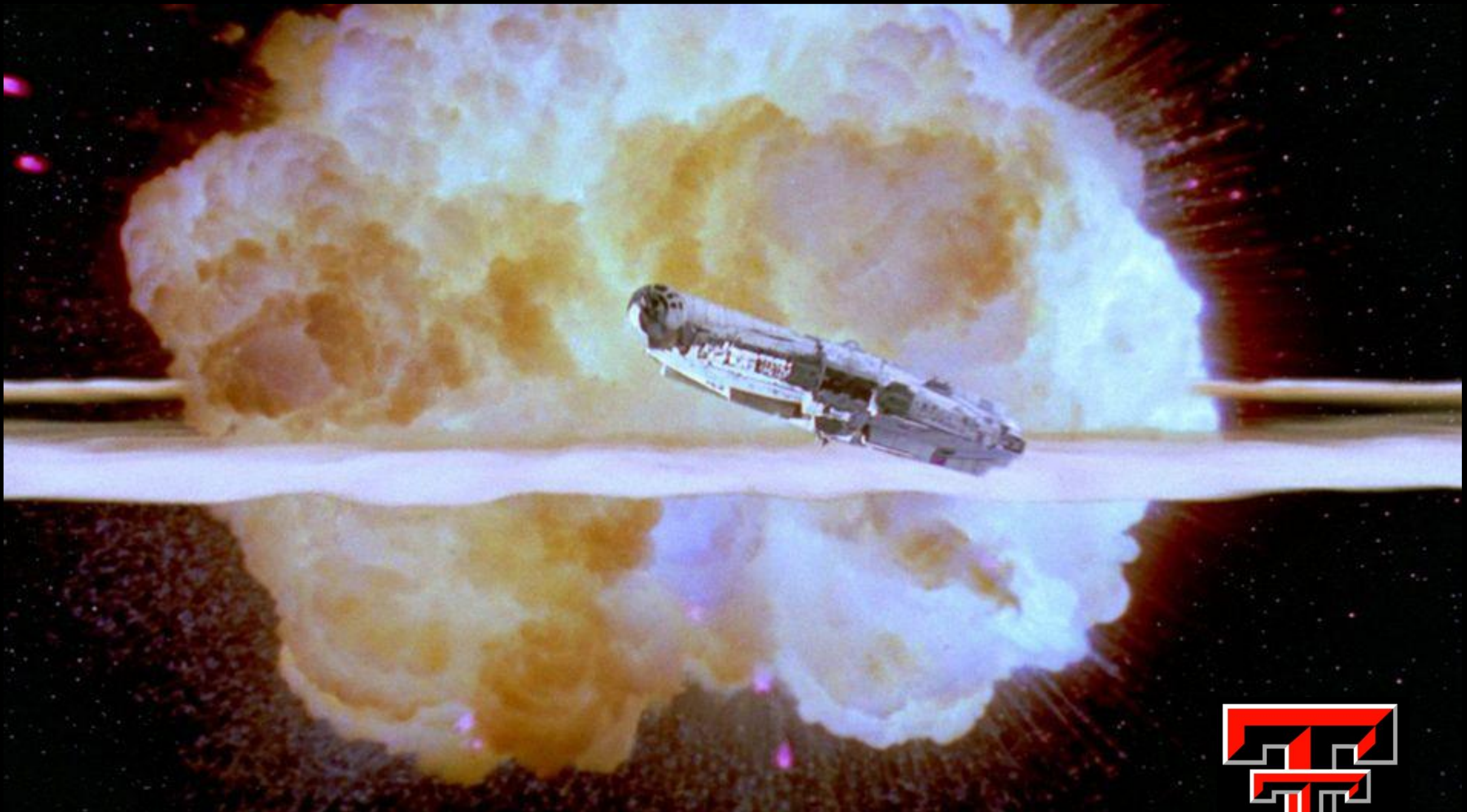
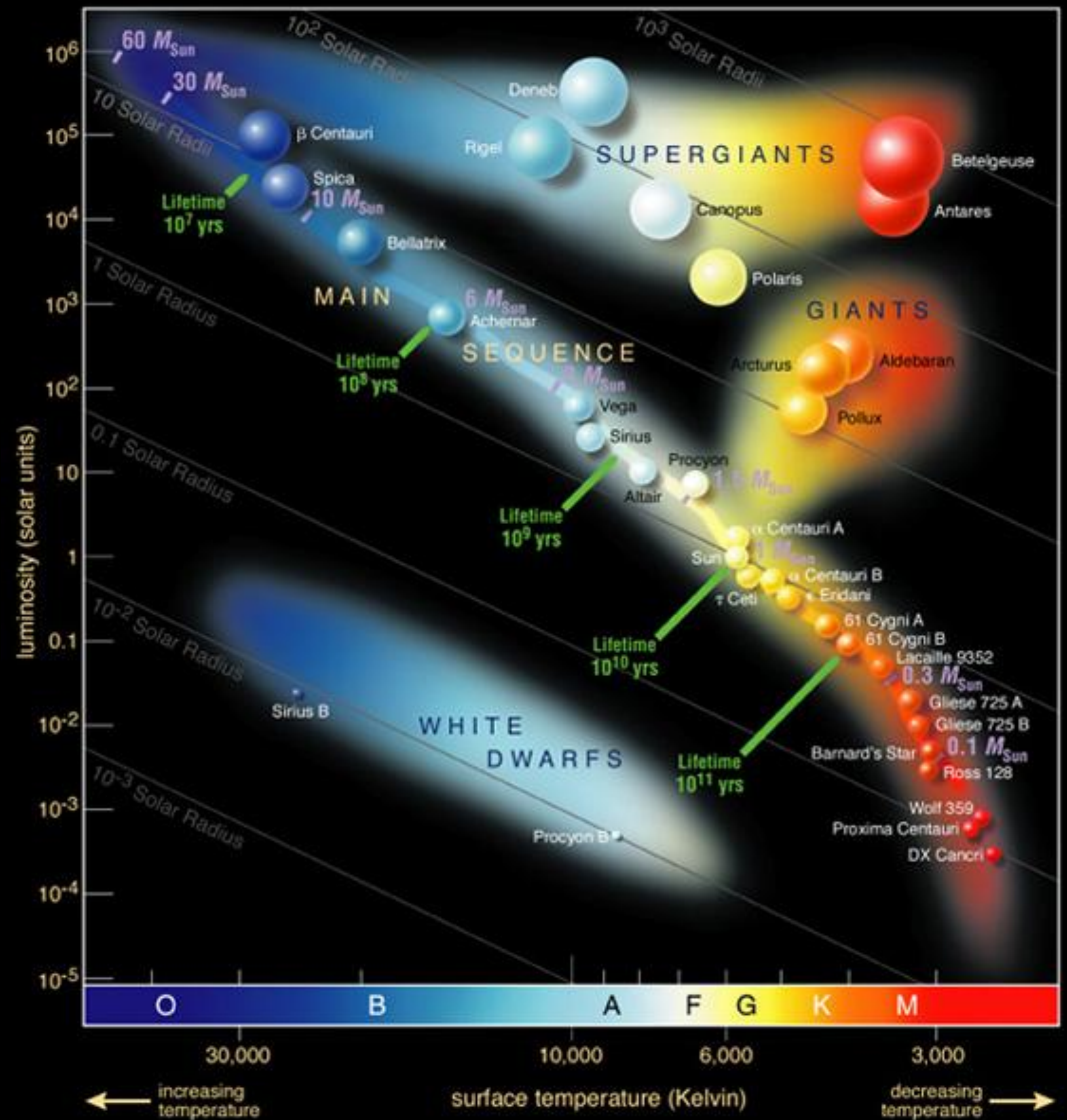
The Death of Stars



Ra Inta, Texas Tech University

I: Stellar Evolution

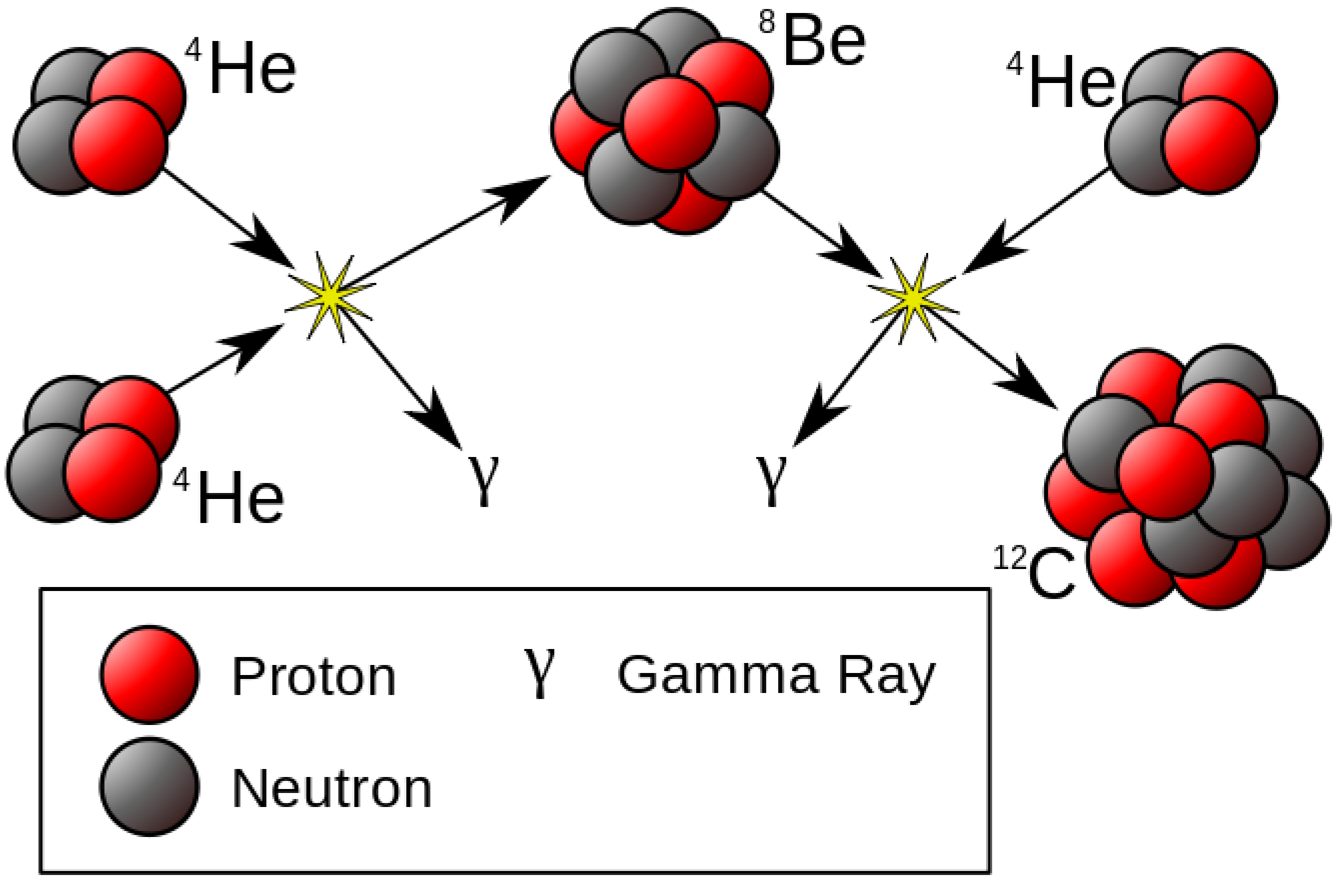


[ESO](https://www.eso.org/public/images/eso0728c/)
https://www.eso.org/public/images/eso0728c/

