Magnetized White Dwarfs

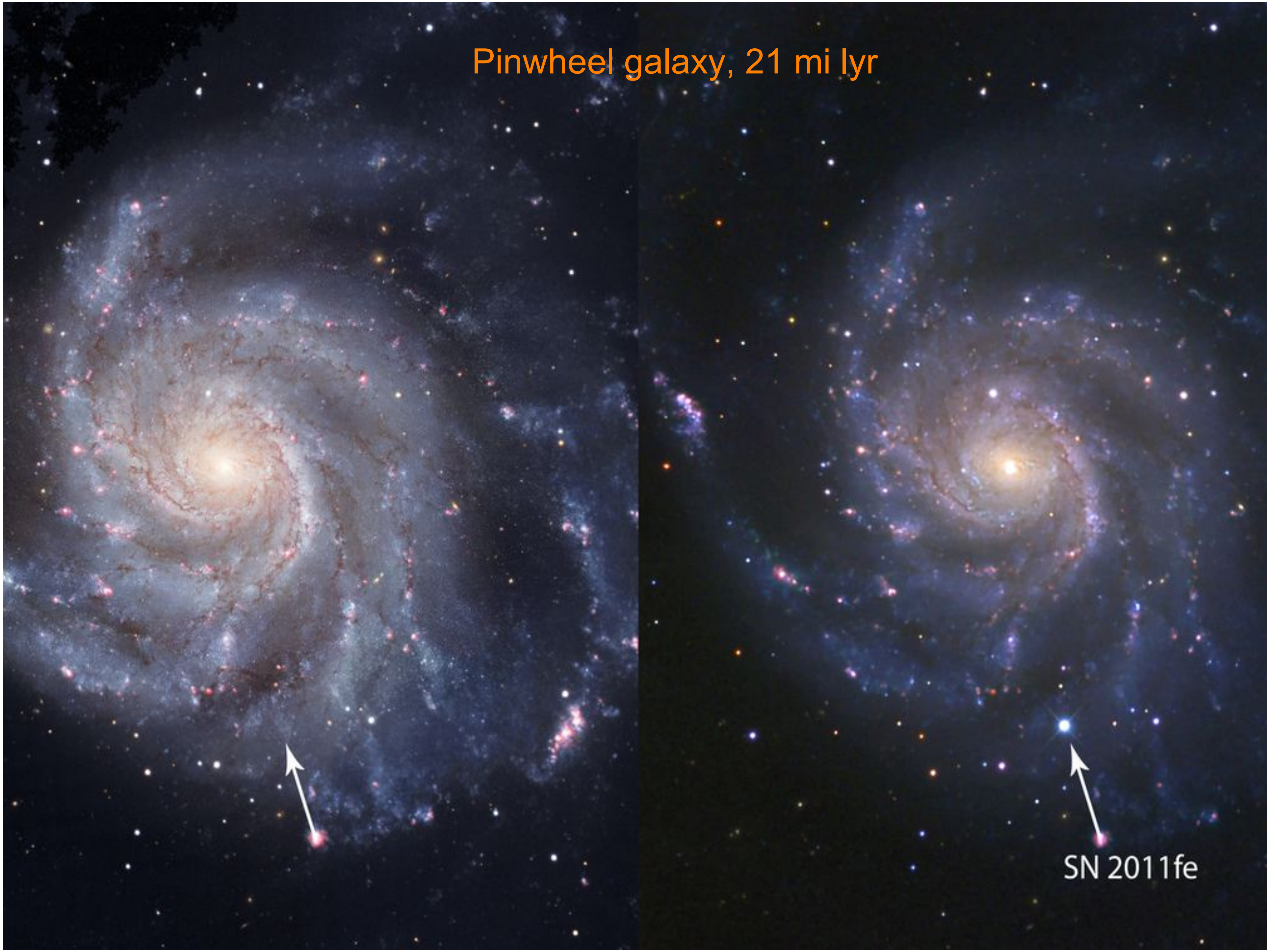
Phys.Rev. D92 (2015) 8, 083006

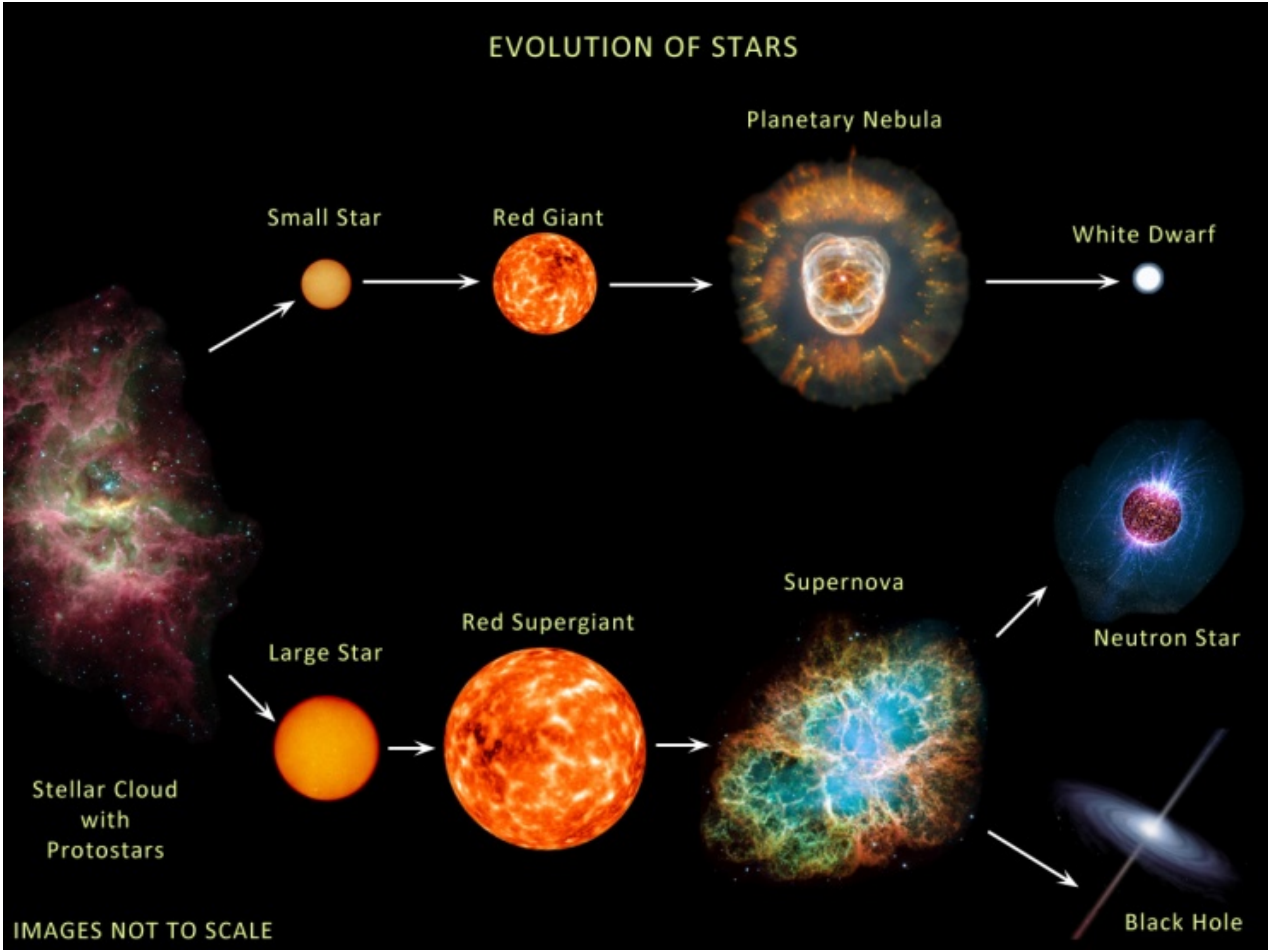
Mon.Not.Roy.Astron.Soc. 456 (2015) 2937-2945

