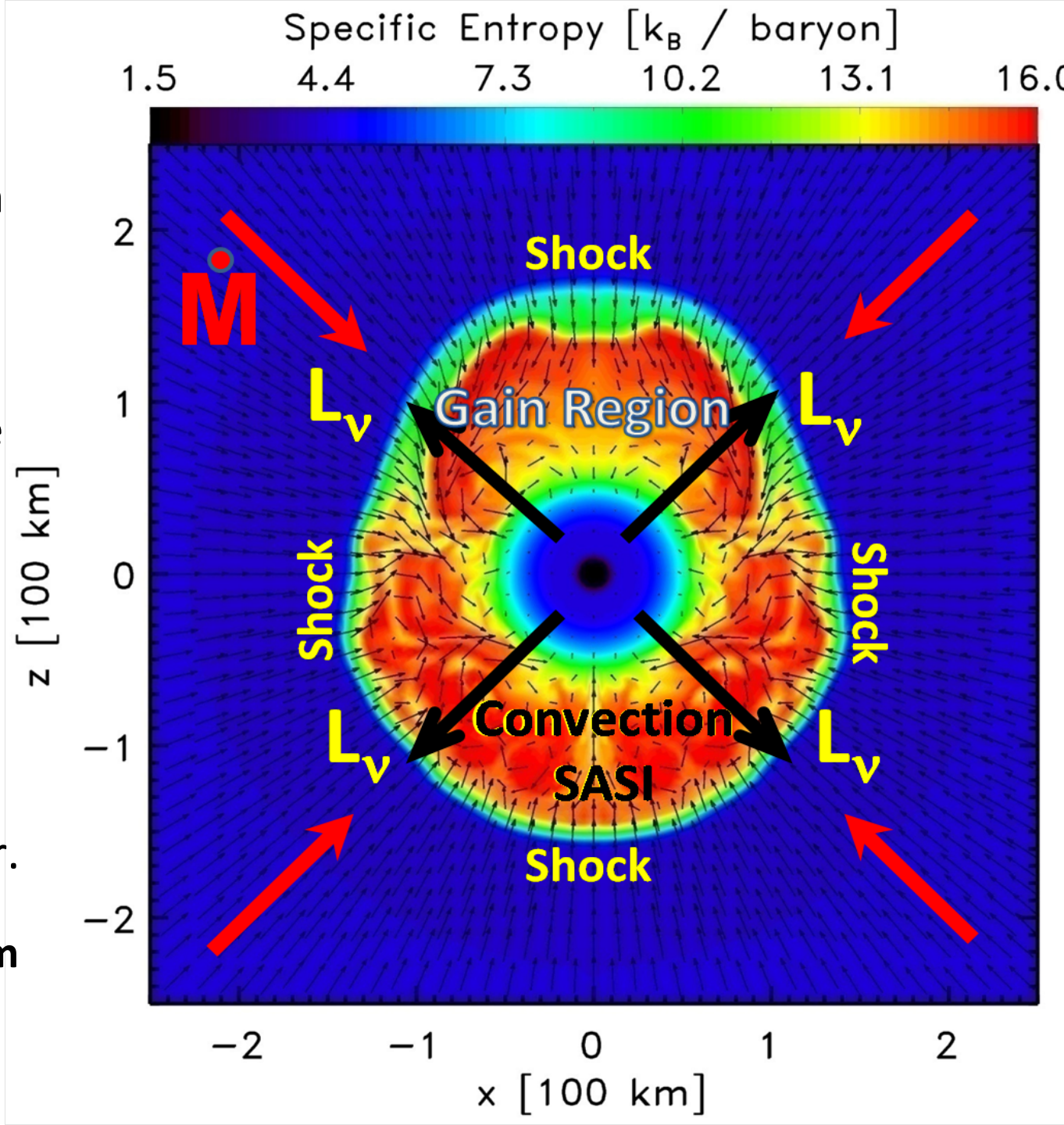
The Supernova Problem



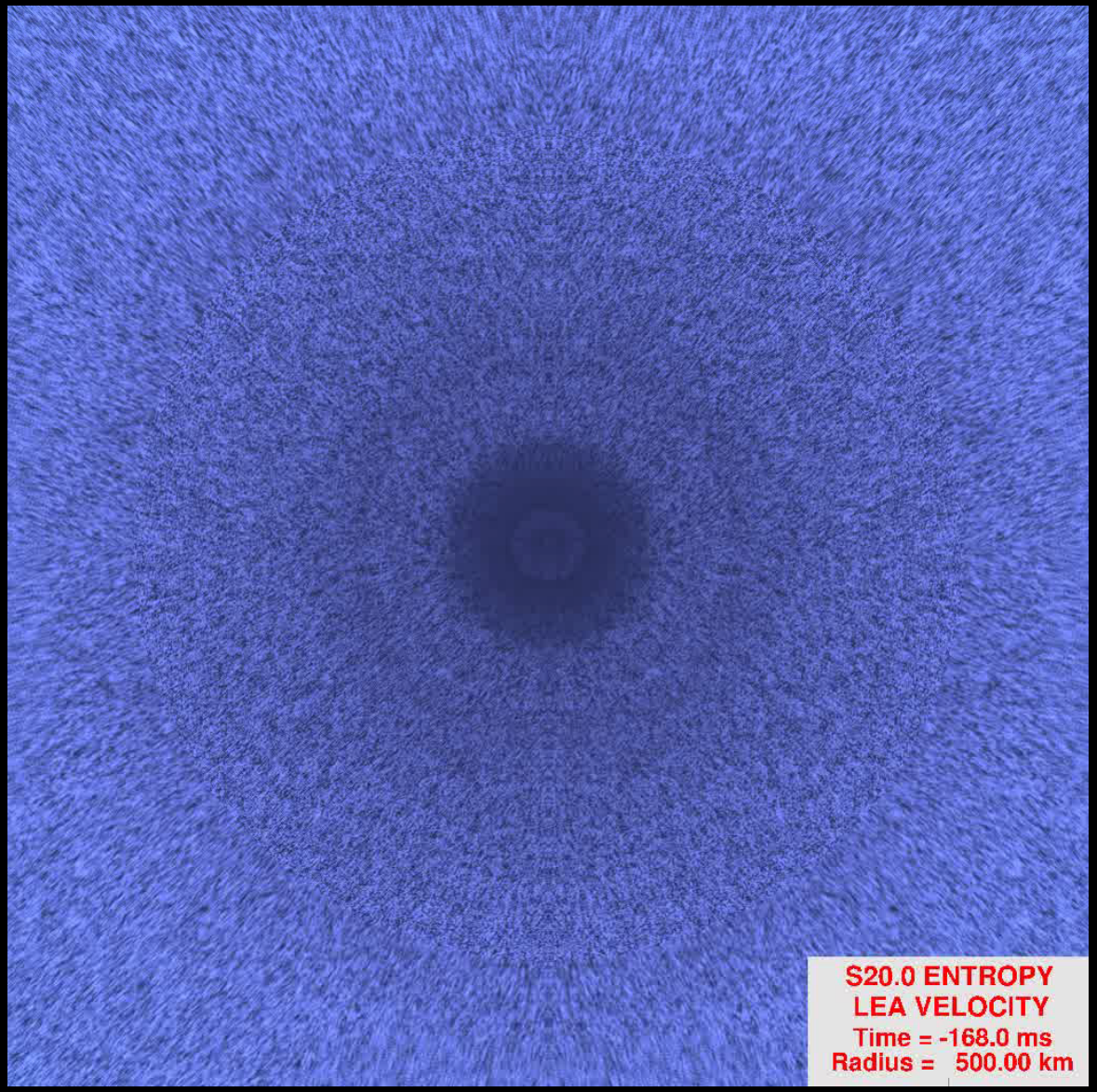
Shock "stalls" and must be revived:
What is the mechanism that revives the shock?

- 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



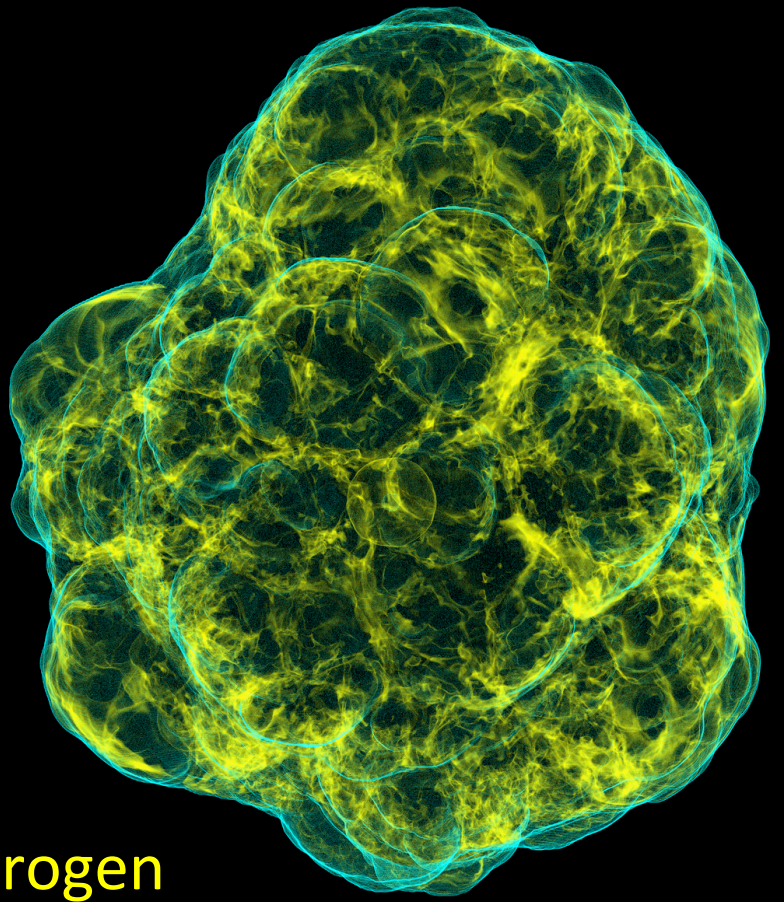
Standing Accretion Shock Instability



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

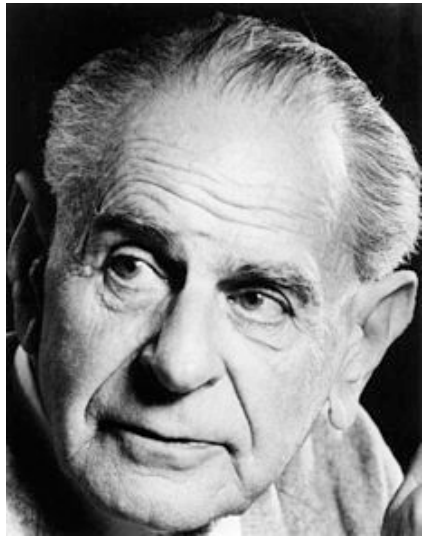
Technical name in Astronomy: **Type II Supernovae**