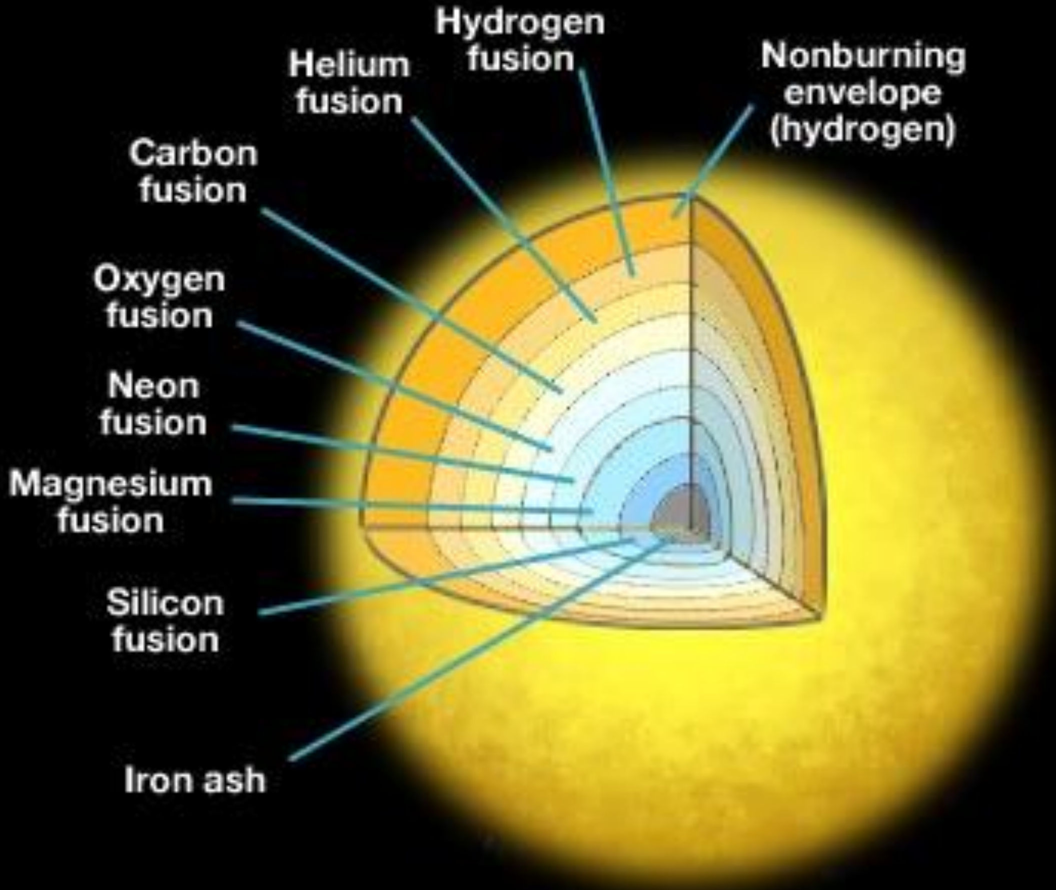
Burning stages of a 25 $M_\odot$ star

Fuel	Product(s)	Duration
H	He	100 Myr
He	C, O	1 Myr
C	Ne, Na, Mg, Al	1000 yr
Ne	O, Mg	3 yr
O	Si, S, Ar, Ca	180 days
Si	Ni	1-5 days

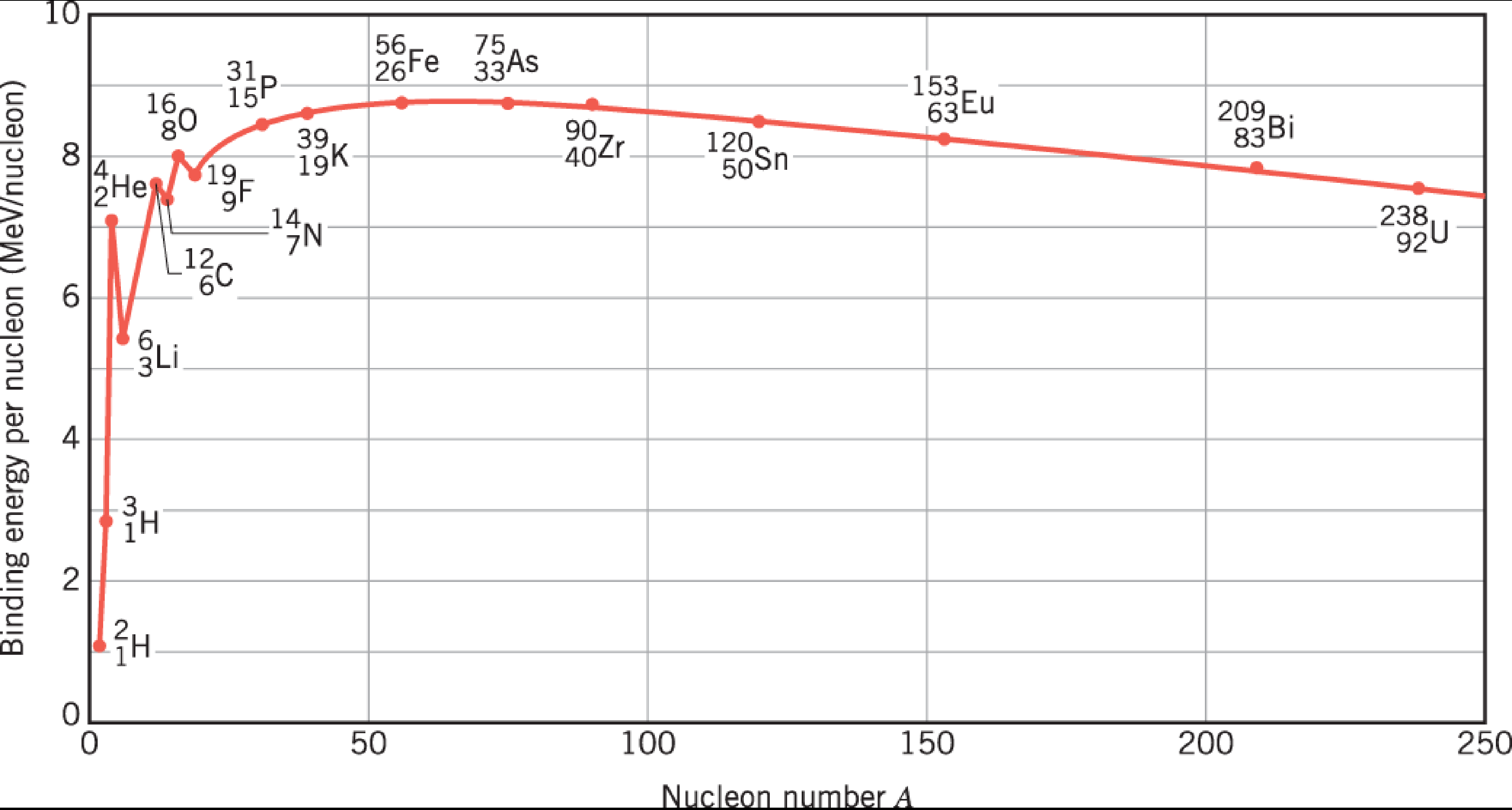
Triple-alpha process



‘Onion skin’ fusion layers



Nucleon binding energies

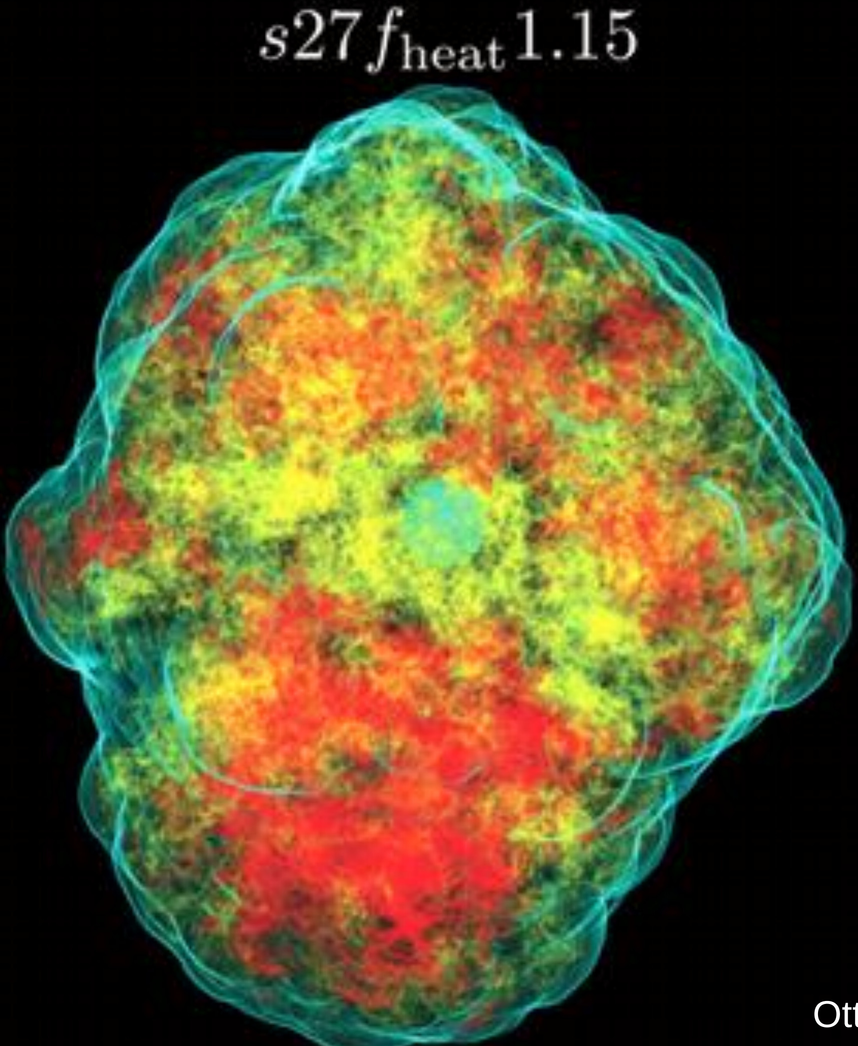


Electron degeneracy pressure: Chandrasekhar limit

- Pauli Exclusion Principle – e⁻ are fermions
- Form Fermi-Dirac gas
- Solve hydrostatic equation

$$M_{Chandra} = \left(\frac{\omega_3^0 \sqrt{3\pi}}{2} \right) \left(\frac{\hbar c}{G} \right)^{3/2} \left(\frac{1}{\mu_e m_H} \right)^2 \sim 1.39\, M_{Sun}$$