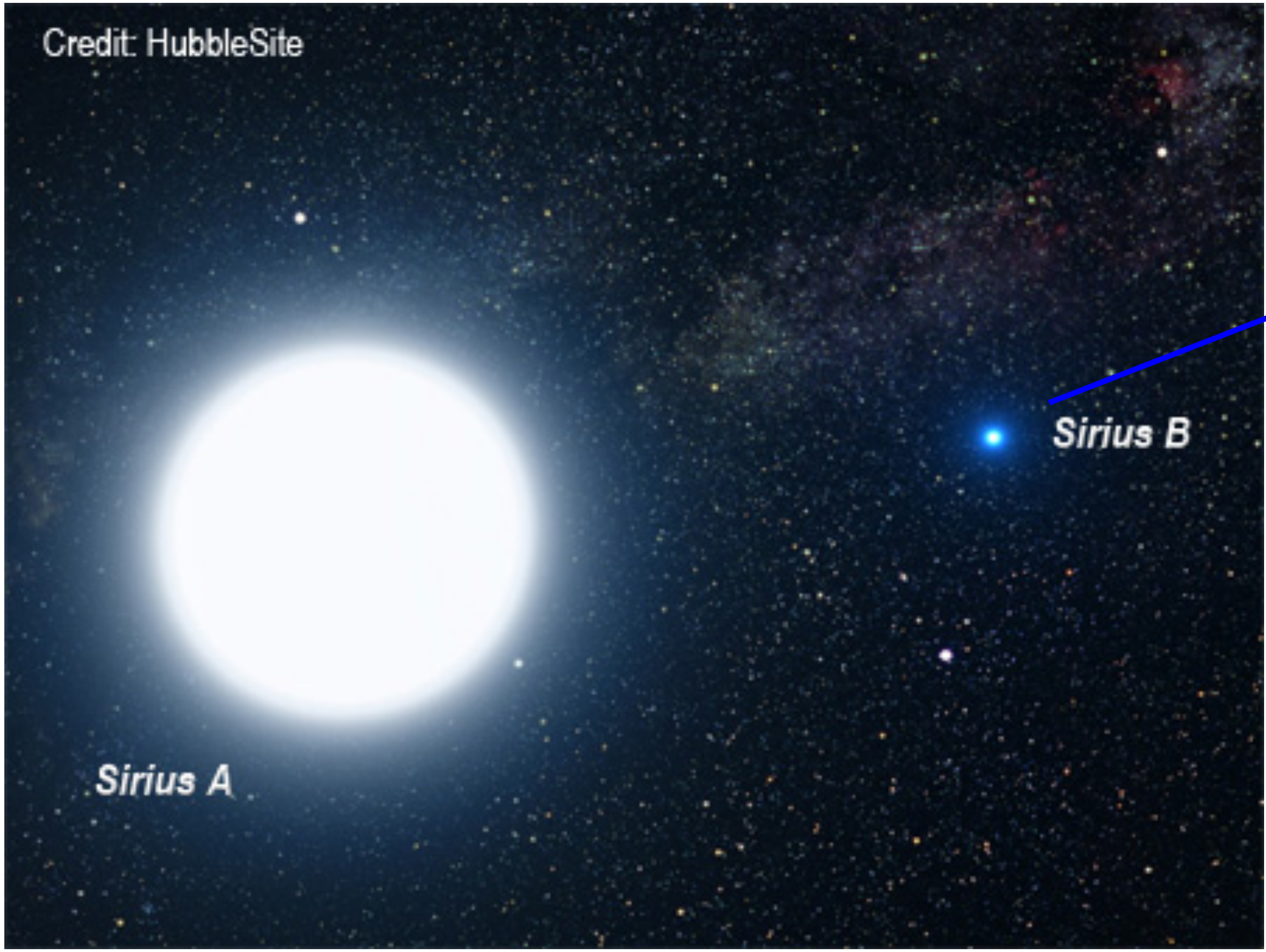
Bruno Franzon
Collaborators: V. Dexheimer, S. Schramm

Frankfurt Institute for Advanced Studies

Compact Stars in the QCD phase diagram V, May, 2016


Pinwheel galaxy, 21 mi lyr
SN 2011fe

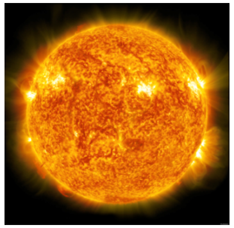

EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Cloud
with
Protostars
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
IMAGES NOT TO SCALE



White Dwarf

$M = 0.98\ M_{sun}$
$R = 0.0084\ R_{sun}$

SUN

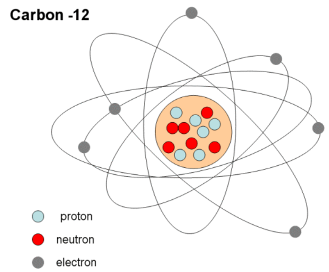


$M_{sun} = 2x10^{32}$ kg
$R_{sun} = 700.000$ km

I. Sirius is the brightest star in the Earth's night sky!

II. What the naked eye perceives as a single star is actually a binary star system, consisting of a white main-sequence star, termed Sirius A, and a faint white dwarf, called Sirius B.

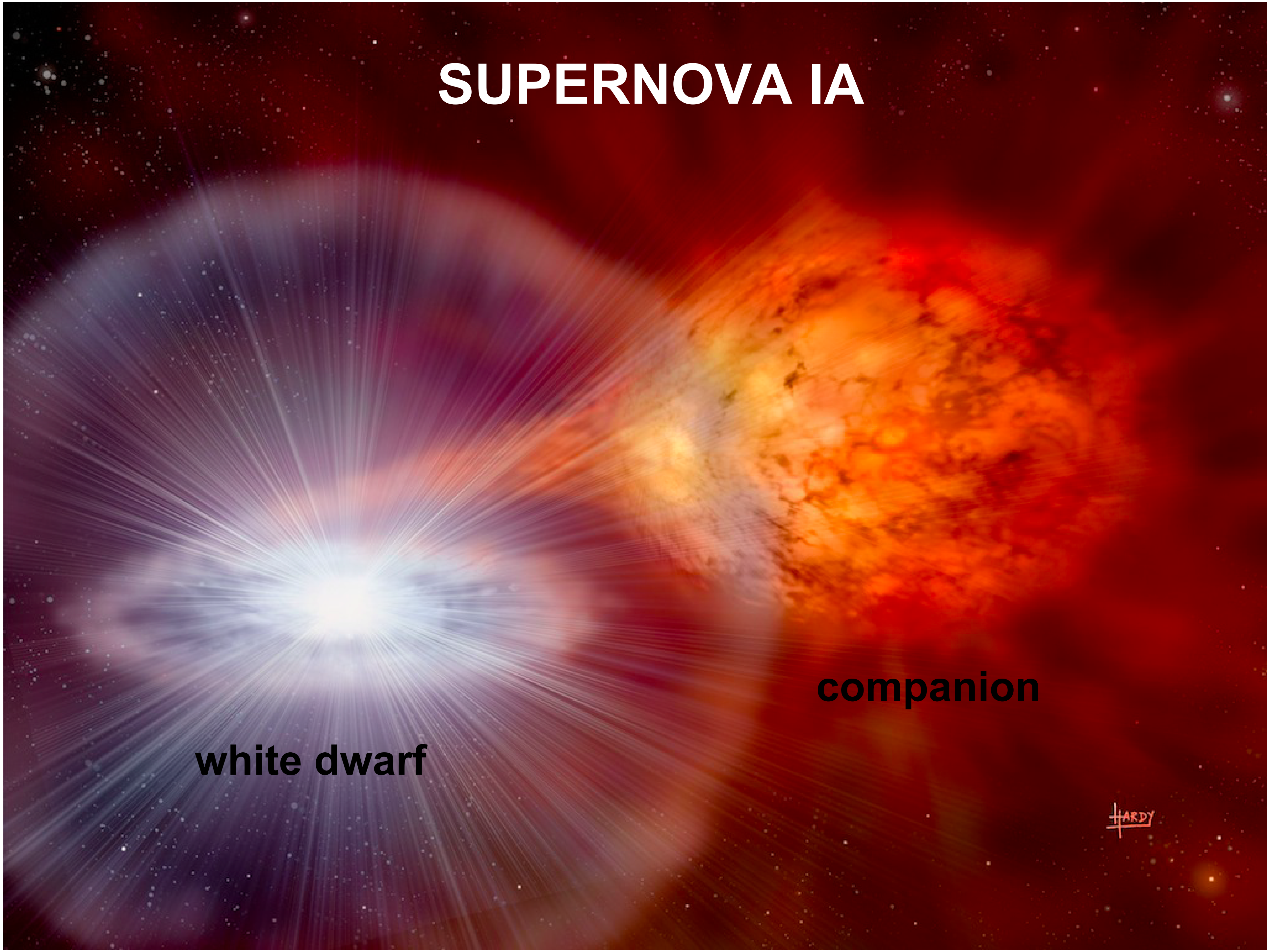
Properties of White Dwarfs and the Maximum Mass