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

Theory → Hypothesis/ Prediction → Experiment → Theory

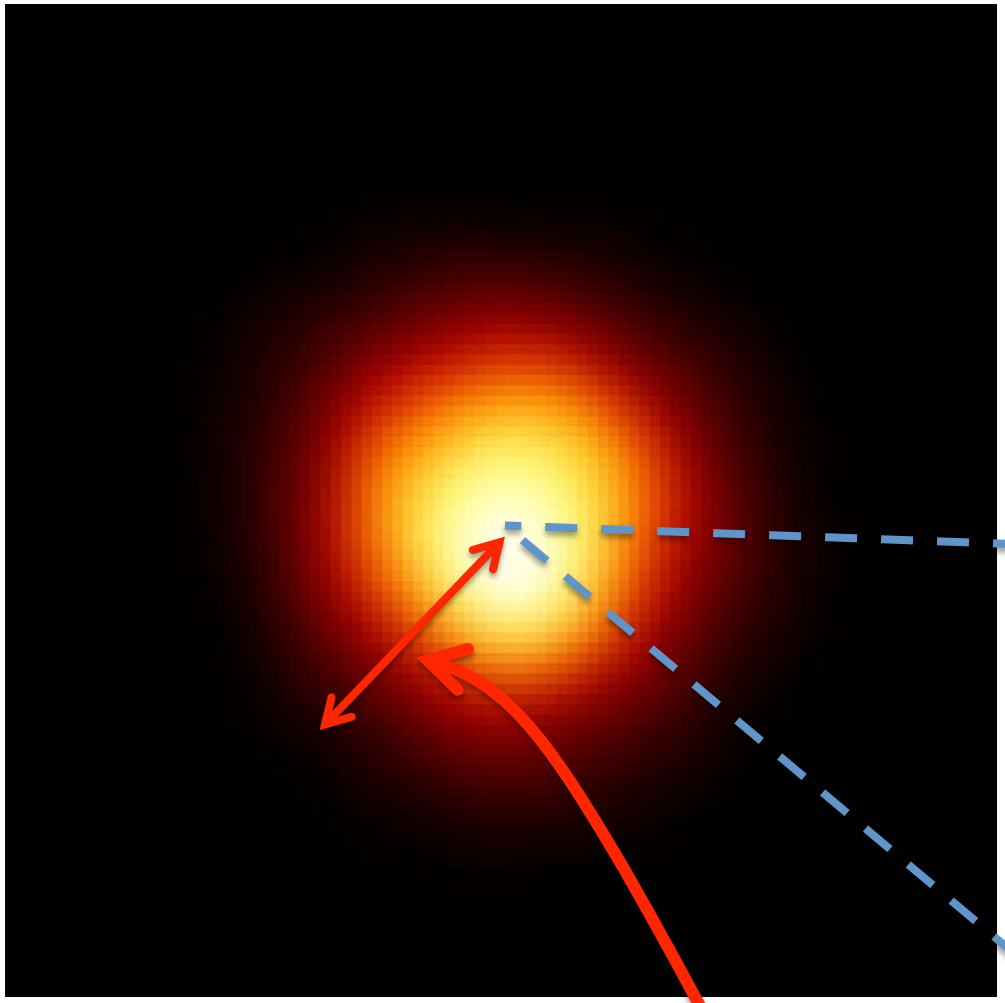
Falsification can rule out theory.
May inspire new theory.

Test of Hypothesis/Prediction

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

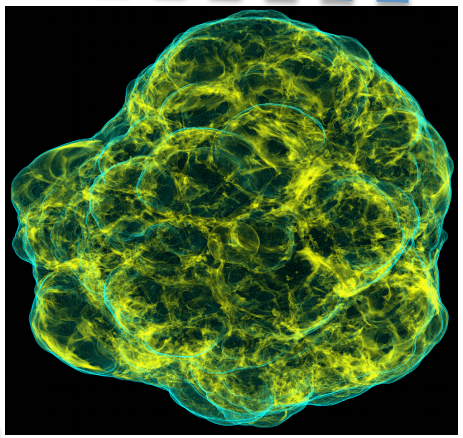
In Astrophysics:
Cannot experiment with stars: Observation replaces Experiment.

Observing the Core-Collapse Supernova Engine



Red Supergiant
Betelgeuse
Distance:
~600 lightyears

Supernova “Central Engine”



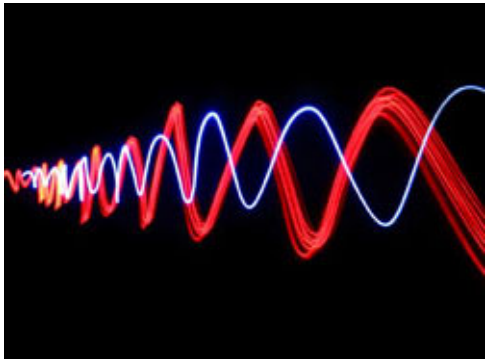
HST

800 million km

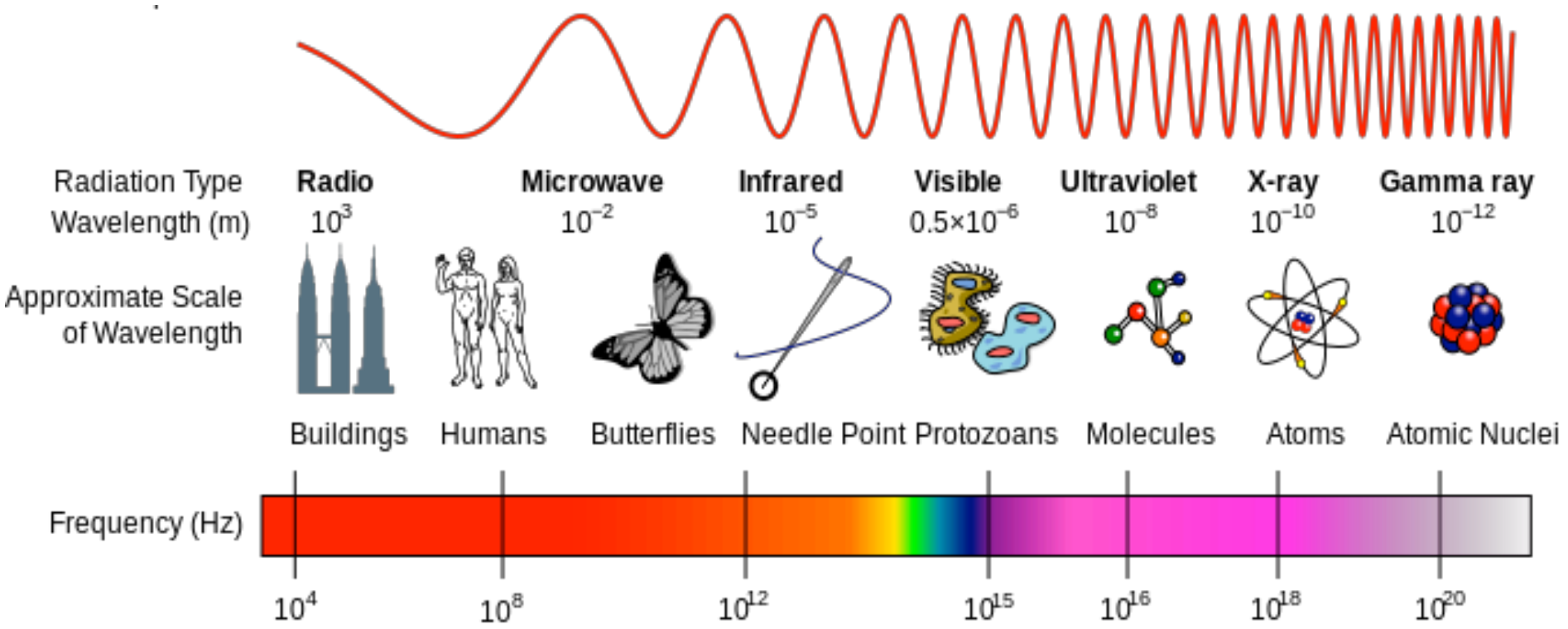
300 km

Instruments of Observational Astronomy

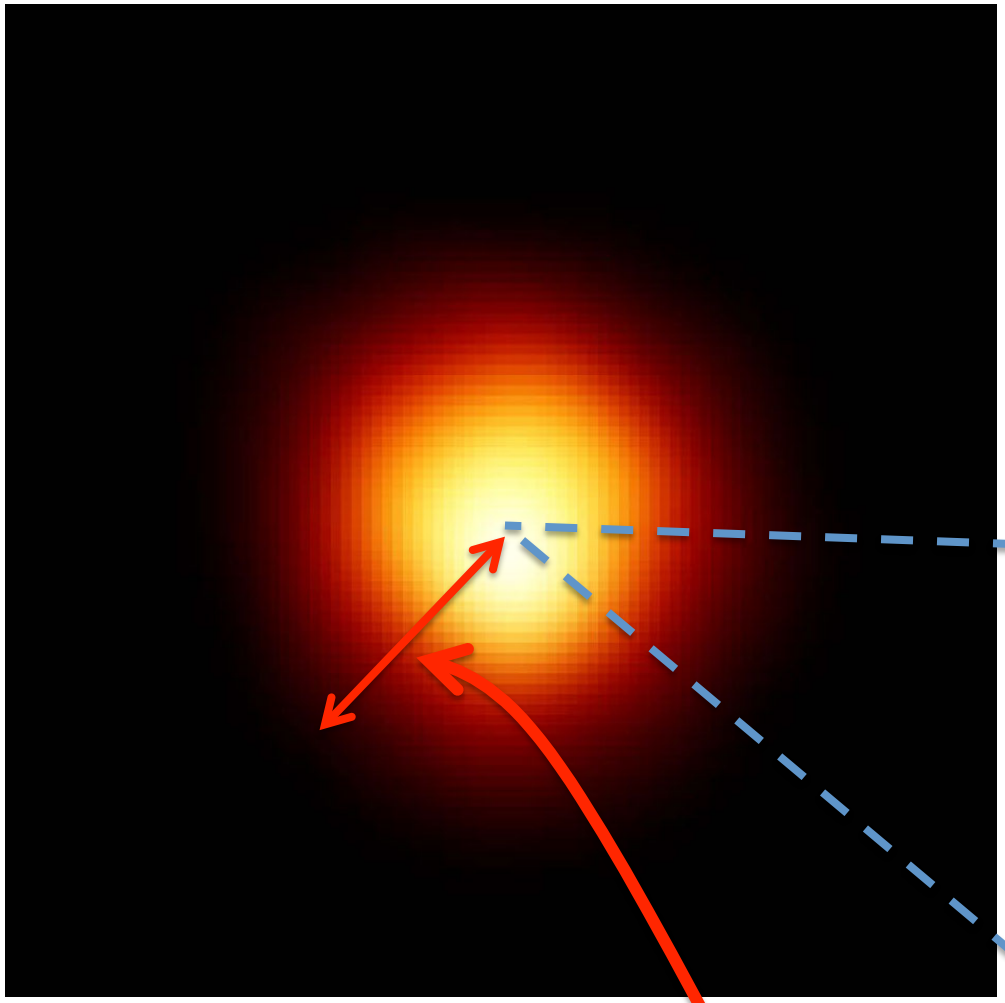
These telescopes all look for **electromagnetic waves**!
(radio, infrared, light, UV,
X-rays, Gamma rays)