Core collapse

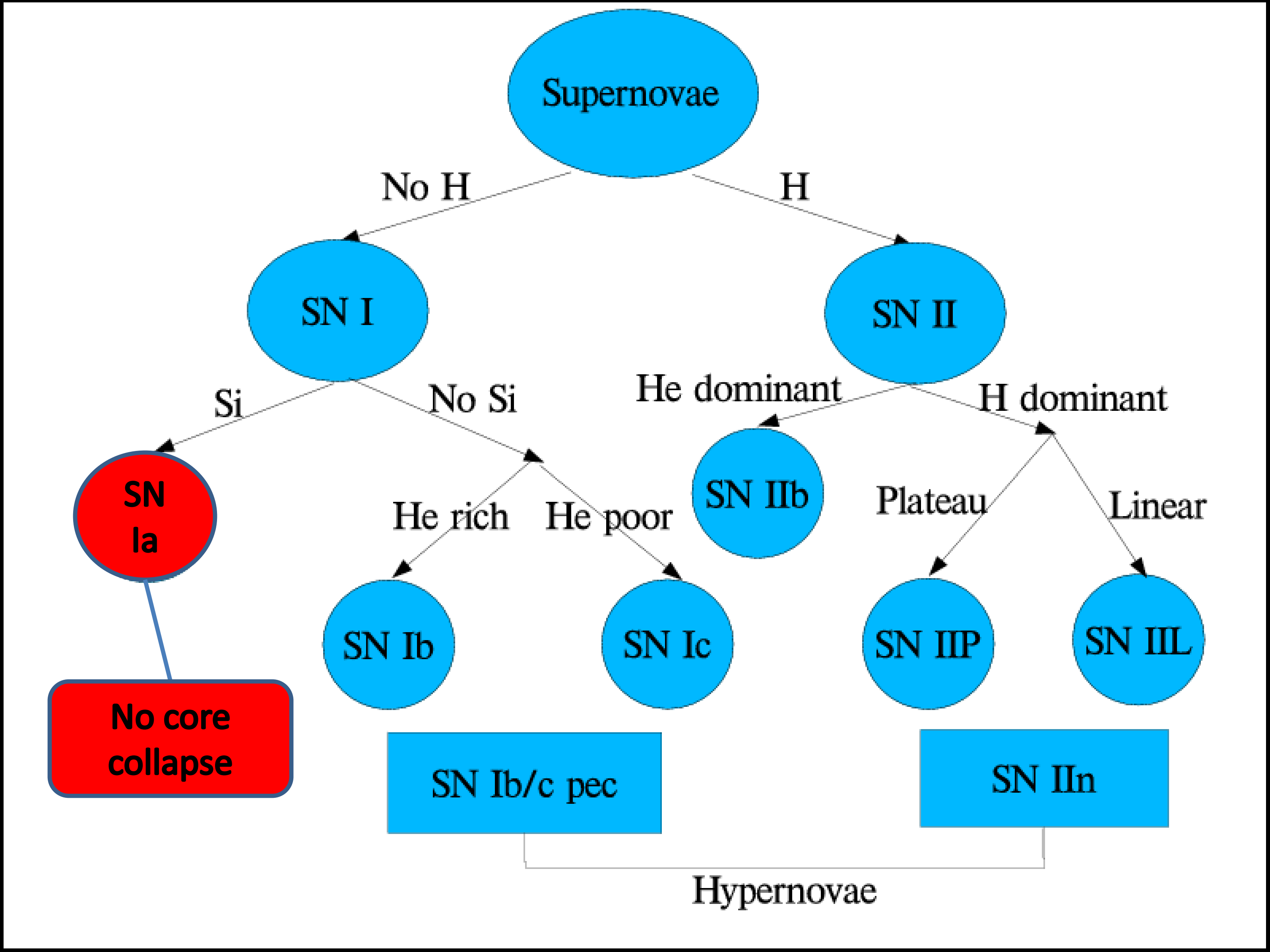


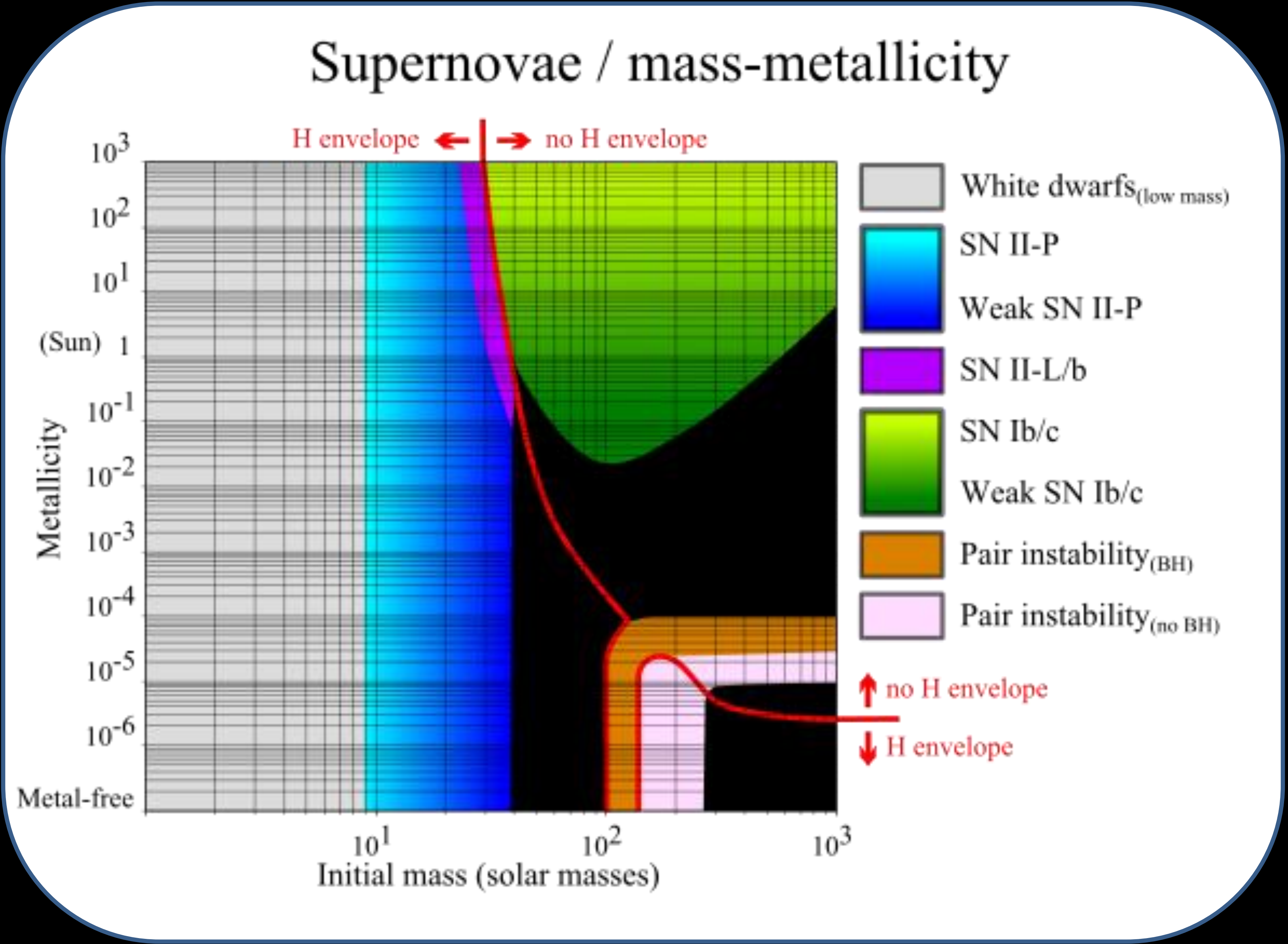
Ott C,. et al. *ApJ* **768**(2) 115, (2013)

II: Supernovae

- Electron degeneracy pressure can’t keep Fe core from collapsing (core-collapse supernova)
- Neutron formation is energetically preferred (e^- capture)
- Massive neutrino flux
- Huge gravitational potential energy released: ~10^{46} J

II: Supernovae





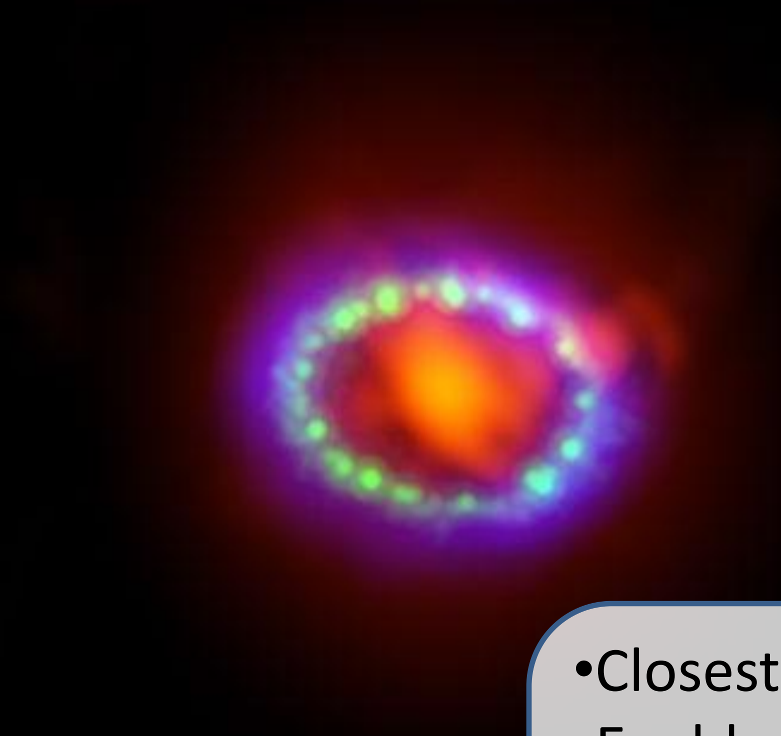
https://upload.wikimedia.org/wikipedia/commons/1/14/Supernovae_as_initial_mass-metallicity.svg

III: Supernova remnants

- Some supernovae leave behind material (gas and/or dust) expelled from supernova
- Three expansion phases:

1. Free expansion (up to few hundred yr)
2. Adiabatic expansion (kyr)
3. ‘Snow-plow’ (Myr)

Famous supernova remnants (SNRs)