1. The **sizes** are ~ the size of the planet Earth
2. **Densities** ~ 10^{5-9} g/cm^3
3. Typical composition: **C and/or O**
4. Gravity is balanced by the **electron degeneracy pressure**
5. The masses are up to **~ 1.4 M_{sun}**, the **Chandrasekhar limit**

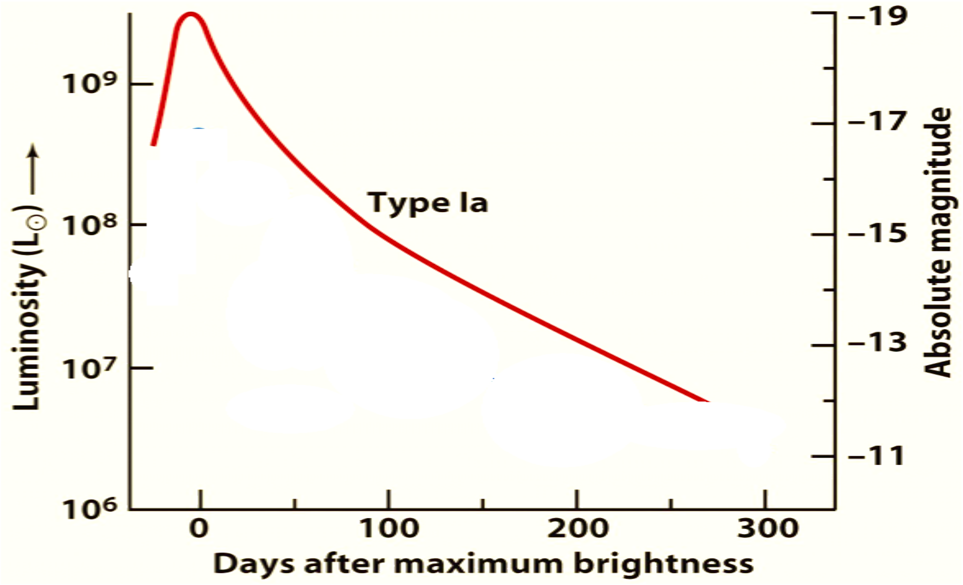
The Nobel Prize in Physics 1983
"for his theoretical studies of the physical processes of importance to the structure and evolution of the stars"

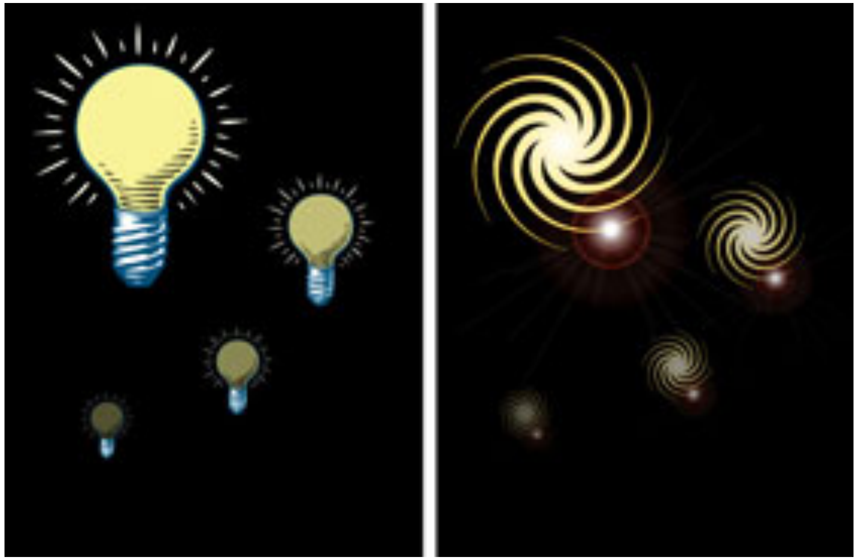
Beyond that mass, pressure cannot balance the gravity, and the white dwarf will collapse into a neutron star ou black hole.


SUPERNOVA IA
companion
white dwarf
HARDY

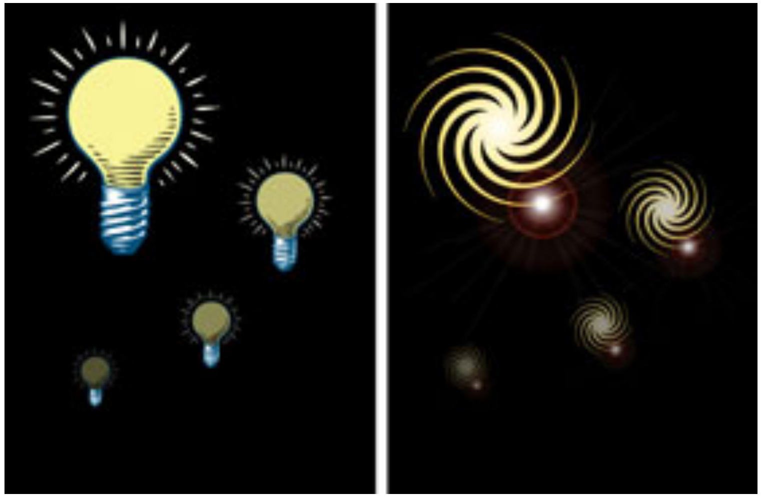
This category of supernovae produces consistent peak luminosity because of the uniform mass of white dwarfs that explode via the accretion mechanism. The stability of this value allows these explosions to be used as standard candles to measure the distance to their host galaxies, because the visual magnitude of the supernovae depends primarily on the distance.

All look similar





Standard Candles



EXPANSION OF THE UNIVERSE 2011

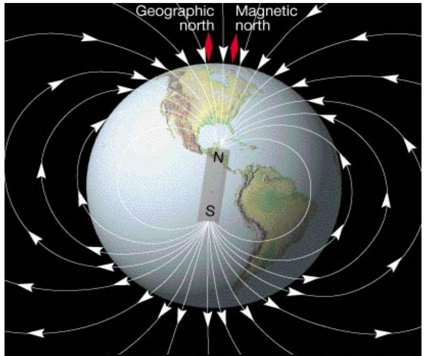
Saul Perlmutter
Brian P. Schmidt
Adam G. Riess

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

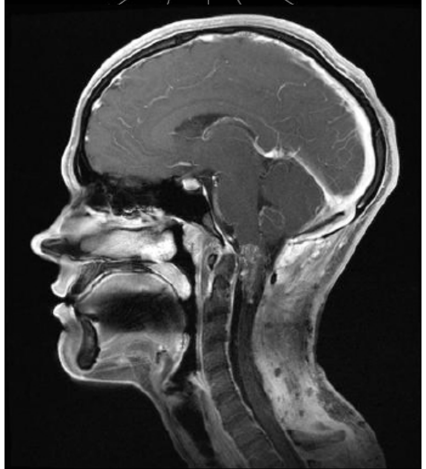
But, motivated by **observations** of supernova that appears to be **more luminous** than expected (e.g. SN 2003fg, SN 2006gz, SN 2007if, SN 2009dc), it has been argued that the progenitor of such super-novae should be a **white dwarf with mass above the well-known Chandrasekhar limit (2.0 - 2.8 M_{sun})**, in other words, a super-Chandrasekhar white dwarf.

How to get higher WD masses?