Spectrum of Electromagnetic Waves:



Observing the Core-Collapse Supernova Engine



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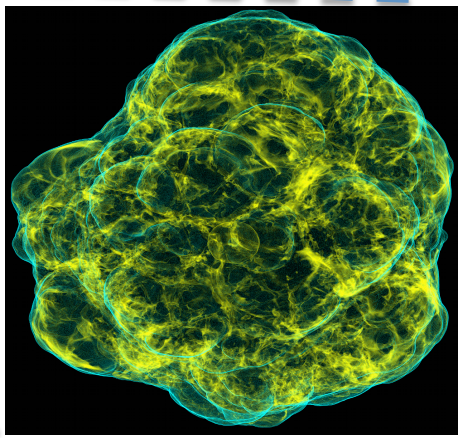

HST

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:
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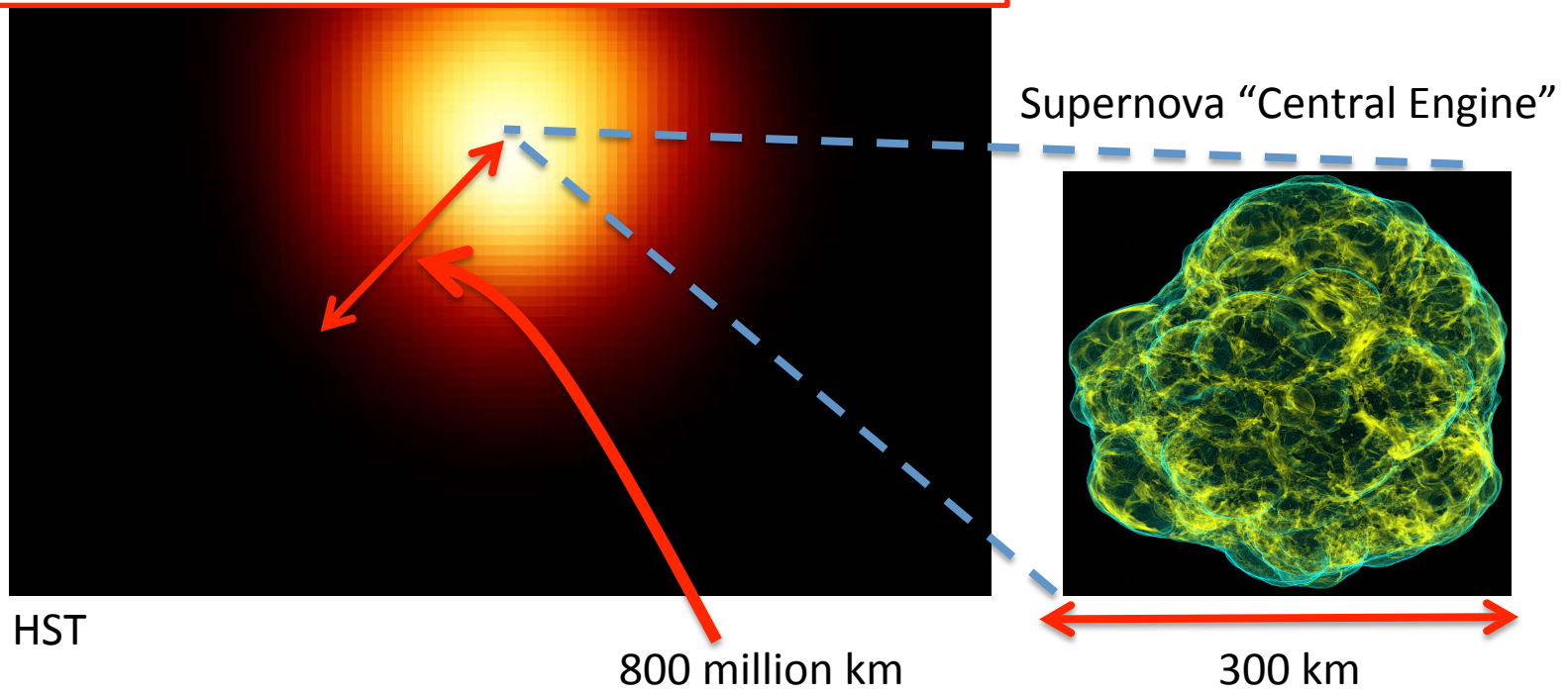

Observing the Core-Collapse Supernova Engine

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-> Neutrinos (-> Neutrino Observatories)

Red Supergiant Betelgeuse
Distance:
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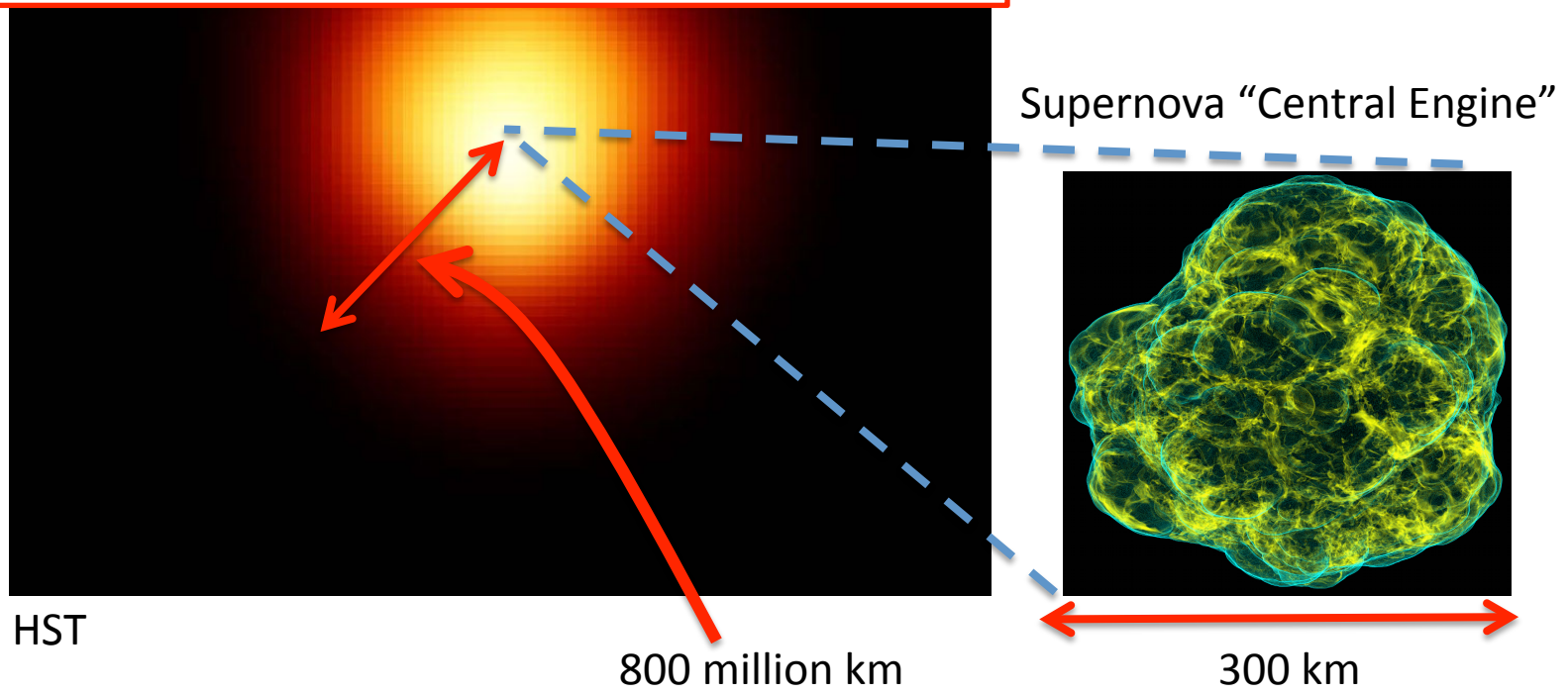
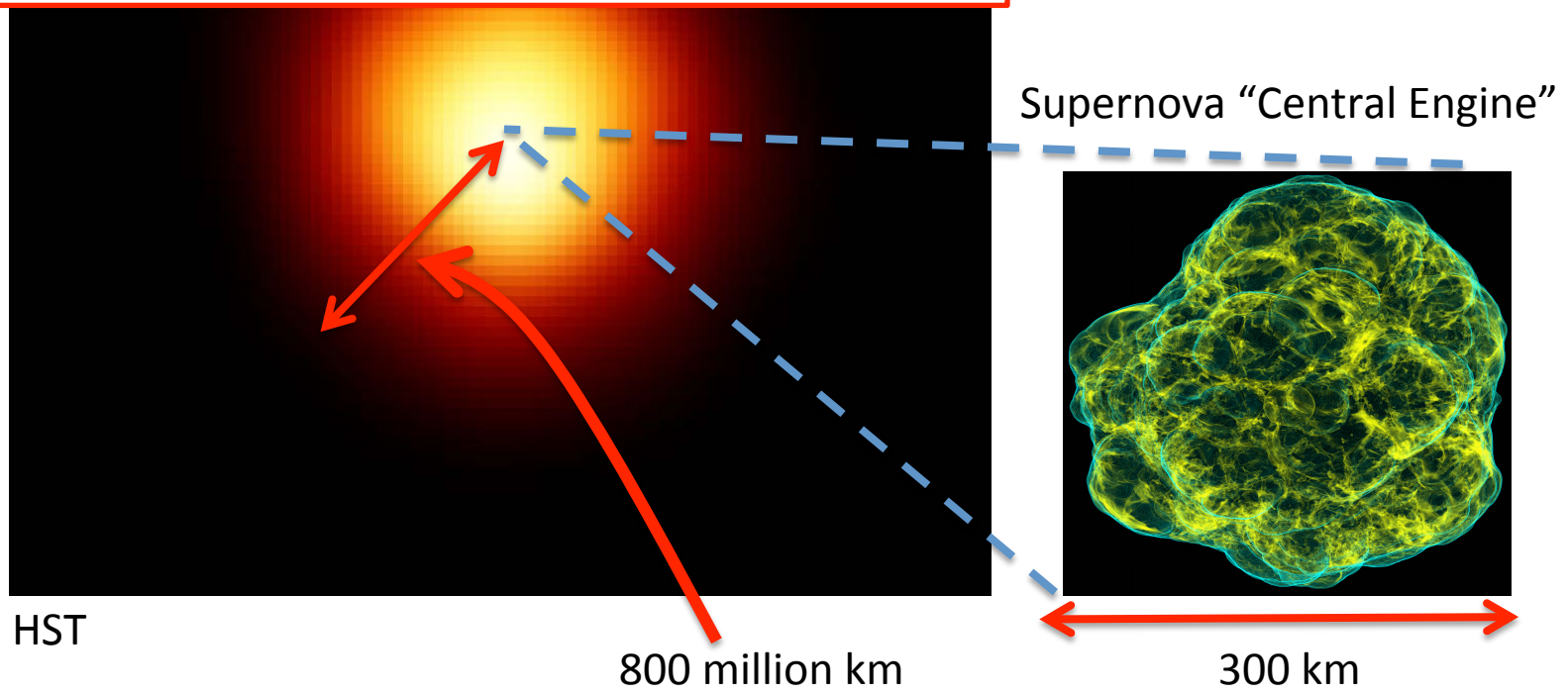