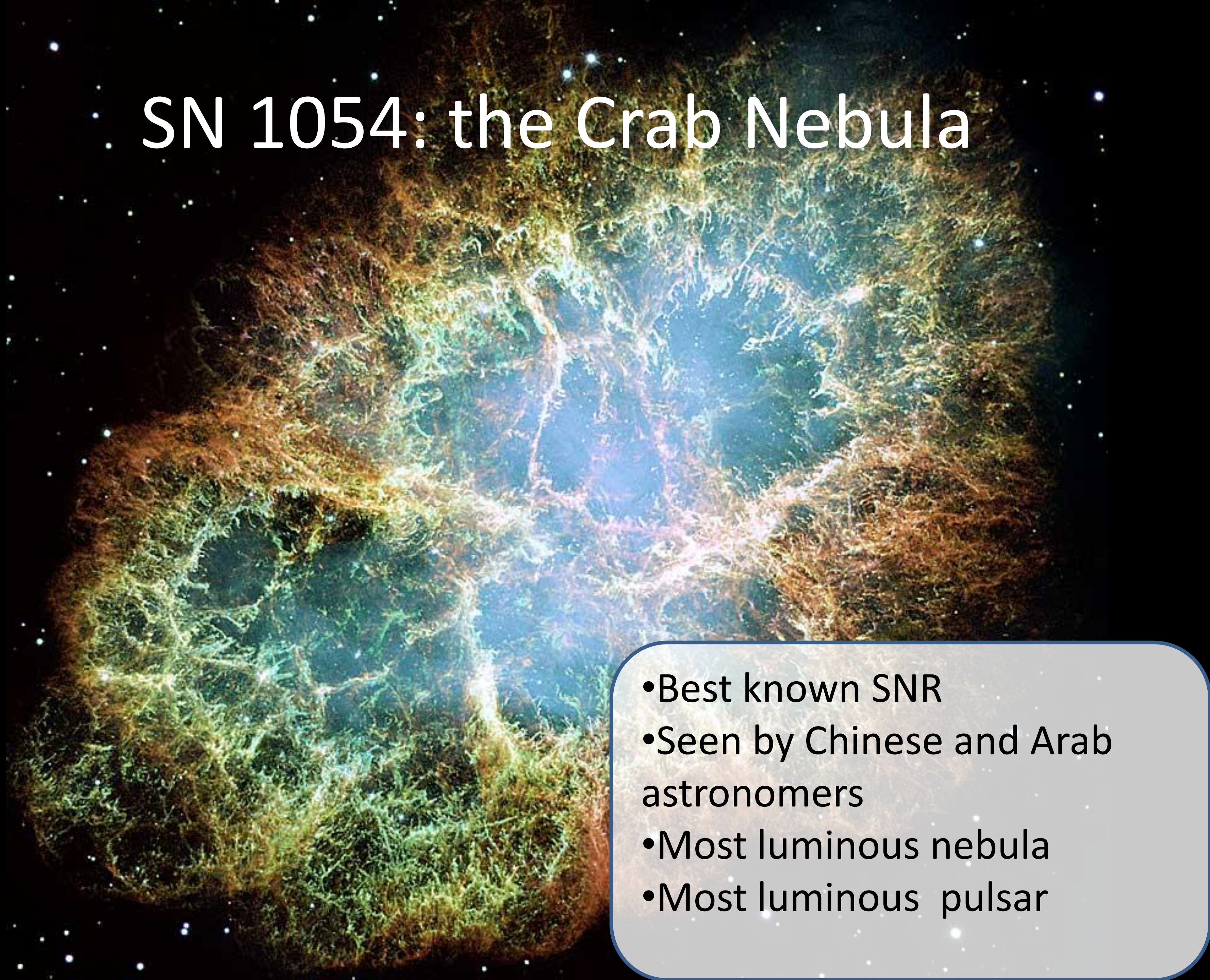


SN1987A

ALMA (ESO/NAOJ/NRAO)/A. Angelich.
Visible: Hubble Space Telescope
X-Ray: Chandra

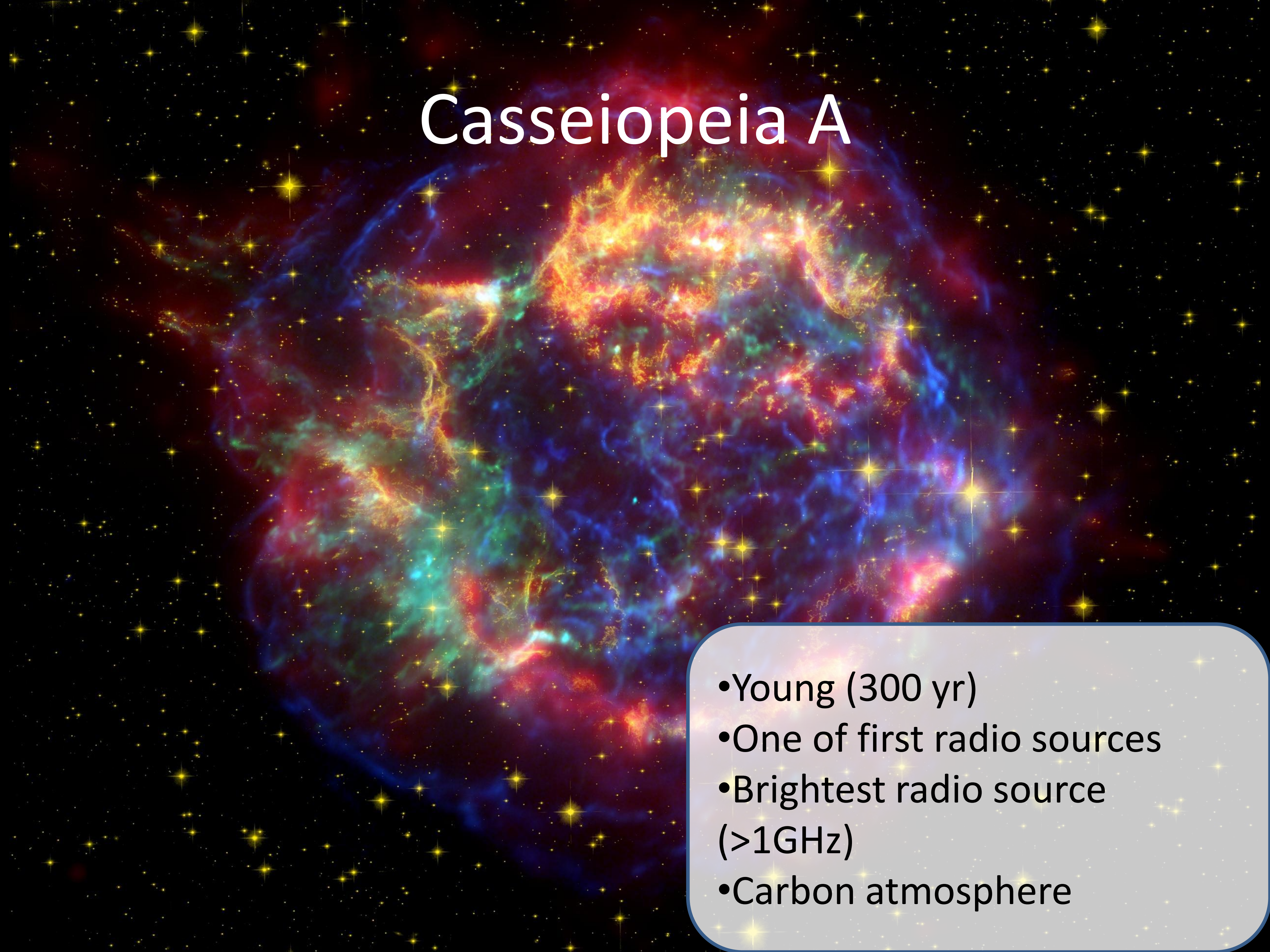
- Closest SN in 400 yr
- Enabled observation of radionucleides
- Neutrinos detected
- Blue supergiant progenitor

SN 1054: the Crab Nebula



- Best known SNR
- Seen by Chinese and Arab astronomers
- Most luminous nebula
- Most luminous pulsar

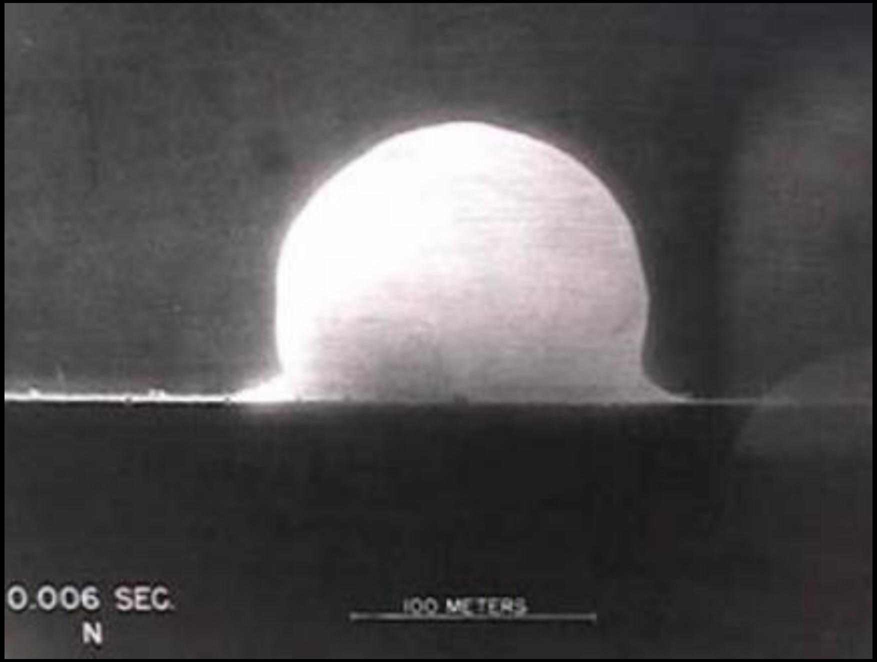
Casseiopeia A



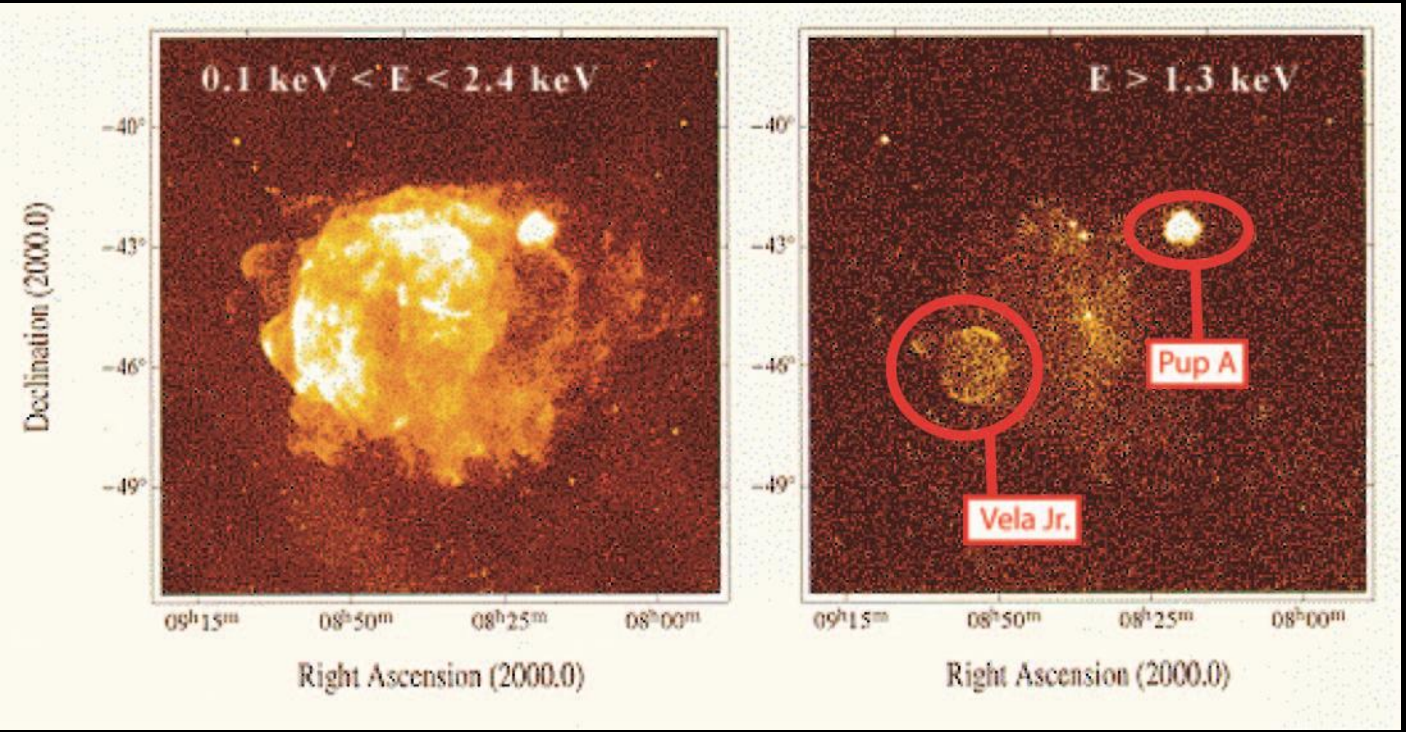
- Young (300 yr)
- One of first radio sources
- Brightest radio source (>1GHz)
- Carbon atmosphere

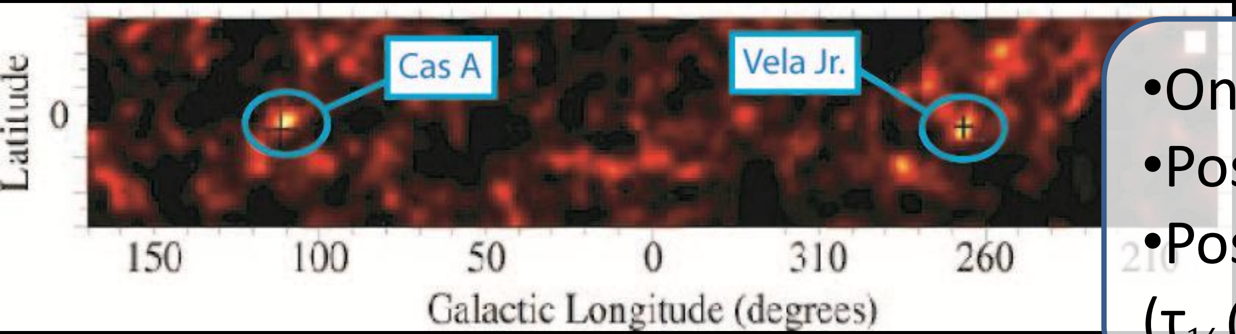
Sedov-Taylor expansion

$$t^2 = \left(\frac{\rho}{E}\right)\left(\frac{r}{C}\right)^5$$



Vela Jr.