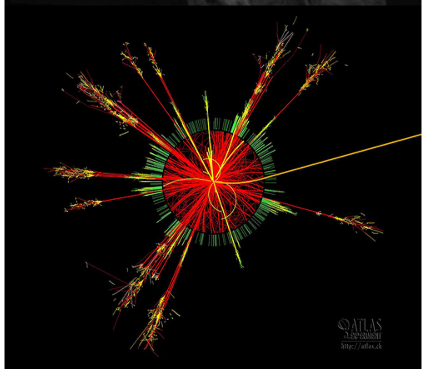
Magnetic Fields



B = 0.5 G



B = 10^3 G



B = 10^{20} G

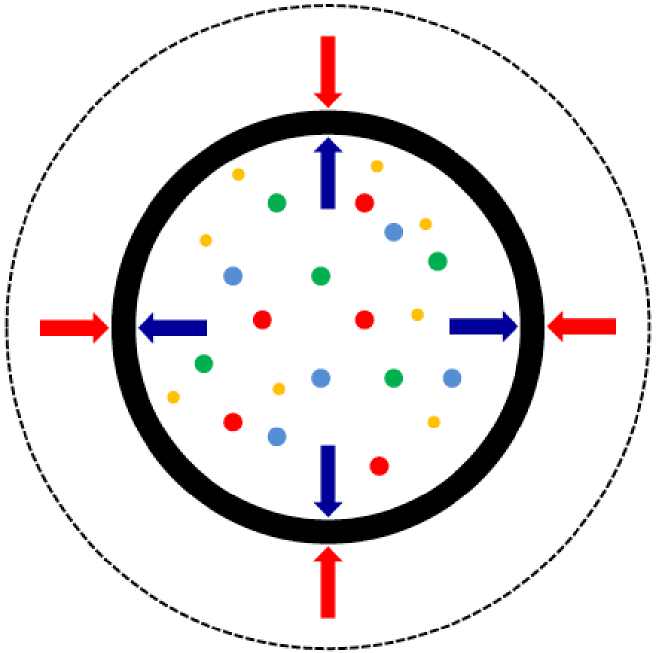
White Dwarfs?

Some white dwarfs are also associated with strong magnetic fields.

From observations, the surface magnetic field of these stars can reach values from 10^6 G to 10^9 G

However, the internal magnetic field in magnetic stars is very poorly constrained by the observations and can be much stronger than in the surface.

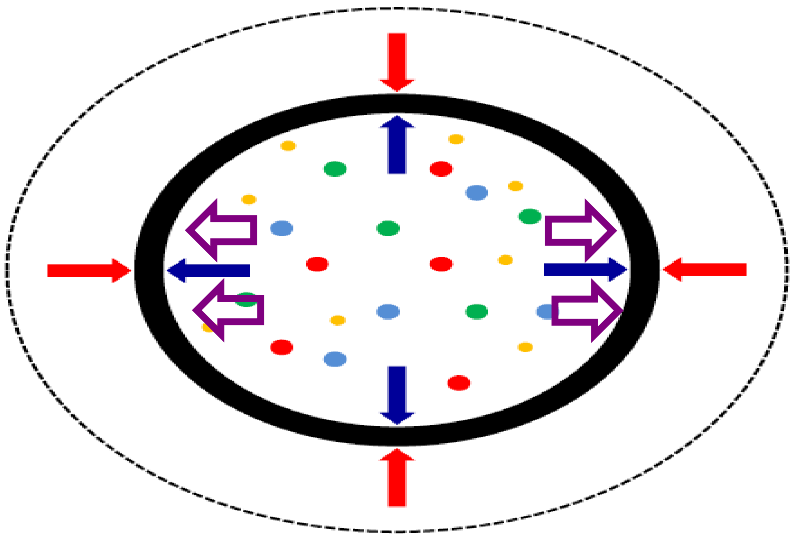
For example, white dwarfs can have internal magnetic fields as large as 10^{13} G (Virial theorem)



Non-magnetized star

- Gravity pulls the matter in the star inwards
- Outward pressure from nuclear reactions and quantum effects

Spherical



Magnetized star

- Gravity pulls the matter in the star inwards
- Outward pressure from nuclear reactions and quantum effects
- Magnetic force: Lorenz force

Oblate

How to model highly magnetized stars

Einstein Equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Geometry

1. Spherical: TOV
2. Perturbation
3. Fully-GR

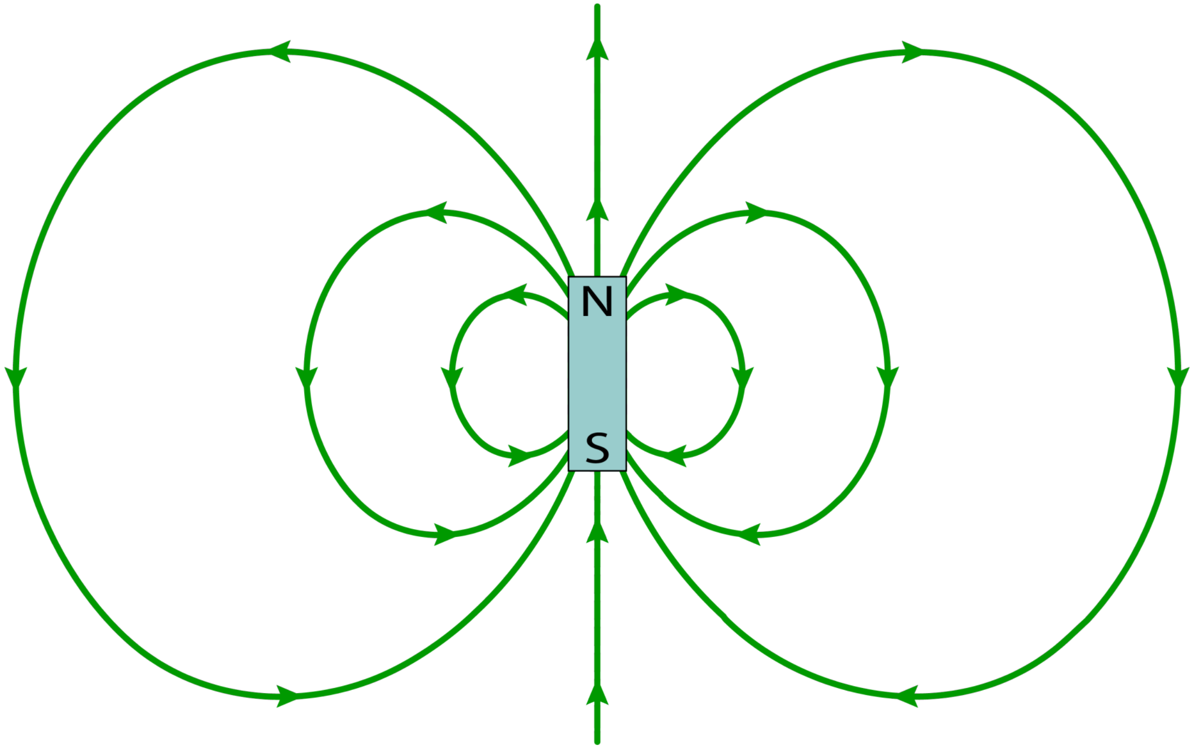
Energy Content

1. Matter: particles
2. Fields: magnetic field

Maxwell equations

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{\mathbf{c}}\mathbf{J}$$



- Magnetized Neutron Stars: fully-general relativistic approach
  Langage Objet pour la RElativité NaumériquE (LORENE)

S. Bonazzola at all Astron. Astrophys. 278 421 (1993)

M. Bocquet at all Astron. Astrophys. 301, 757 (1995)

D. Chatterjee at all Mon. Not. Roy. Astron. Soc. 447, 3785 (2015)

B. Franzon; **Dexheimer, V.**; **Schramm, S.**, **Mon. Not. Roy. Astron. Soc, 10.1093 (2015)**

B. Franzon and S.Schramm Phys.Rev. D92 (2015) 083006

Mathematical setup

- The energy-momentum tensor:

$$T^{\mu\nu} = (e+p)u^{\mu}u^{\nu} + pg^{\mu\nu} + \frac{1}{\mu_0}\left(-b^{\mu}b^{\nu} + (b\cdot b)u^{\mu}u^{\nu} + \frac{1}{2}g^{\mu\nu}(b\cdot b)\right)$$

with b the length of the magnetic field 4-vectors.