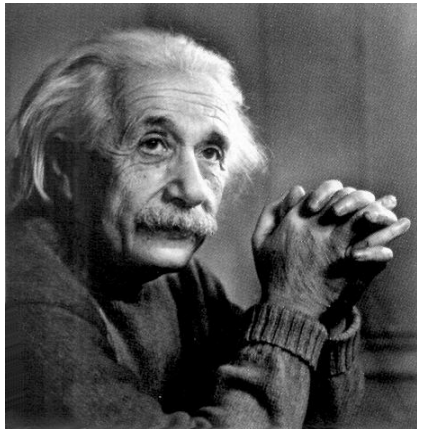
Observing the Core-Collapse Supernova Engine

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

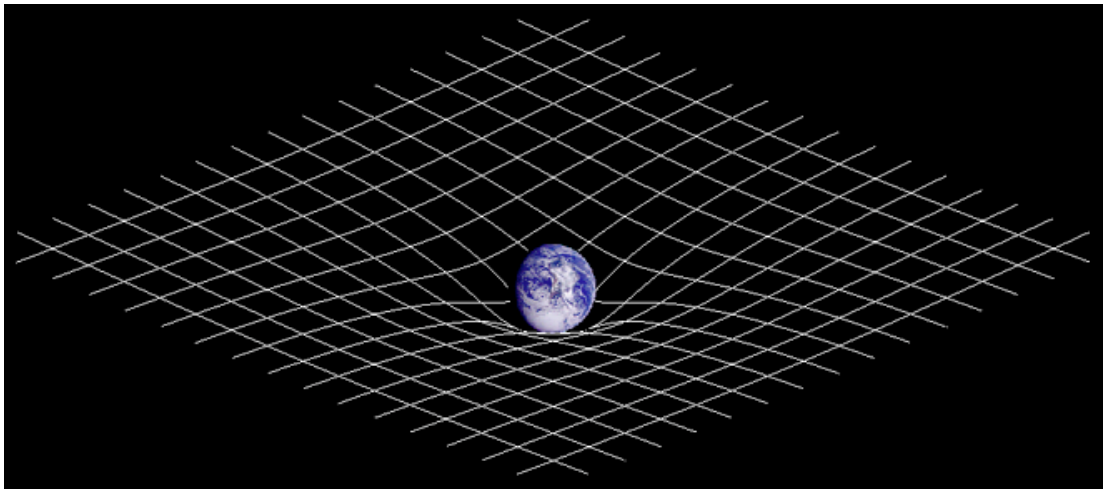


Gravitational Wave Astronomy



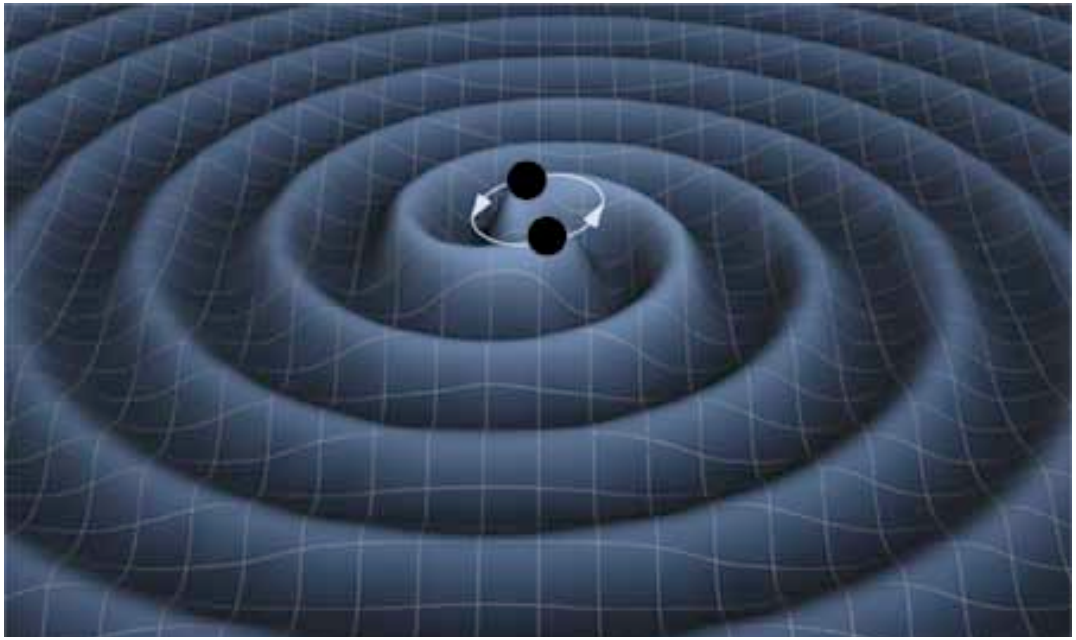
Albert Einstein
1879-1955

Einstein's **General Theory of Relativity**

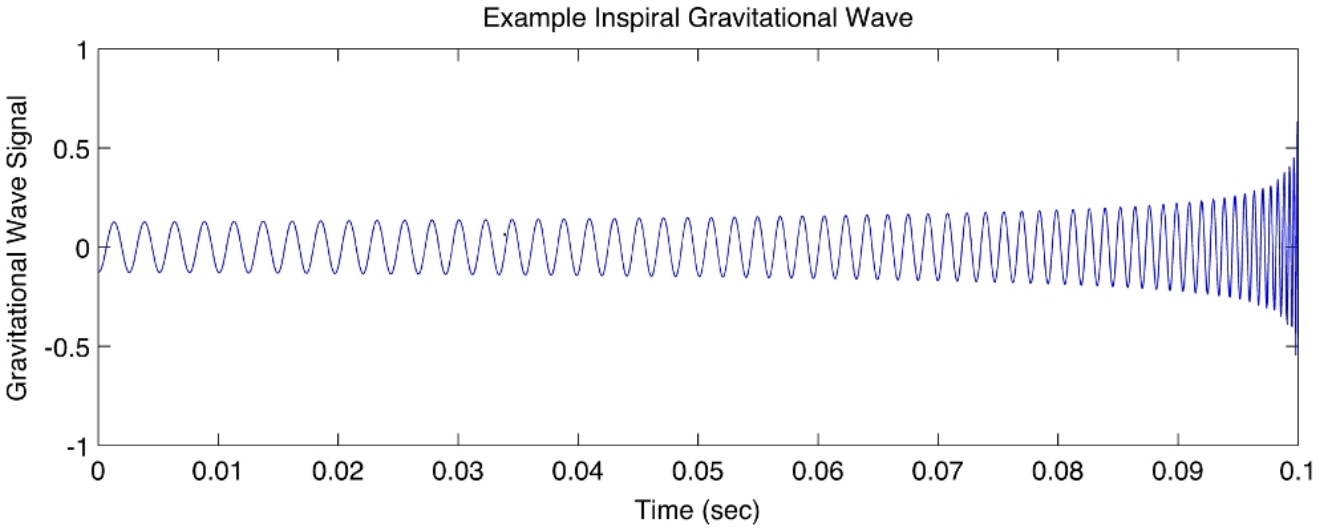


- Matter "curves" spacetime (geometric interpretation of gravity).
- Matter wobbling/moving around: creates ripples in spacetime
  -> **Gravitational Waves**
- Gravitational waves cannot be used to make an image of their source. Instead, they encode their source's dynamics.
- Gravitational waves have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