- Only seen in x-ray or higher
- Possibly only 200pc away
- Possibly only 780 yr old ($\tau_{1/2}(\,^{44}\mathrm{Ti}\,) = 60$ yr)

The cosmic ray mystery

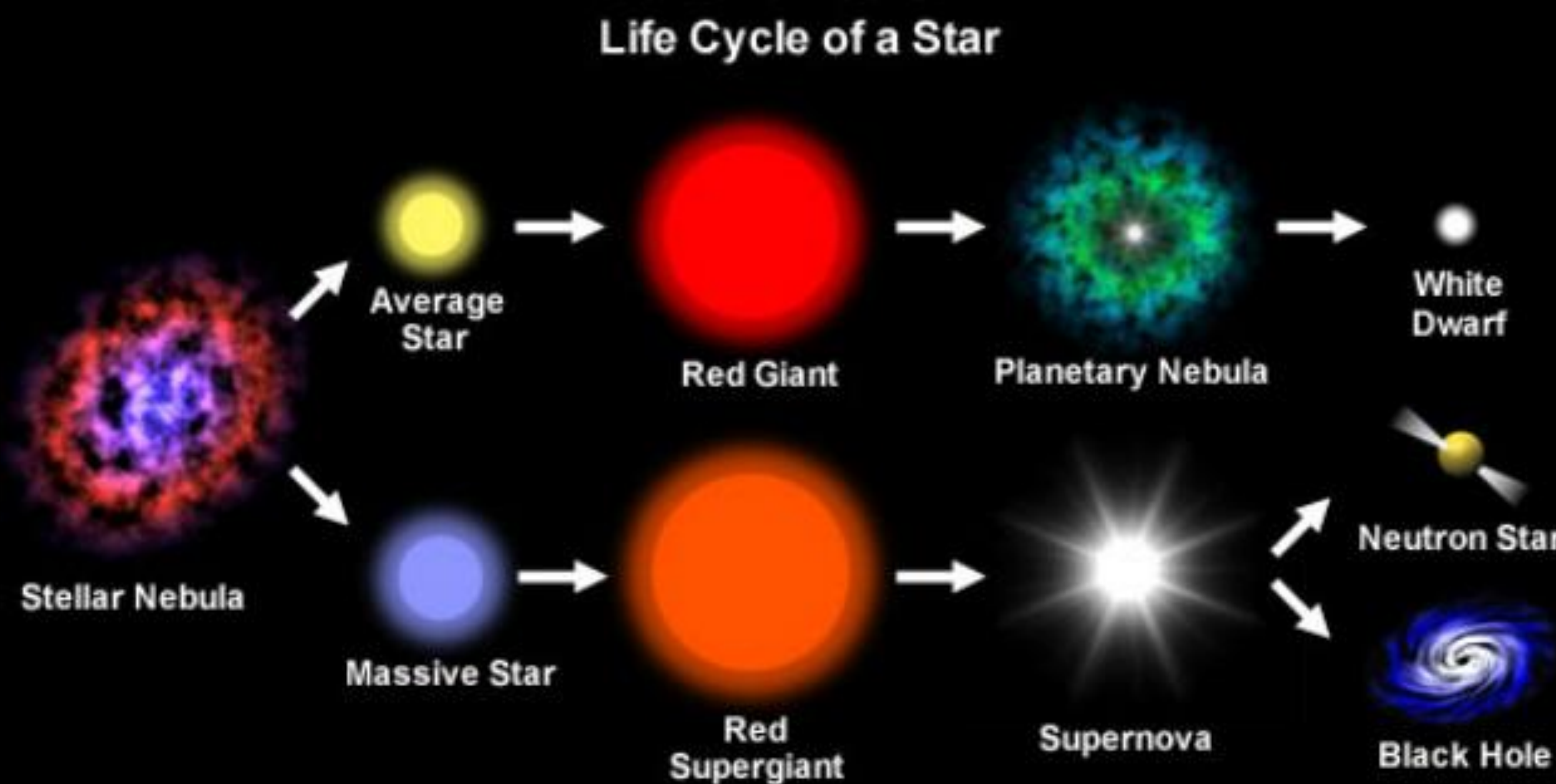
- Ice cores
- ^{60}Fe in the sea floor
- Periodic global ice ages/warming
- Tree rings?

IV: Neutron Stars

Tolman-Oppenheimer-Volkoff limit
(neutron degenerate analogy to Chandrasekhar limit)

$$M_{TOV} \sim 1.5 - 3.0\, M_{Sun}$$

- Assume neutrons form degenerate cold Fermi gas
- Strong nuclear force much shorter range
- Equation of state highly uncertain
- We've observed ~$2M_{\odot}$ neutron stars


Life Cycle of a Star
Average
Star
Red Giant
Planetary Nebula
White
Dwarf
Stellar Nebula
Massive Star
Red
Supergiant
Supernova
Neutron Star
Black Hole

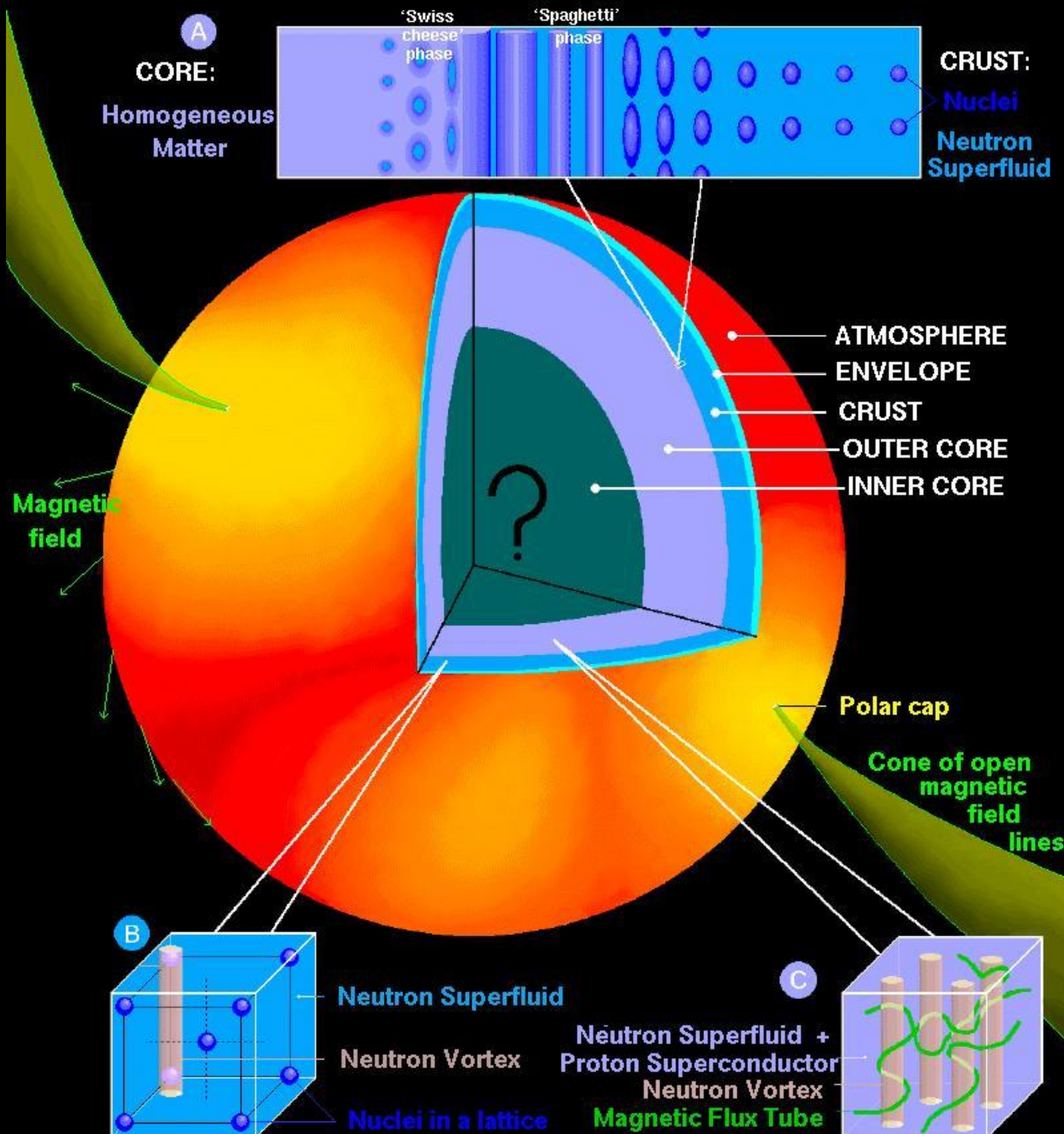
Neutron degeneracy

- Exclusion principle
- Degenerate electrons
- Inverse beta decay (creates neutron ‘soup’)

Properties of neutron star (NS)

- Hot (but ‘cold’)
- **Huge** magnetic fields
- Strongest material known
- Exotic core?