- In the rest frame of the fluid:

$$T^{\mu\nu} = \textit{fluid} + \textit{field (z direction)}$$

$$T^{\mu\nu} = \begin{pmatrix} e+\frac{B^2}{2\mu_0} & 0 & 0 & 0 \\ 0 & p+\frac{B^2}{2\mu_0} & 0 & 0 \\ 0 & 0 & p+\frac{B^2}{2\mu_0} & 0 \\ 0 & 0 & 0 & p-\frac{B^2}{2\mu_0} \end{pmatrix}$$

Mathematical setup

- Stationary and axisymmetric space-time, the metric is written as:

$$ds^2 = -N^2 dt^2 + \Psi^2 r^2 \sin^2\theta (d\phi - N^\phi dt)^2 + \lambda^2 (dr^2 + r^2 d\theta^2)$$

  where N^ϕ, N, Ψ and λ are functions of (r, θ).
- A poloidal magnetic field satisfies the circularity condition:

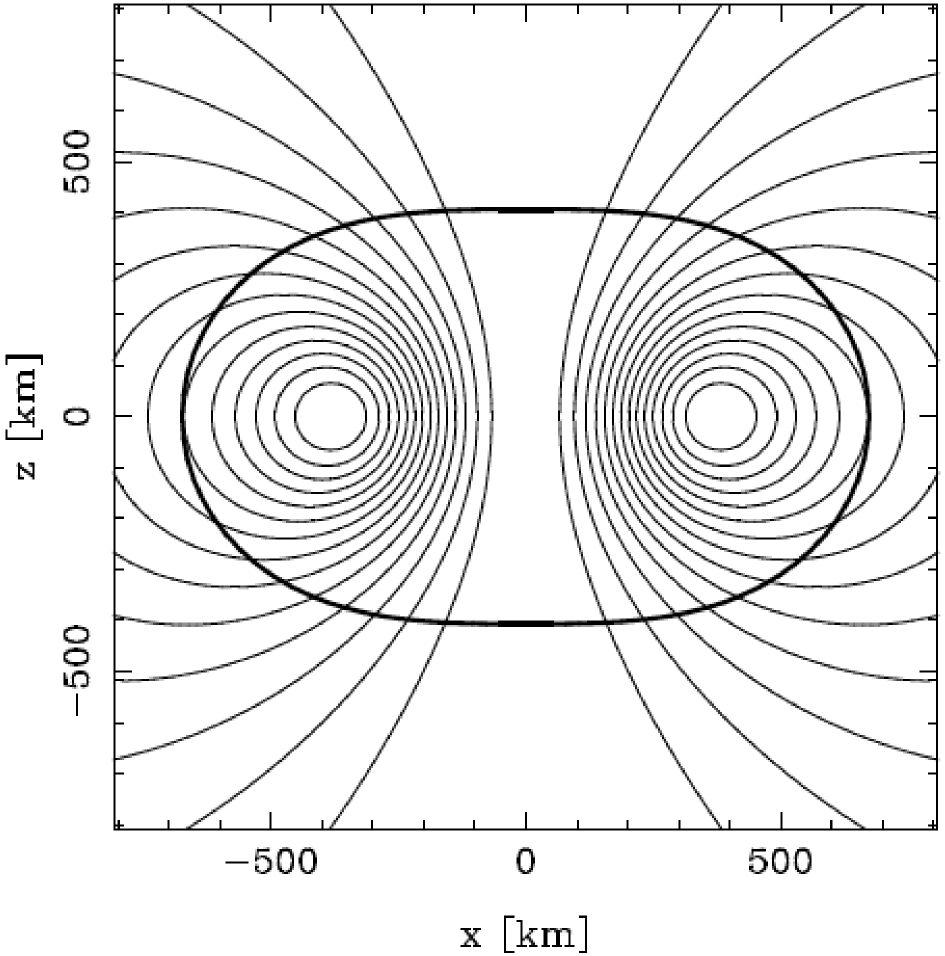
$$A_\mu = (A_t, 0, 0, A_\phi)$$

- The magnetic field components as measured by the observer $(\mathcal{O}_0)$ with n^μ velocity can be written as:

$$B_\alpha = -\frac{1}{2}\epsilon_{\alpha\beta\gamma\sigma} F^{\gamma\sigma} n^\beta = \left(0, \frac{1}{\Psi r^2 \sin\theta}\frac{\partial A_\phi}{\partial \theta}, -\frac{1}{\Psi \sin\theta}\frac{\partial A_\phi}{\partial r}, 0\right)$$

$$A_t, A_\phi \rightarrow \mathit{Maxwell\ \ Equations}$$

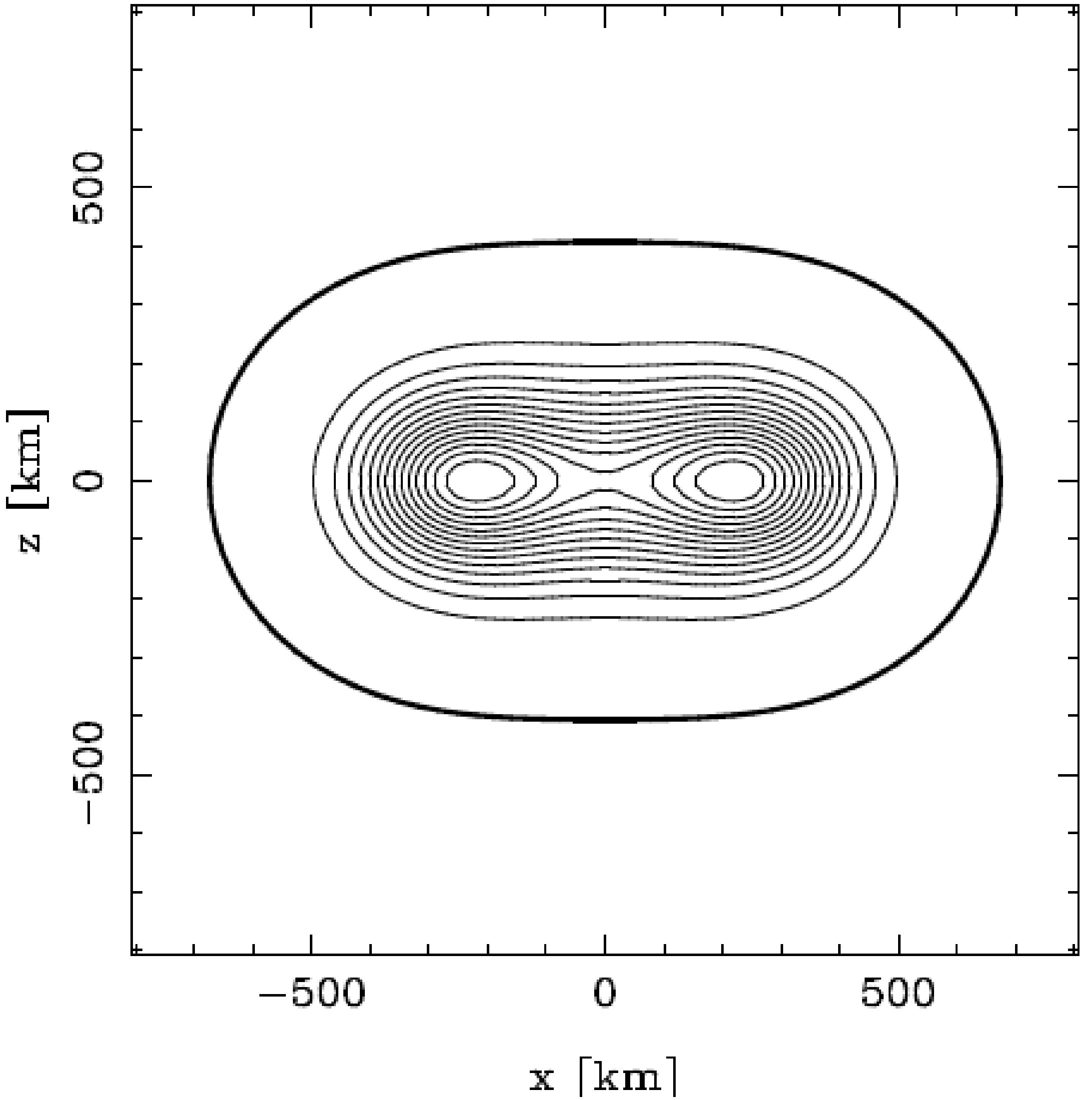
Magnetic Field Lines



1. **Isocontours of the magnetic field strength in the (x, z) plane, with a gravitational mass of 2.09 M_{sun}**