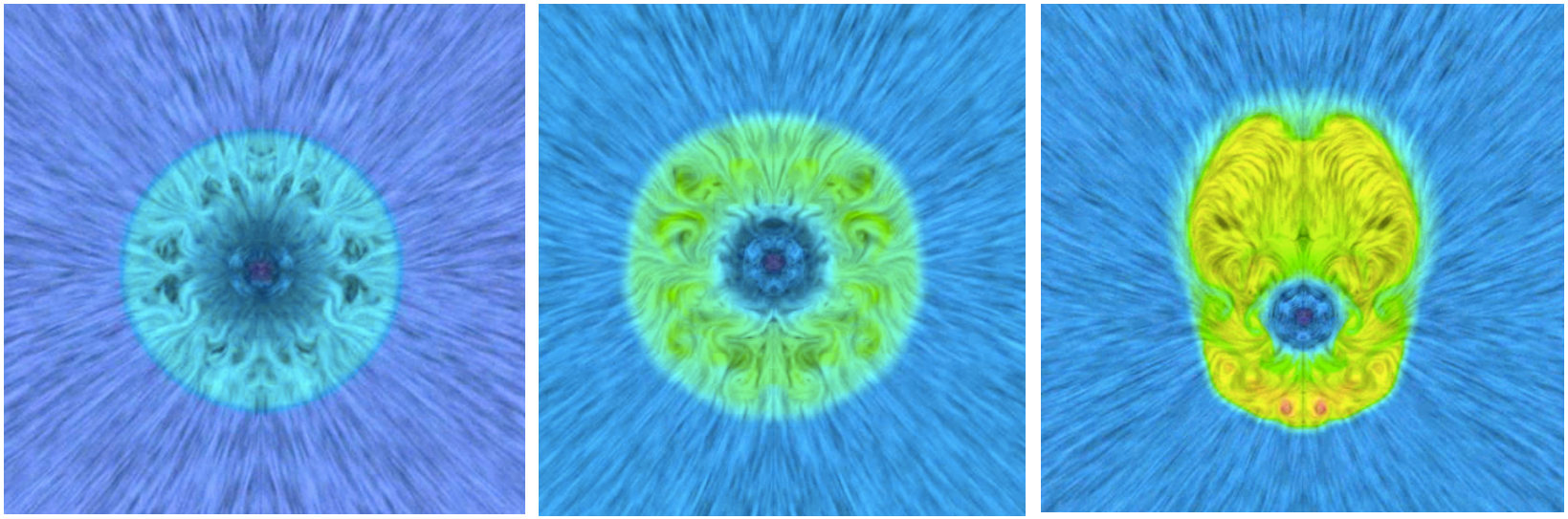
Example: Merging Double Neutron Stars

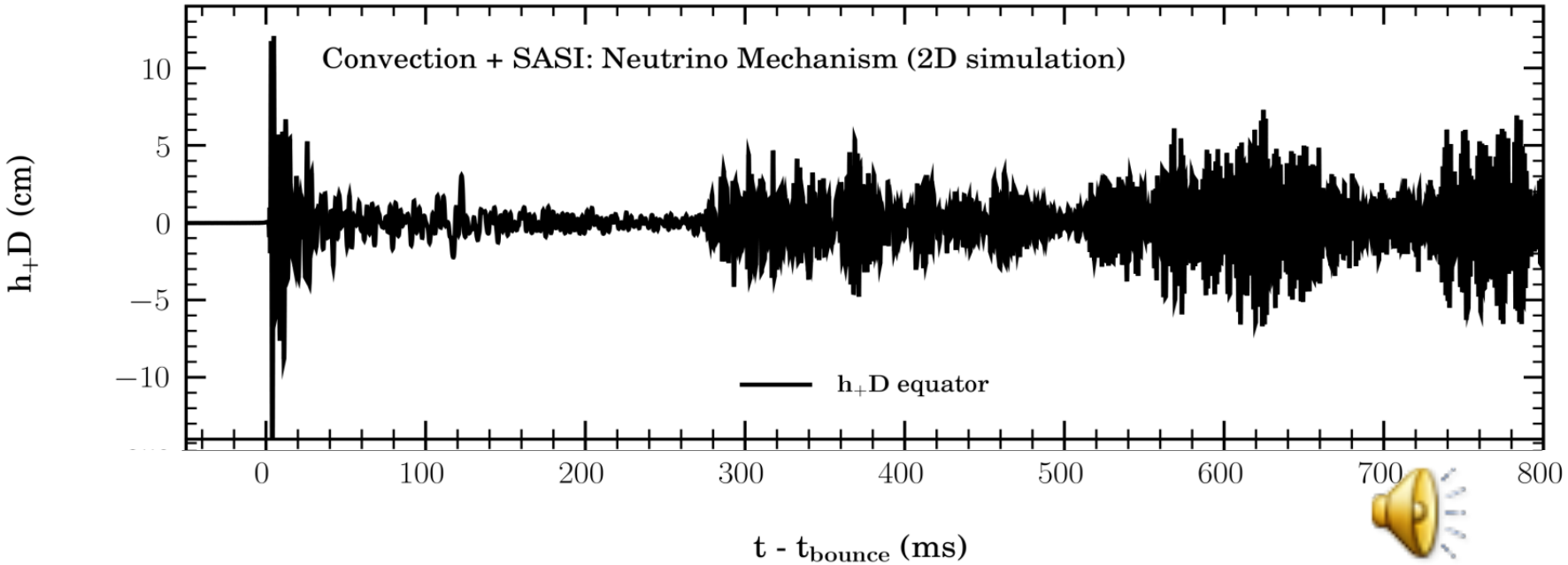


- Gravitational waves carry away energy from the orbit.
  -> Orbit shrinks
- Eventually the two stars merge.
- Emitted waves are in the audible band!



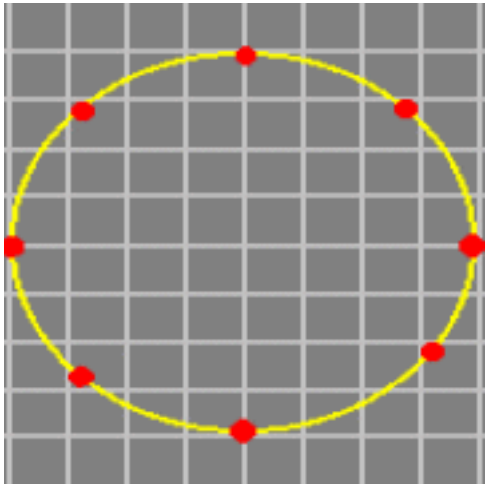
Example: Core-Collapse Supernova

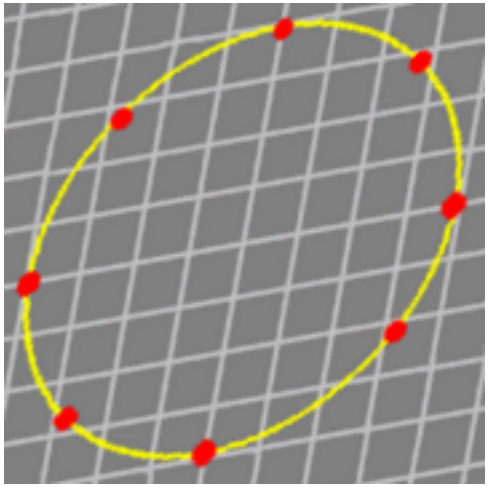




Gravitational Wave Observation

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





http://www.johnstonsarchive.net/relativity/pictures.html

"+ Polarization"

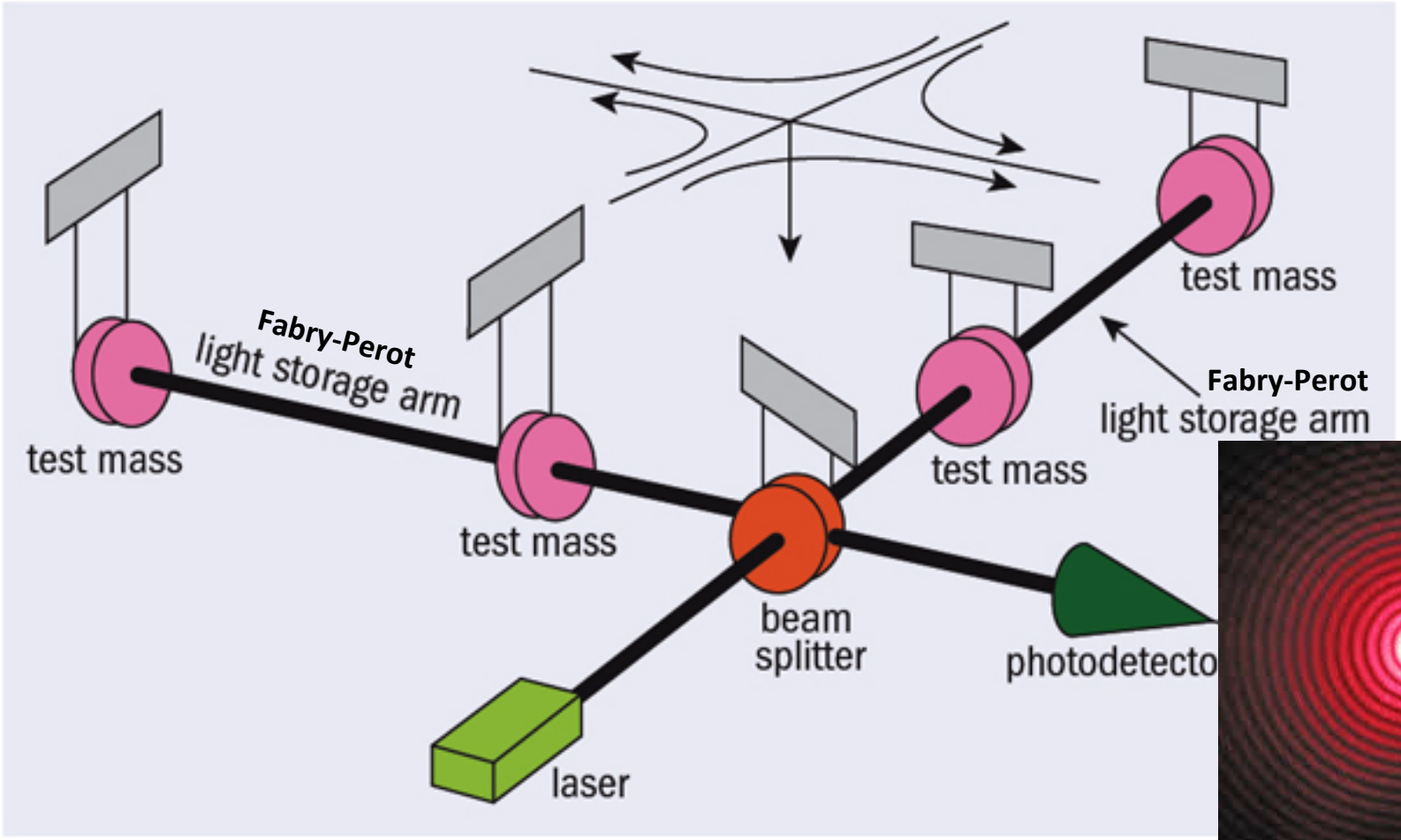
"x Polarization"

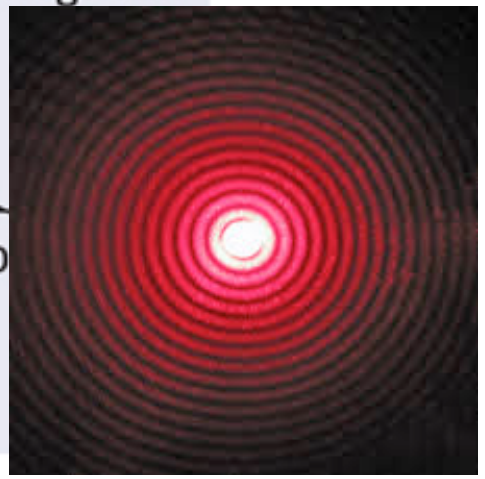
Stretching & Squeezing:

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

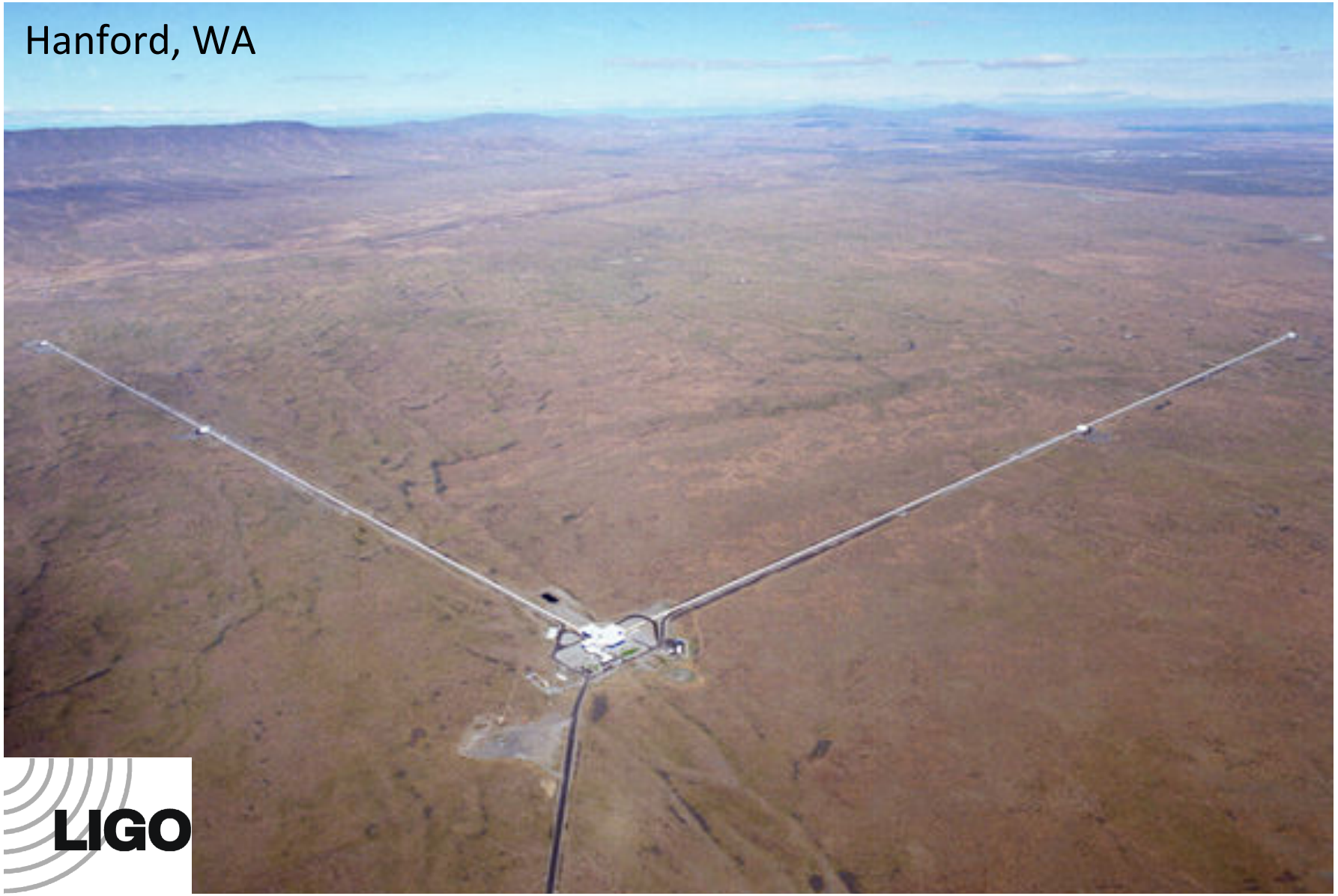
- GWs change the distance between test masses very slightly.
  Distance change: ΔL Distance: L
- Strength of a GW from a Milky Way supernova:

$$\Delta L/L \sim 10^{-22} = \frac{1}{100000000000000000000000}$$

- Want to have a large L so that ΔL is not too tiny.

Kip Thorne, Rai Weiss, Ron Drever

Laser Interferometer Gravitational-Wave Observatory



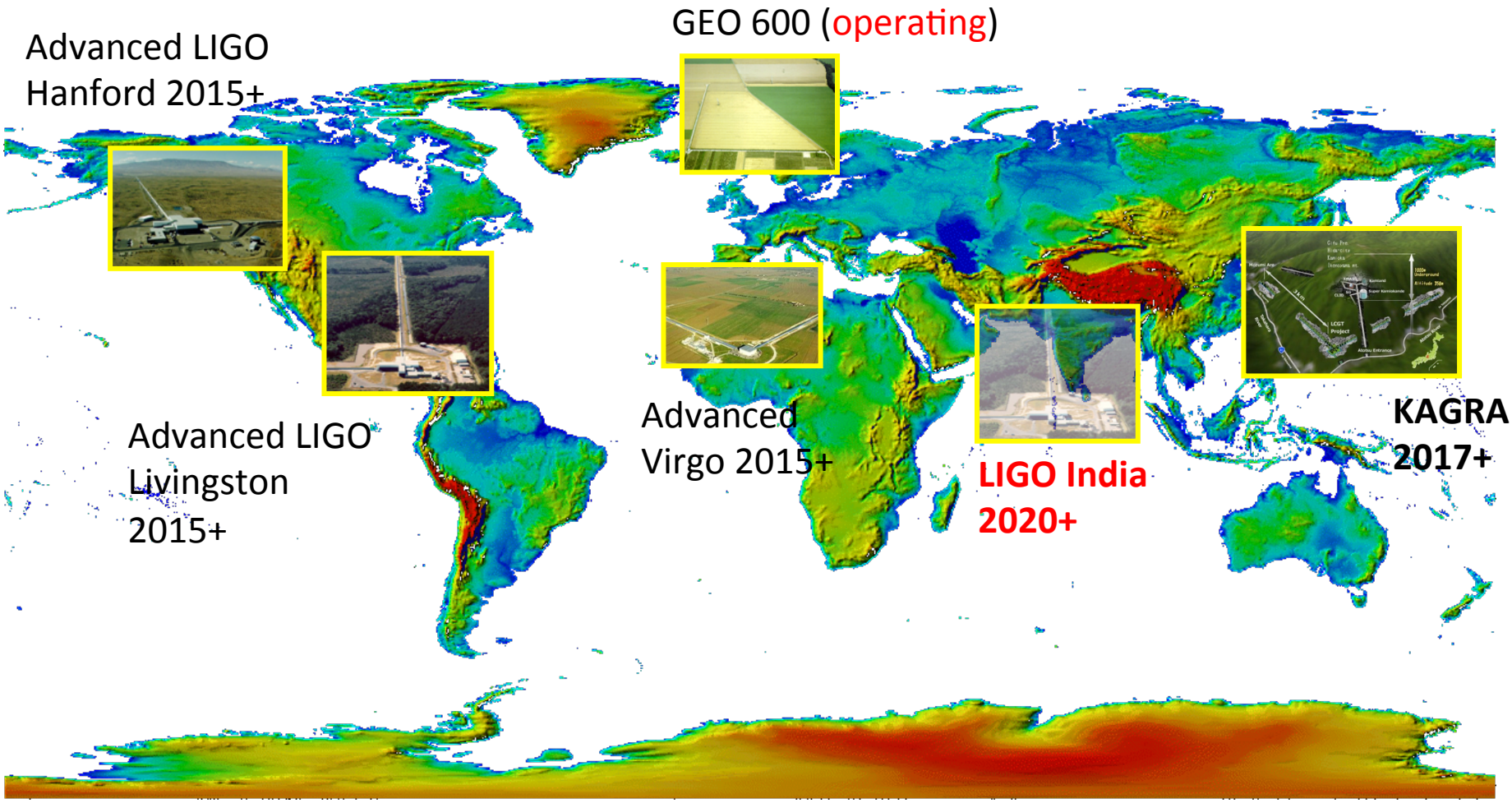

mid station

Laser Interferometer Gravitational-Wave Observatory

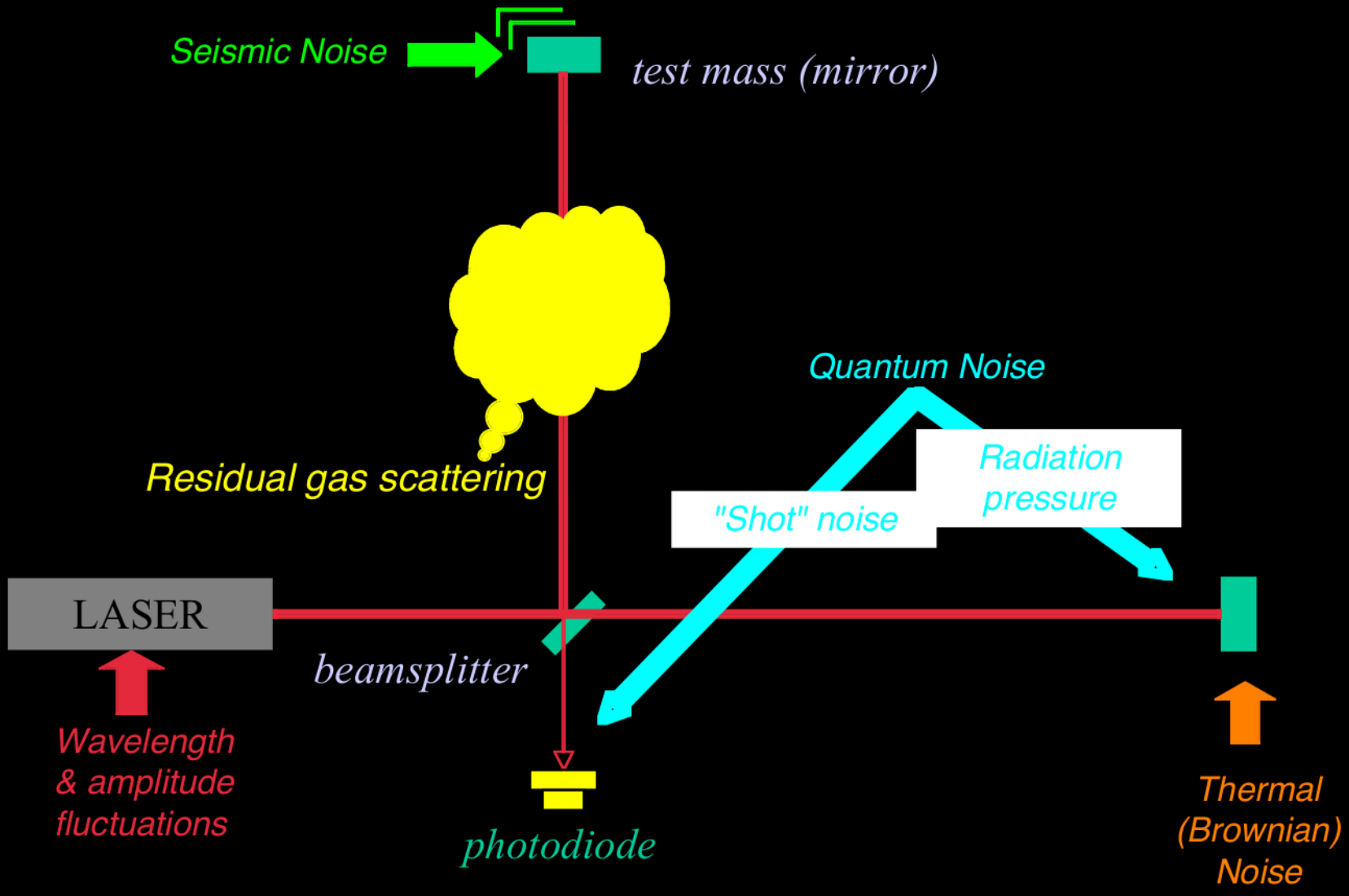
Initial LIGO: 2000-2010
currently being upgraded
to **Advanced LIGO**

Advanced LIGO will be 10 x more sensitive!