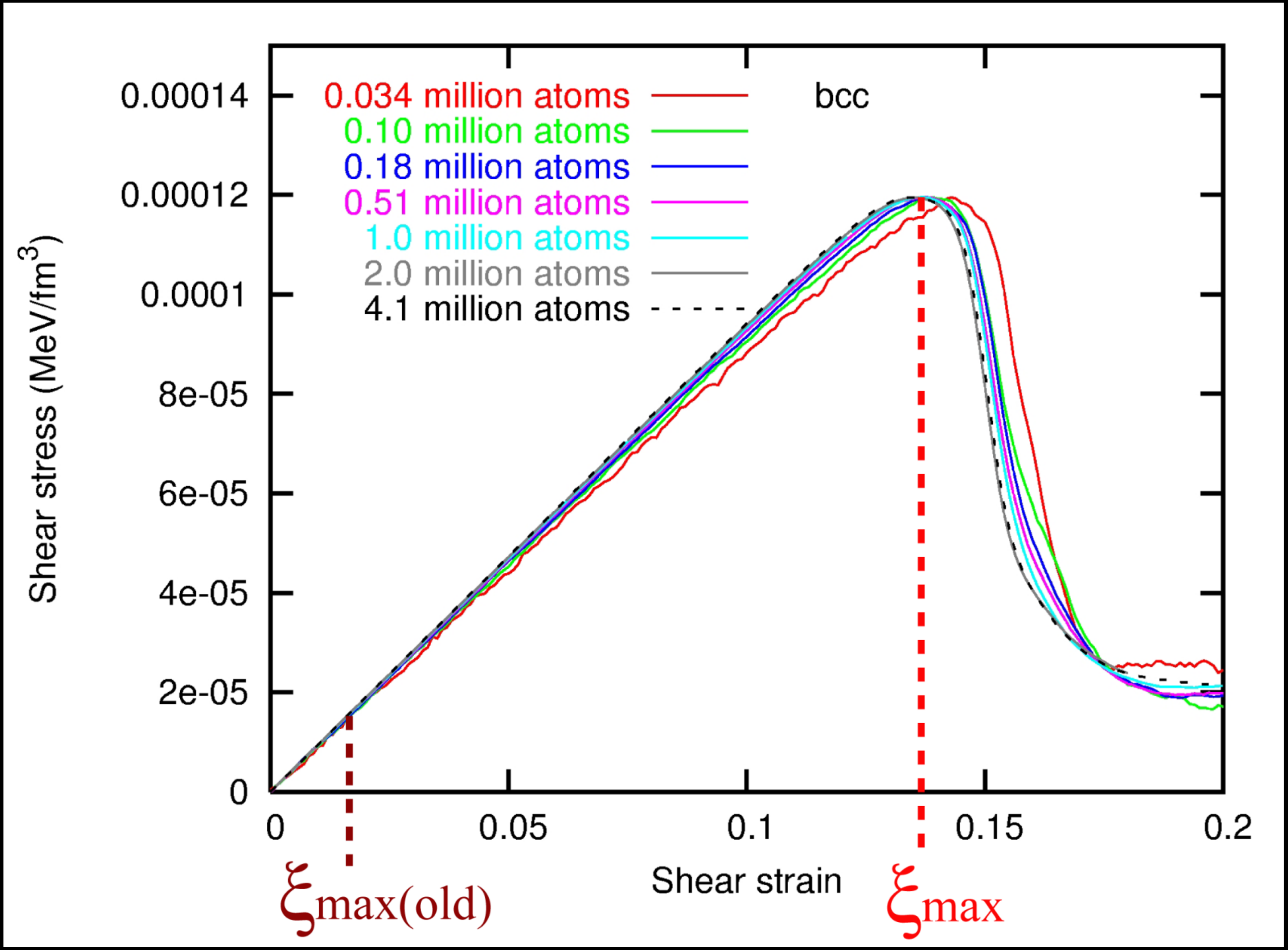
A NEUTRON STAR: SURFACE and INTERIOR



Material properties of NS crust (BCC phase):

- **Pre-2008:** Extrapolation from Terrestrial metals [Smoluchowski, R.: "Frequency of Pulsar Starquakes," *Phys. Rev. Lett.* **24**, pp.923-925 (1970)]
- **Post-2008:** Modelling of crust as a ‘Coulomb solid’ gives 10X shear strength

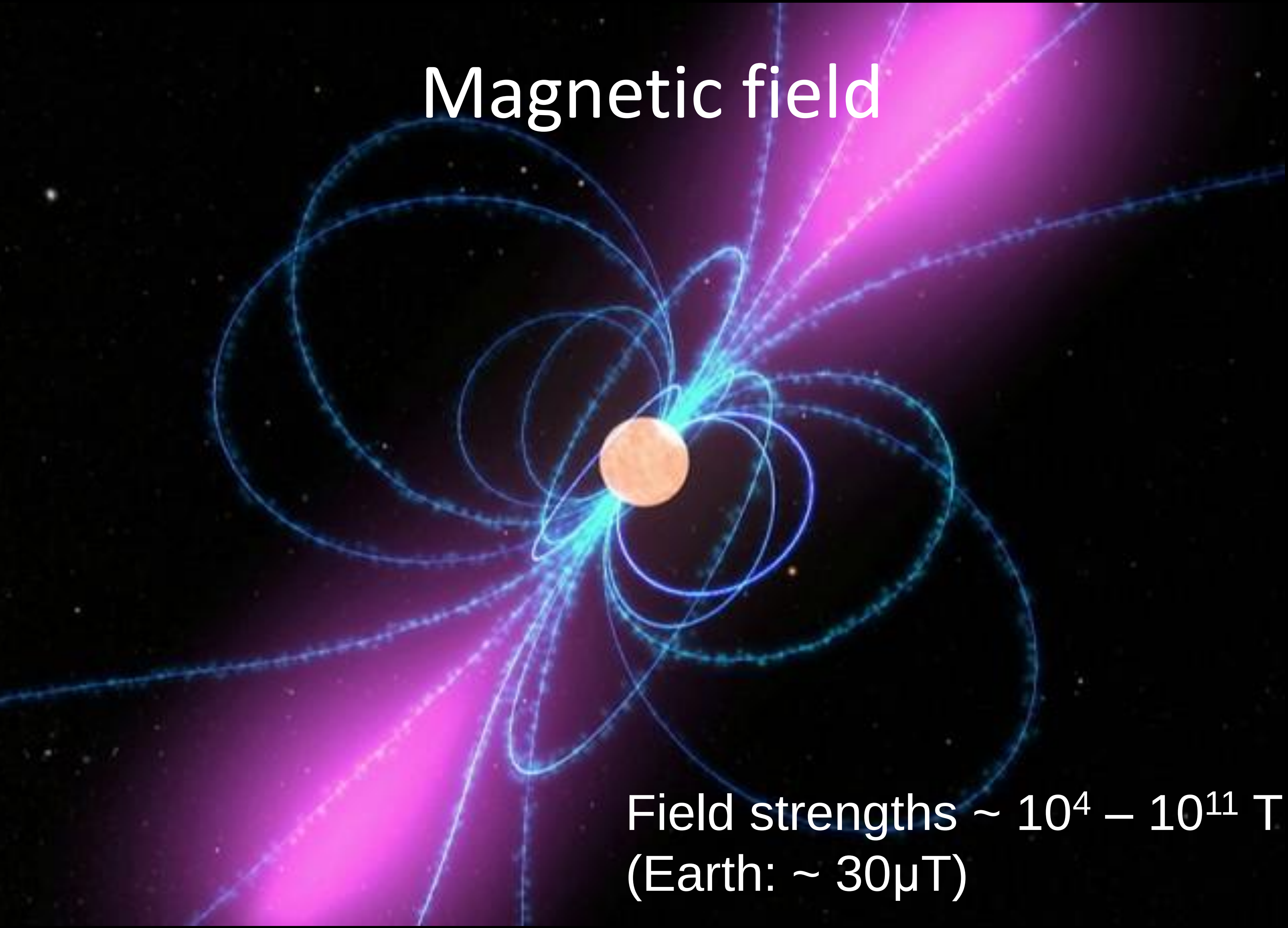
[Horowitz, C.J. and Kadau, K.: "Breaking Strain of Neutron Star Crust and Gravitational Waves," *PRL* **102**, 191102 (2009)]



$F_{Gravity}$ > $F_{Coulomb}$, and electron degeneracy

So local defects not supported!

Magnetic field

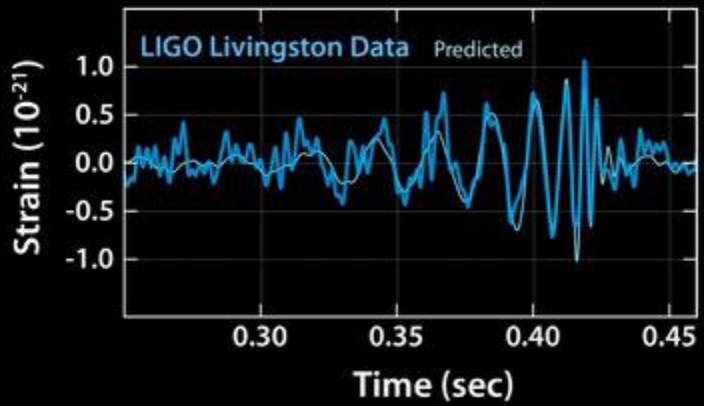


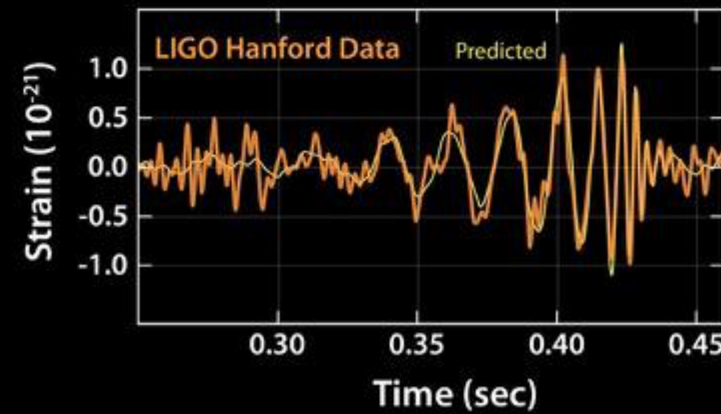
Field strengths ~ 10^4 – 10^{11} T
(Earth: ~ 30μT)

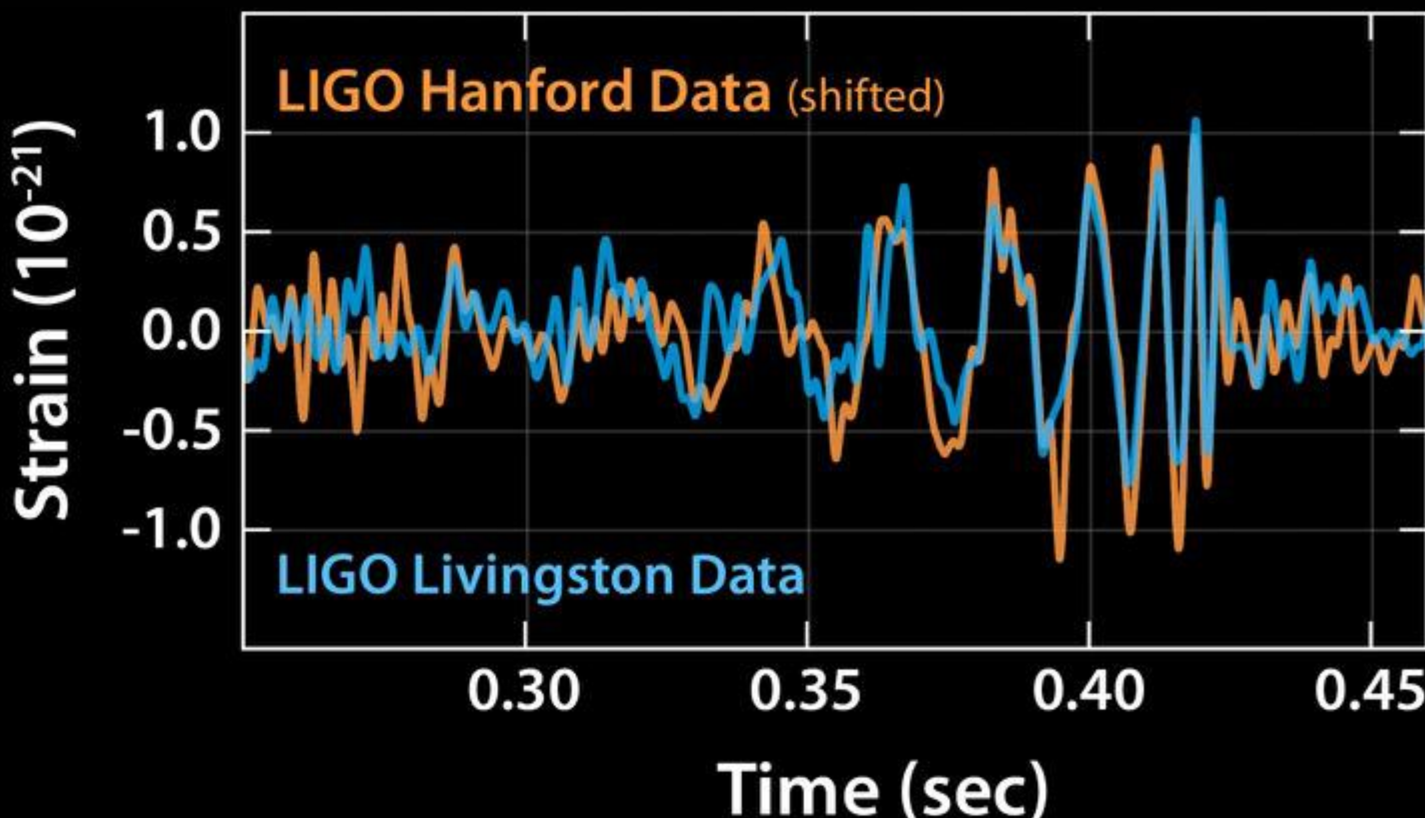
V: Persistent Gravitational Waves

- Gravitational waves: travelling perturbations in space-time
- Produced by (non-axisymmetric) acceleration of mass/energy
- Perturbation seen as a strain (δL/L)
- Tiny amplitudes:

$$\bar{h}_{ij} = \frac{2G}{c^4 D} \ddot{I}_{ij}$$


LIGO Livingston Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

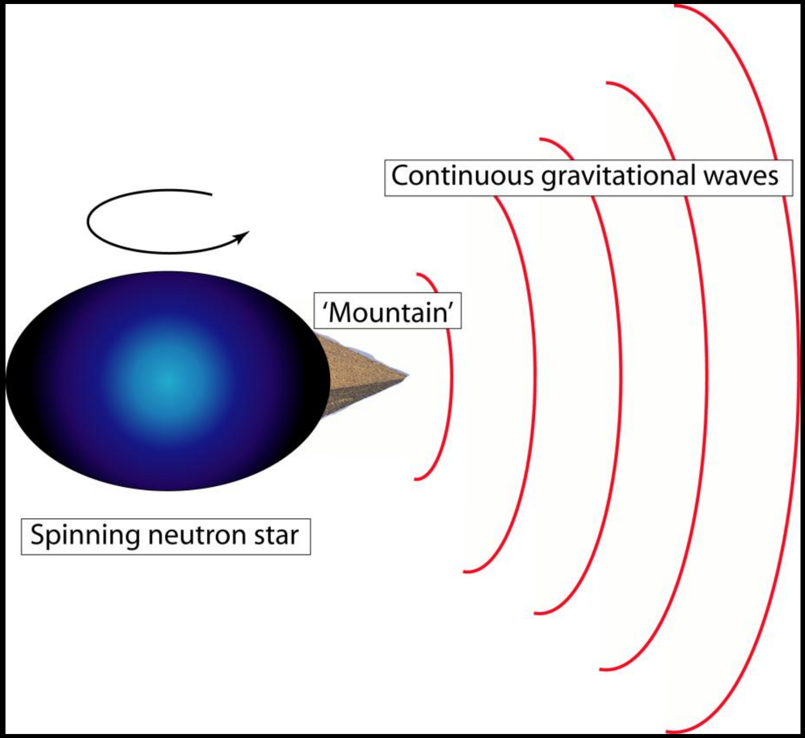

LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

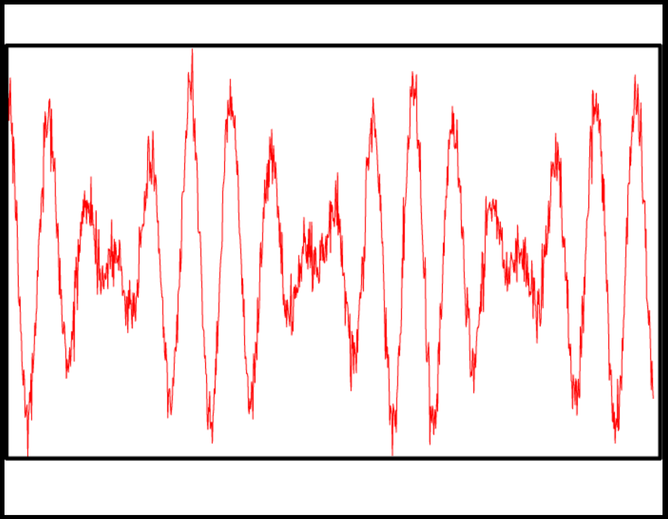
Triaxial model

- Rotating, non-axisymmetric neutron stars

(and possibly axions...)

- Low $h_0(t)$ ... but can average





Divergence from axisymmetry: ellipticity

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}} \qquad \varepsilon_{\text{max.}} \sim 5\times 10^{-6} \times \left(\frac{\xi_{\text{max.}}}{10^{-1}}\right)$$

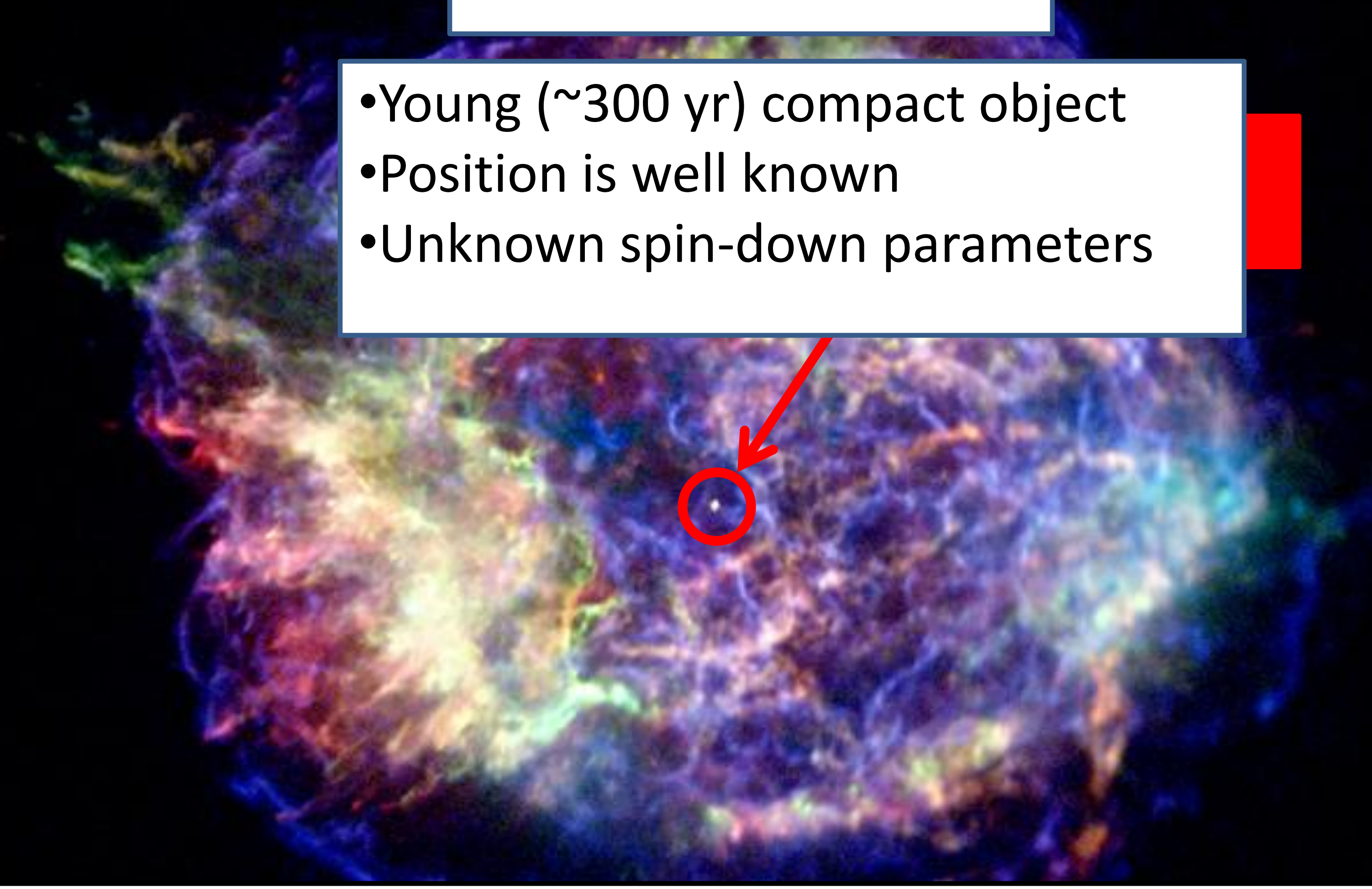
Determines maximum height of 'hills' supported within NS crust (*O*(few mm))

Expected strain amplitude:

$$h_0 = \frac{4\pi^2 G}{c^4} \cdot \frac{I_{zz} f_{GW}^2}{D} \cdot \varepsilon$$

Cassiopeia A

- Young (~300 yr) compact object
- Position is well known
- Unknown spin-down parameters



Wette, K. *et al.:* "Searching for gravitational waves from Cassiopeia A with LIGO," *Class. Quantum Grav.*, **25**(235011):1-8 (2008)

Manifold parameters for Cas A

- f_0 in LIGO band (~10% of pulsars)
- Braking index, n = 5 → quadrupole radiation (but $n_{obs.}$ ~ 3 …)

$$n = \frac{f \cdot \ddot{f}}{\dot{f}^2}$$

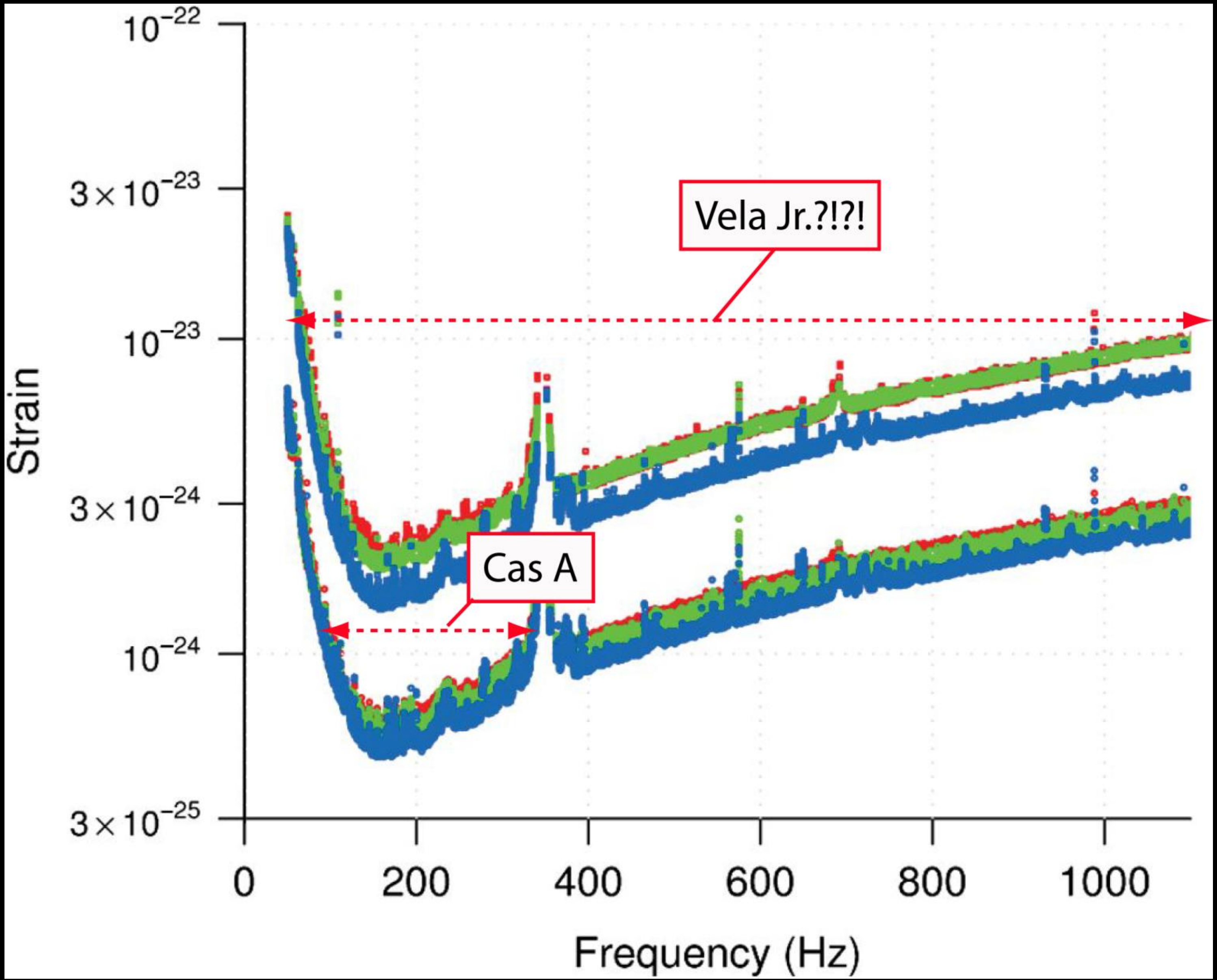
Cas A very young → second spin-down required

$$\text{Spin - down parameters : } f, \dot{f} \text{ and } \ddot{f}$$

$$\text{Manifold parameters : } \lambda_1 = f_0, \lambda_2 = \dot{f}, \lambda_3 = \ddot{f}$$