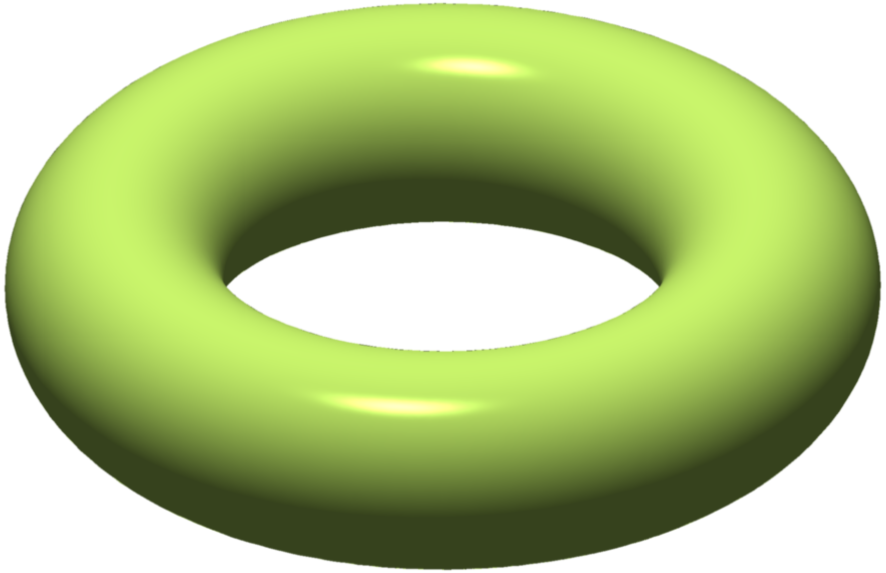
2. **Central magnetic field 3.9×10^{13} G**

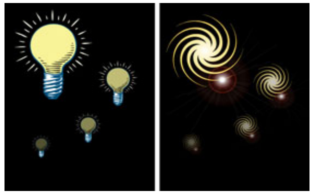
Density Profile



Maximum density: **away from the stellar center!**

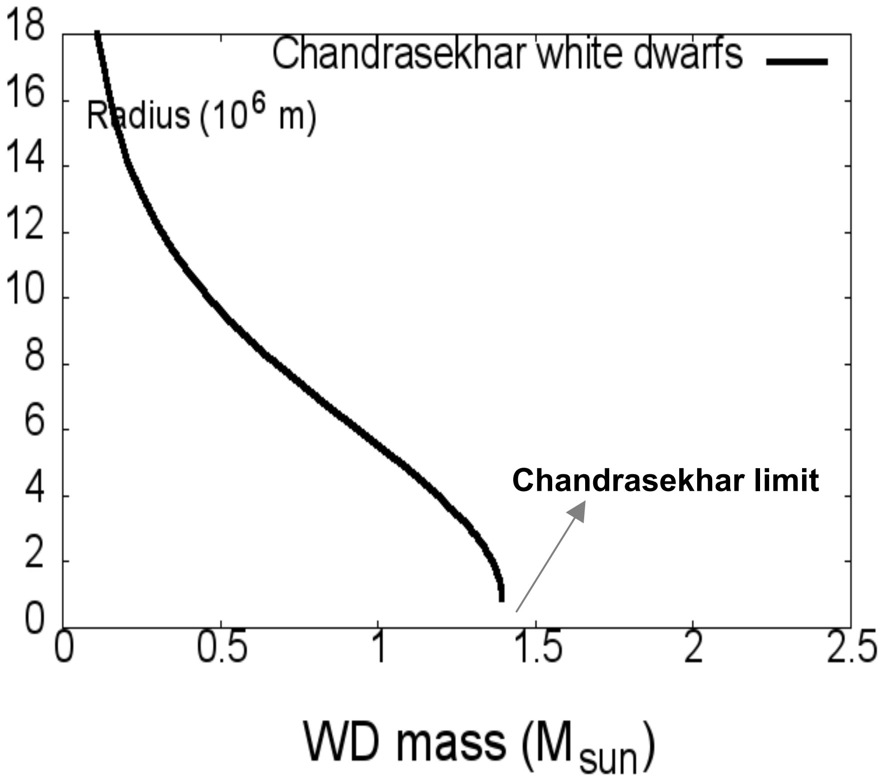
Doughnut-shaped density distribution?

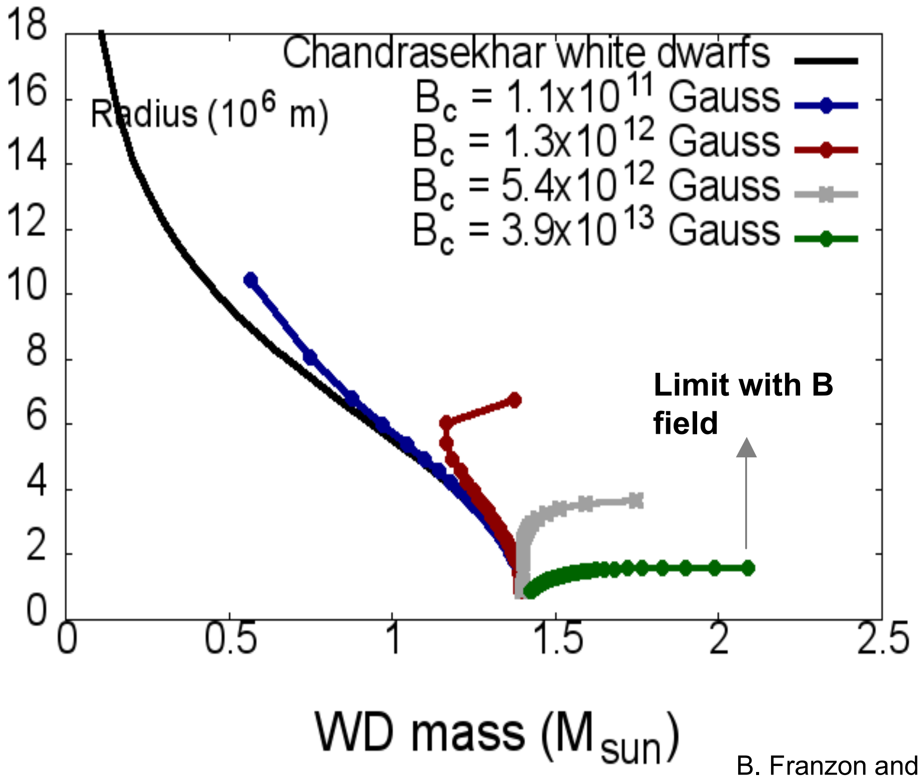




Magnetized White Dwarfs

Progenitors of Type Ia supernovae: Chandrasekhar White Dwarfs





B. Franzon and S.Schramm **Phys.Rev. D92 (2015) 083006**

Non-magnetized WD: 1.40 solar masses

Magnetized WD: 2.10 solar masses

A. Magnetic field effects can considerably increase the star masses and, therefore, might be the source of superluminous SNIa.
B. Consequences in understanding the expansion of the Universe.

Outlook

A. We computed perfect-fluid magnetized white dwarfs in general relativity by solving the coupled Einstein-Maxwell equations

B. In our case, the equilibrium solutions are axisymmetric and stationary, with white dwarfs endowed with a strong poloidal magnetic field.

.

C. The observation of super-luminous Ia supernovae suggests that their progenitors are super-Chandrasekhar white dwarfs, whose masses are higher than 1.4 Msun

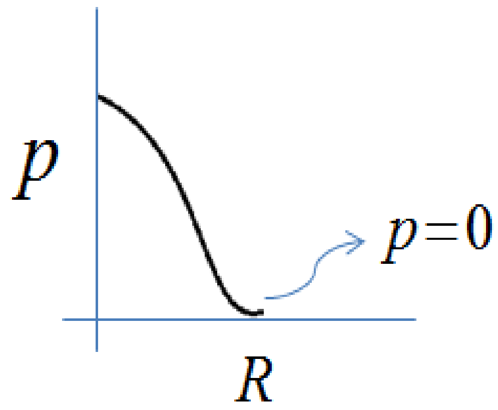
D. Include thermal effects (Veronica Dexheimer) and magnetic field into the EoS.