The Advanced GW Detector Network: 2020+

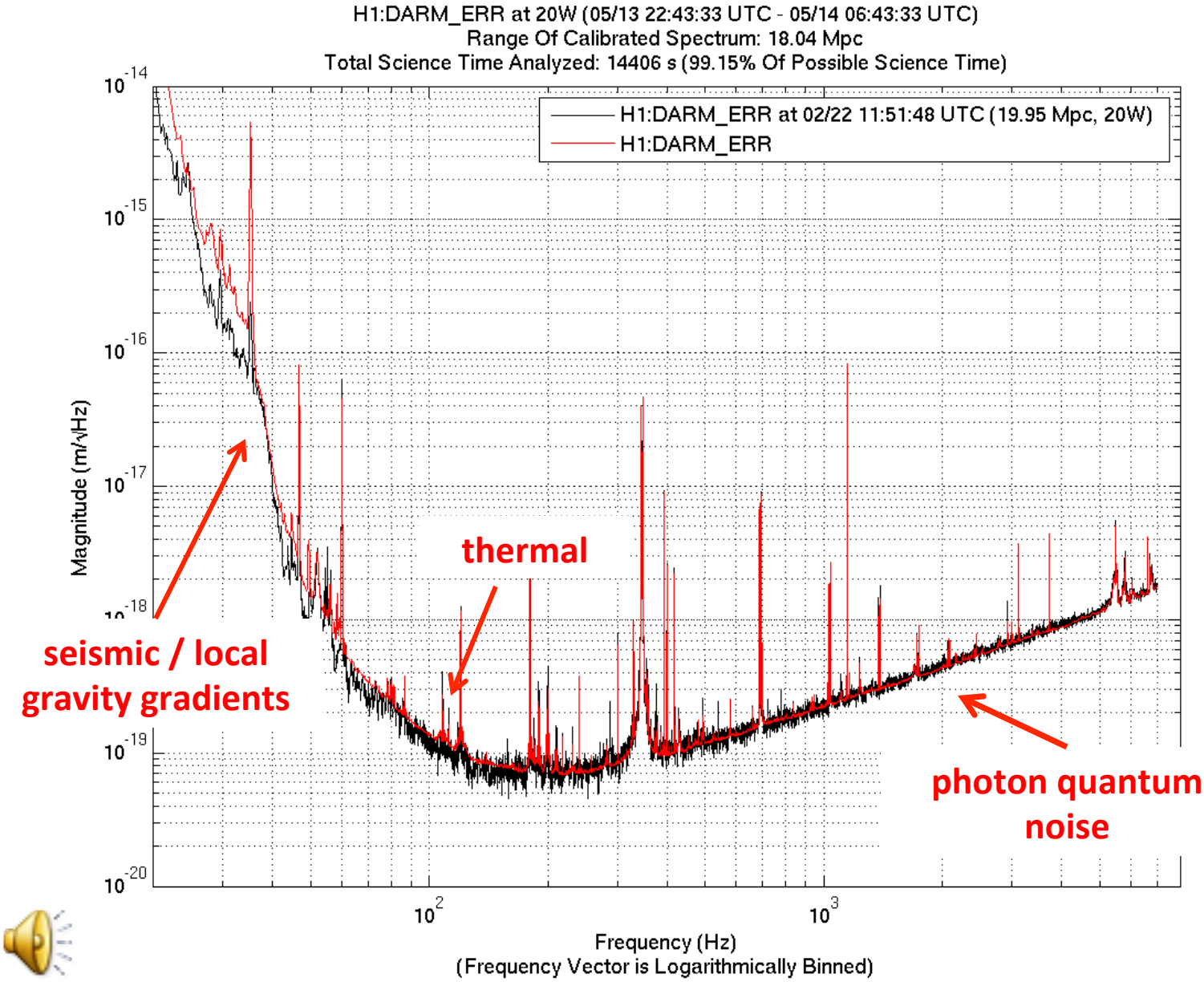


Major Problem: Background Noise!



(by R. Adhikari)

Gravitational Wave Detection



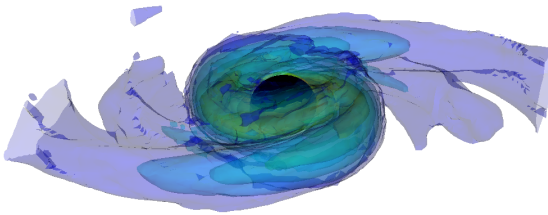
Anthropogenic Noise...

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

What Advanced LIGO will do:

LIGO

- 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!

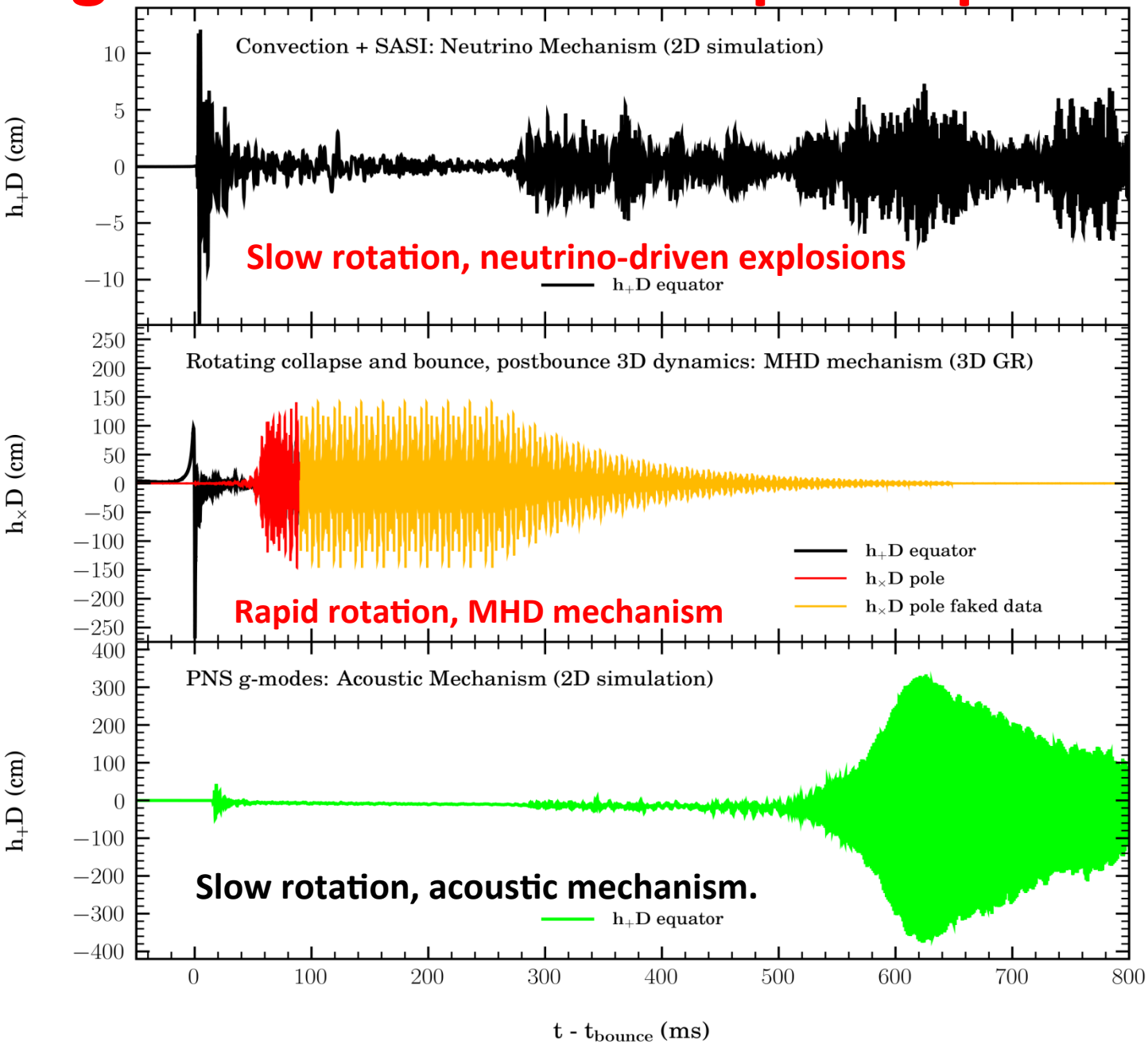


- Detections are expected to be frequent; more than a few per year.
- Network of Advanced LIGO will be able to point normal telescopes for follow-up observations!
- Will detect gravitational waves from the next galactic core-collapse supernova! -> test theoretical supernova models!

+ much more additional exciting astrophysics!

LSC VIRGO

GW Signals from Core-Collapse Supernovae



Now:

Wait for the next galactic supernova!

Betelgeuse
(Hubble Space Telescope)

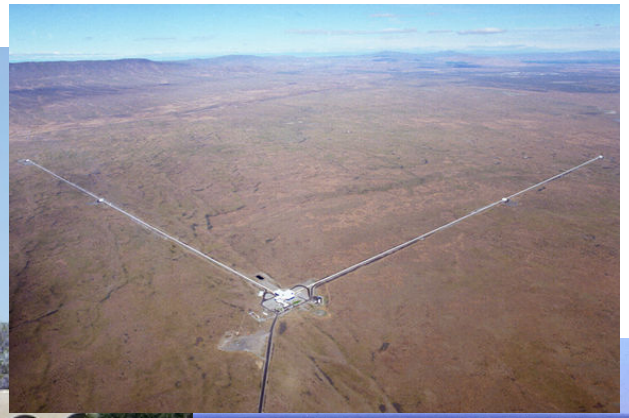
Help us at LIGO next Summer!