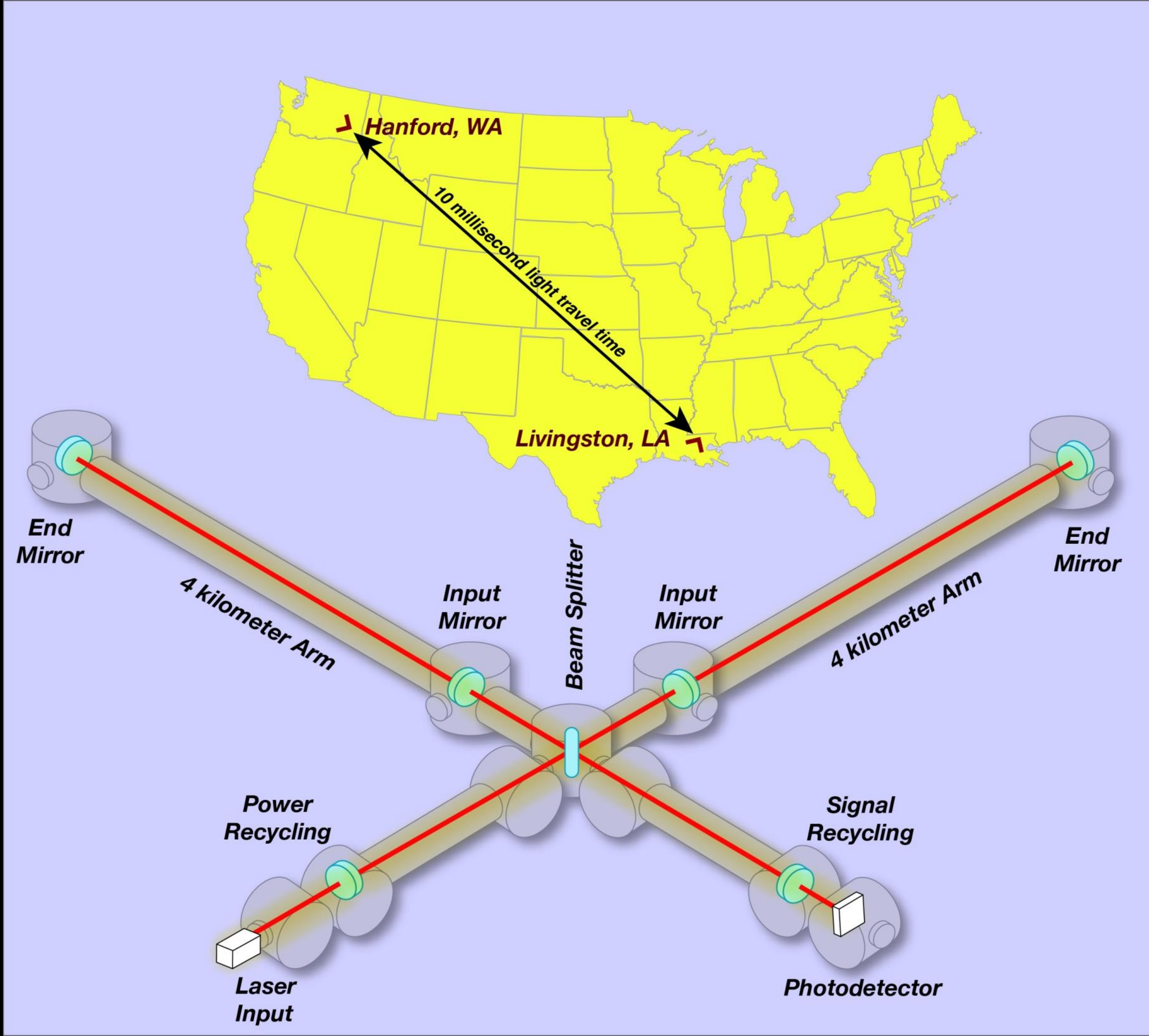
Age-based Upper Limit

$$h_{\text{age}} \le \sqrt{\frac{5GI_{zz}}{8c^3\tau}} = 1.2\times10^{-24} \times \frac{3.4\,\text{kpc}}{D} \times \sqrt{\frac{I_{zz}}{10^{38}\ \text{kg m}^2} \times \frac{300\ \text{yr}}{\tau}}$$



Vela Jr.?!?!
Cas A
Strain
Frequency (Hz)
10^{-22}
3×10^{-23}
10^{-23}
3×10^{-24}
10^{-24}
3×10^{-25}
0
200
400
600
800
1000

How GWs are detected



Credit: Shane Larson, Northwestern University

The LIGO Network

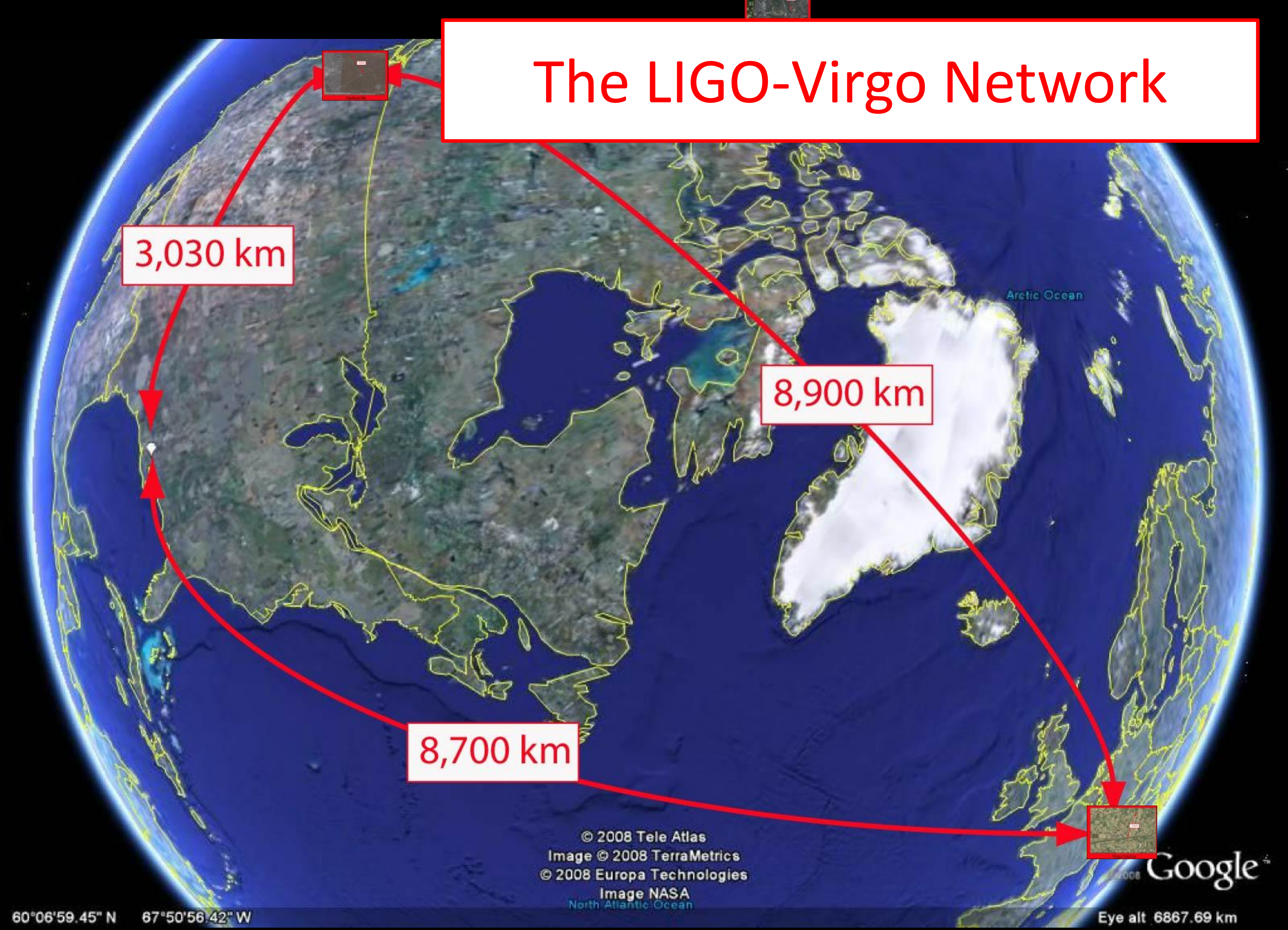
Hanford, WA

Livingston, LA

4 km baseline, seismic isolation


Hanford, WA
4 km
3,030 km
Livingston, LA
4 km
Canada
Saskatchewan
Manitoba
Montana
North Dakota
Minnesota
South Dakota
Wisconsin
Michigan
Toronto
Wyoming
Detroit
Nebraska
Iowa
Chicago
San Francisco
Nevada
Utah
Ohio
San Jose
California
Colorado
Illinois
Indianapolis
Missouri
Kentucky
Los Angeles
North Carolina
Tennessee
San Diego
Arizona
Phoenix
New Mexico
Arkansas
South Carolina
Georgia
Dallas
Texas
San Antonio
Florida
Gulf of California
Image © 2008 TerraMetrics
© 2008 Tele Atlas
Image NASA
© 2008 Europa Technologies
Google
39°30'35.12" N 98°59'49.96" W
Eye alt 3986.21 km

The LIGO-Virgo Network



Computational bound

All this averaging means CW searches are computationally limited

Cas A search took 420,000 CPU hrs on Albert Einstein Institute's Atlas supercomputer

We used this bound explicitly to determine a figure of merit for other targets

What targets we look at

Aasi, J. et al.: “Searches for Continuous Gravitational Waves from Nine Young Supernova Remnants,” *ApJ* **813** (1) 39, 16 pp. (2015)

Young compact objects in SNRs

SNR (G name)	Other name	RA+dec (J2000)	D (kpc)	τ (kyr)
1.9+0.3		174846.9-271016	8.5	0.1
18.9-1.1		182913.1-125113	2	4.4
93.3+6.9	DA 530	205214.0+551722	1.7	5
111.7-2.1	Cas A	232327.9+584842	3.3	0.3
189.1+3.0	IC 443	061705.3+222127	1.5	3
266.2-1.2	Vela Jr. (I)	085201.4-461753	0.2	0.69
266.2-1.2	Vela Jr. (II)	085201.4-461753	0.75	4.3
291.0-0.1	MSH 11-62	111148.6-603926	3.5	1.2
347.3-0.5		171328.3-394953	0.9	1.6
350.1-0.3		172054.5-372652	4.5	0.6

Upper limit plots