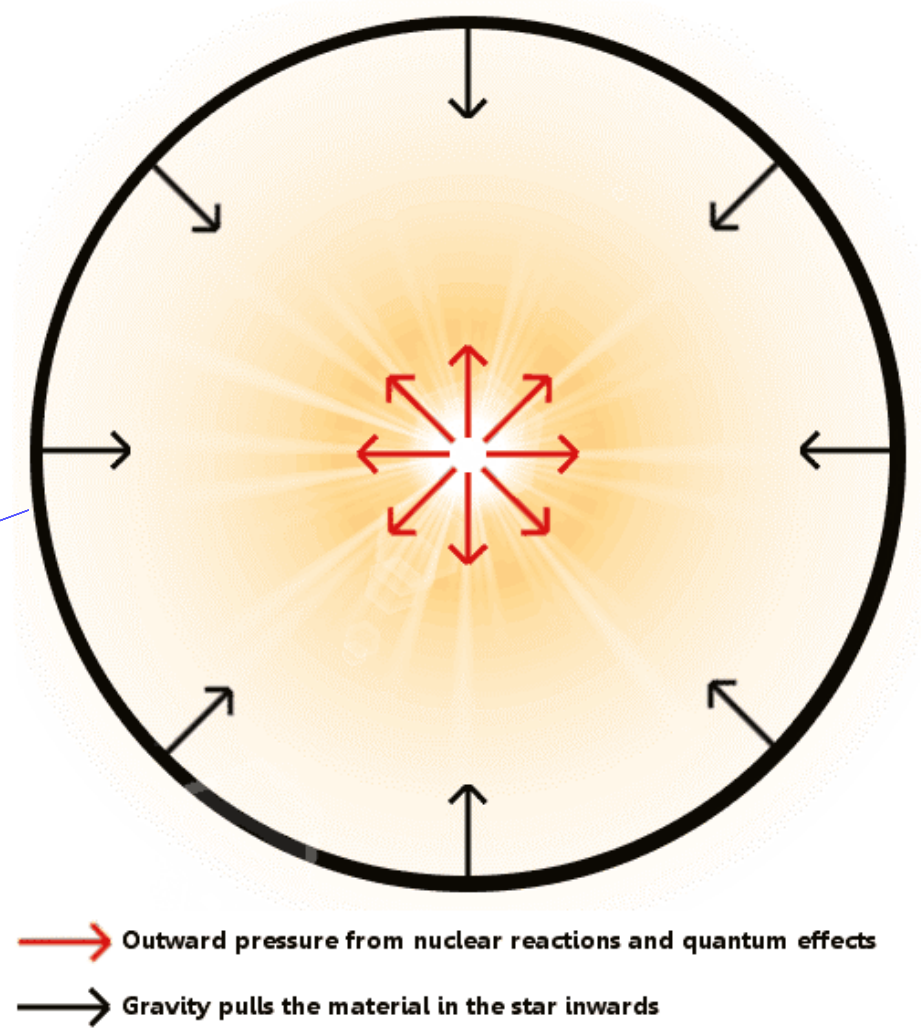
Thank you!

$$\frac{dm}{dr} = 4\pi\rho r^2$$

$$\frac{dP}{dr} = -\frac{(\rho + P)(m + 4\pi r^3 P)}{r(r - 2m)}$$

Boundary Conditions: P(R) =0, M(0) =0





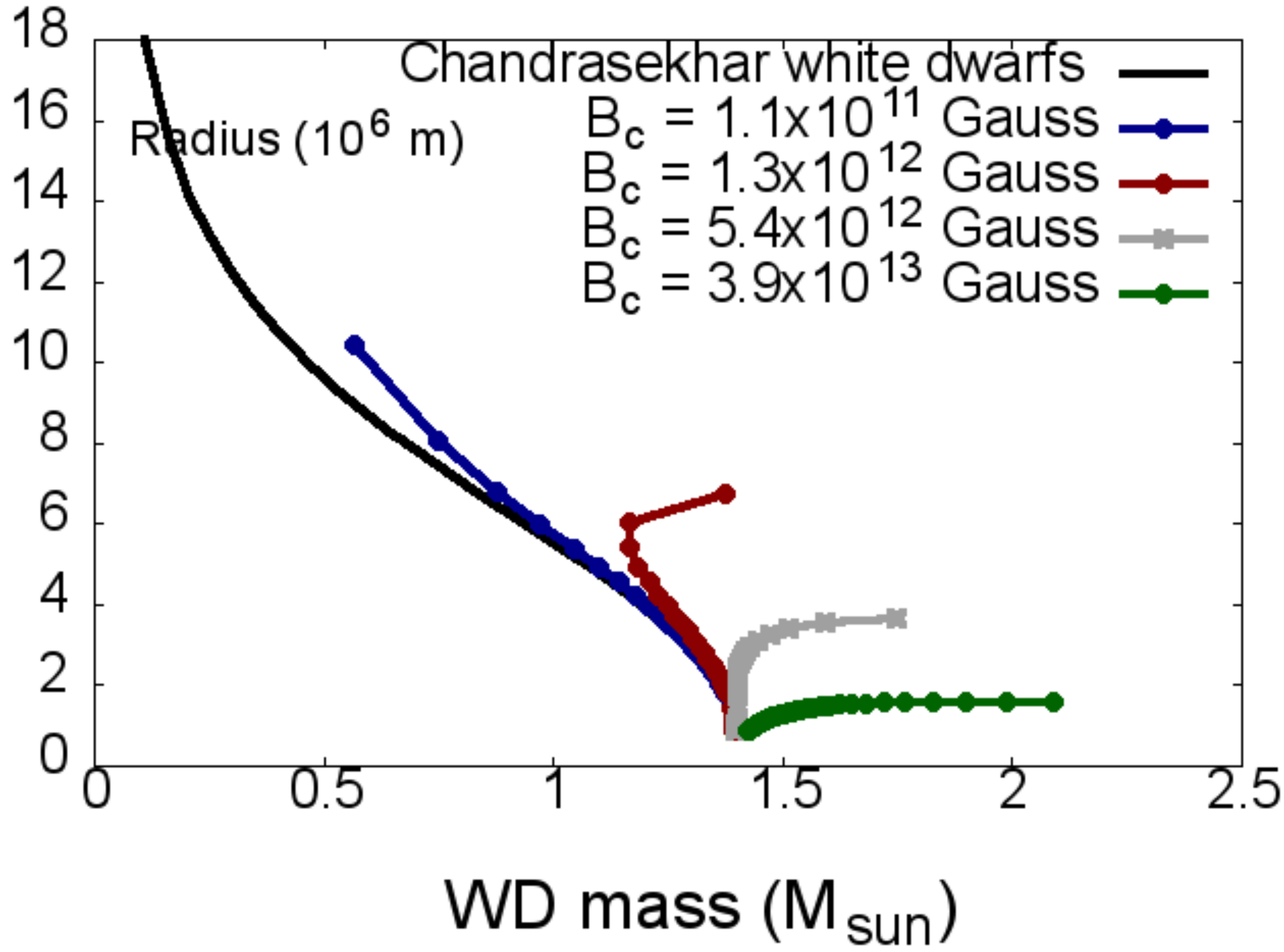
$$M \equiv \mathcal{M}(r) = 4\pi \int_0^R dr\, r^2 \varepsilon(r)$$

The Equation of State for an Electron Gas

$$P = \frac{\pi m_e^4 c^5}{6h^3}\left[x(2x^2-3)\sqrt{(1+x^2)} + 3\sinh^{-1}(x)\right]$$

$$x = \frac{p_f}{m_e c}$$

Pressure balances gravity, keeps stars from collapsing



Radius (10^6 m)
Chandrasekhar white dwarfs
$B_c = 1.1 \times 10^{11}$ Gauss
$B_c = 1.3 \times 10^{12}$ Gauss
$B_c = 5.4 \times 10^{12}$ Gauss
$B_c = 3.9 \times 10^{13}$ Gauss
WD mass (M_{sun})
0
2
4
6
8
10
12
14
16
18
0
0.5
1
1.5
2
2.5