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

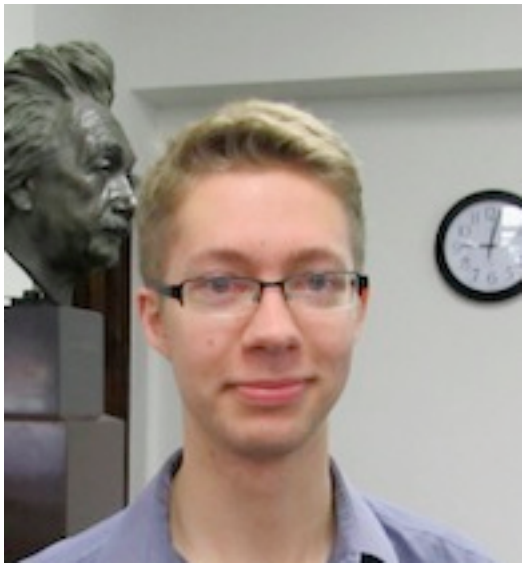


Interested?

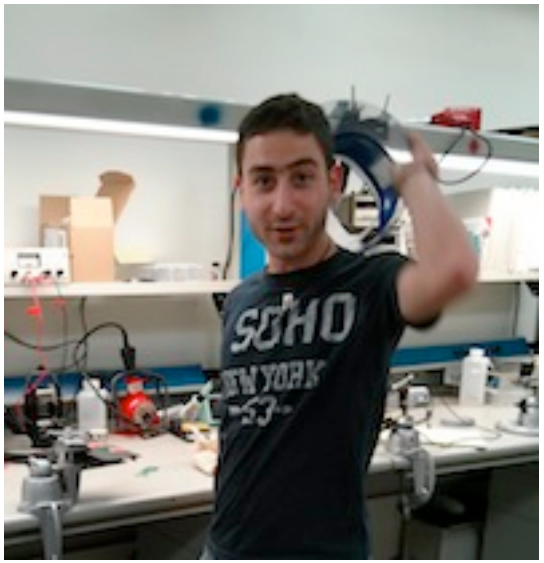
E-mail Prof. Steve Drasco

drascost@grinnell.edu

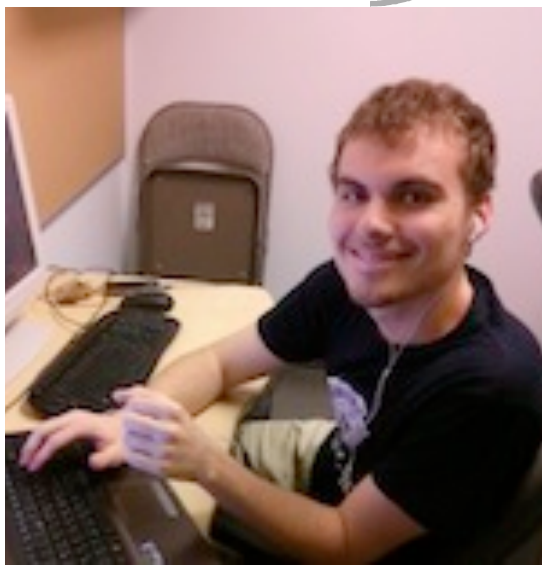
Grinnell Students @ Caltech/LIGO



James St. Germain-Fuller

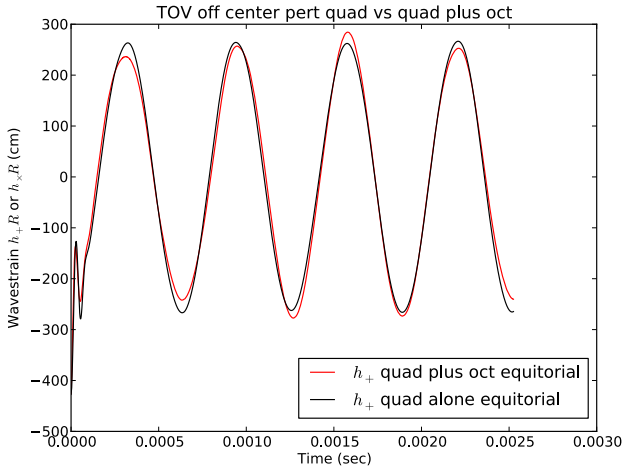


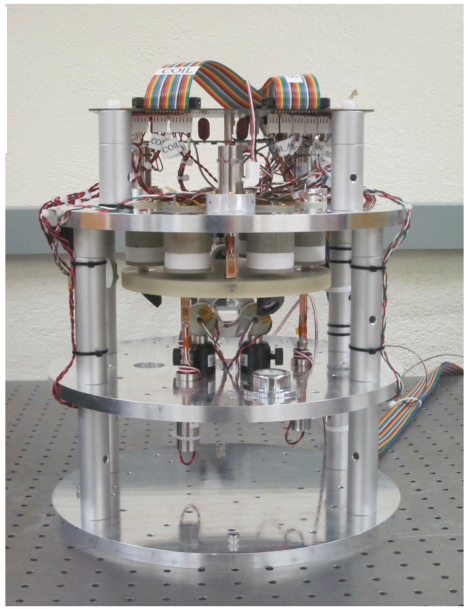
Giorgos Mamakoukas

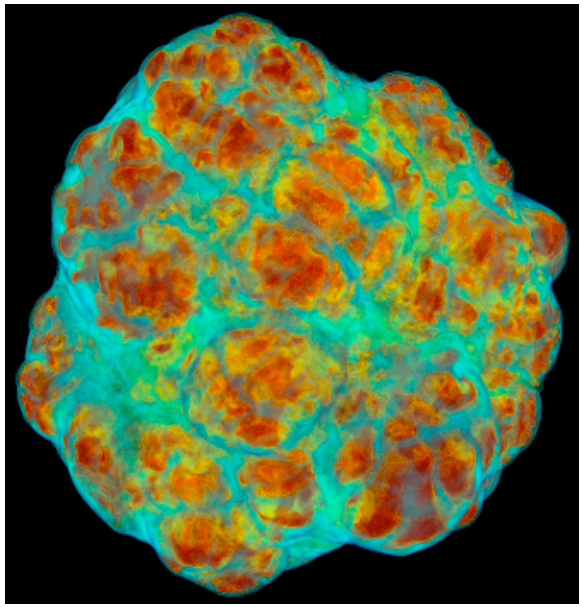


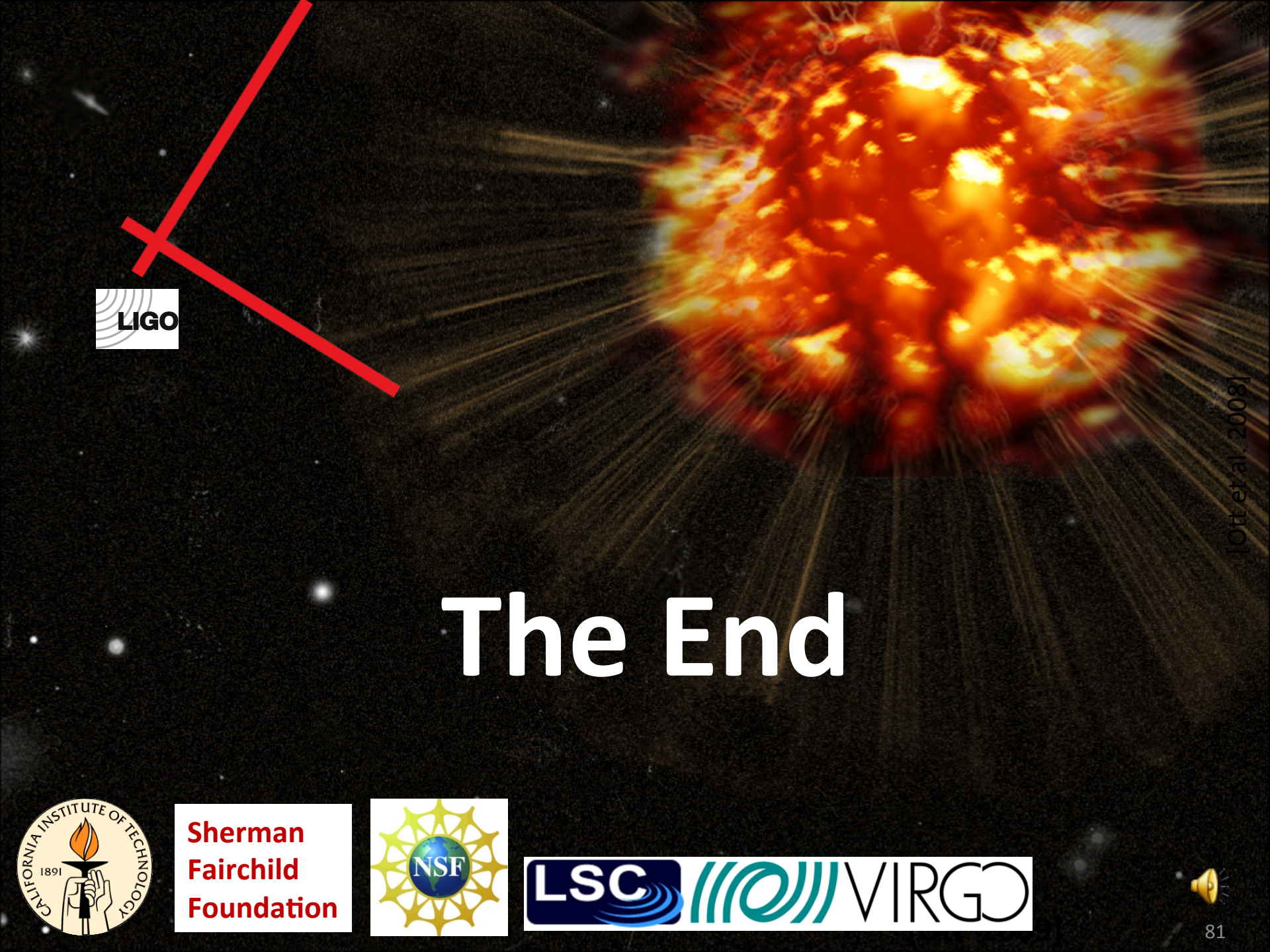
Marios Tsekitsidis

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








LIGO
[Ott et al. 2008]
The End
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