Chandrasekhar EoS equation of state

Pressure

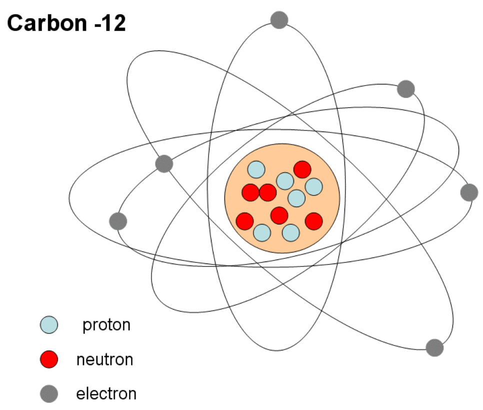
$$P_{Ch} = P_N + P_e \approx P_e$$

$$x = \frac{p_f}{m_e c}$$

$$P = \frac{\pi m_e^4 c^5}{6h^3}\left[x(2x^2-3)\sqrt{(1+x^2)} + 3\sinh^{-1}(x)\right].$$

Energy density

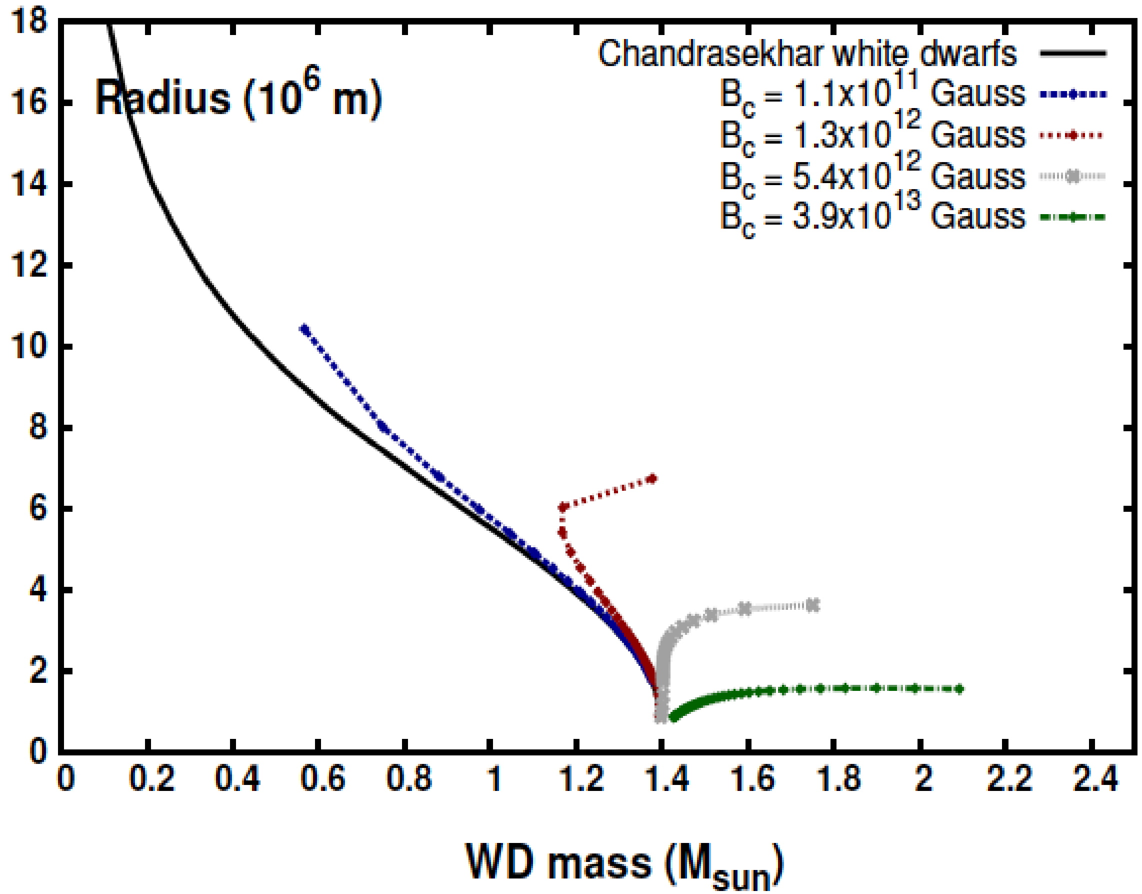
$$\mathcal{E}_{Ch} = \mathcal{E}_N + \mathcal{E}_e \approx \mathcal{E}_N = \frac{A}{Z} M_u c^2 n_e$$



^{12}C: $A/Z = 2$

Pressure balances gravity, keeps stars from collapsing

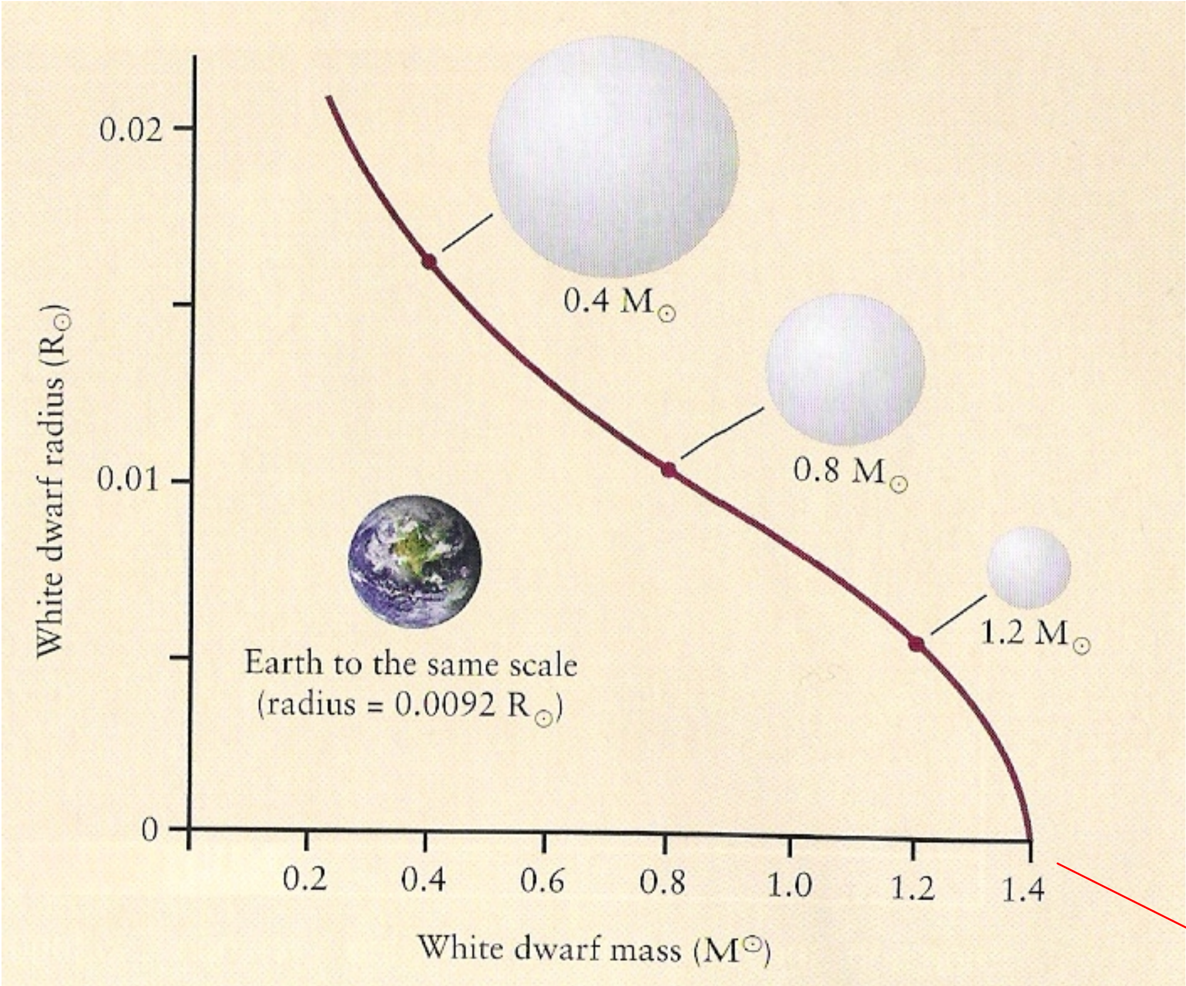
Mass-radius diagram for magnetized white dwarfs



Franzon, B. ; Schramm, S. 2015, Physical Review D, 92, 083006

→ **Magnetic field** effects can considerably increase the star masses and, therefore, might be the **source of superluminous SNIa.**

Mass Radius diagram for White Dwarfs



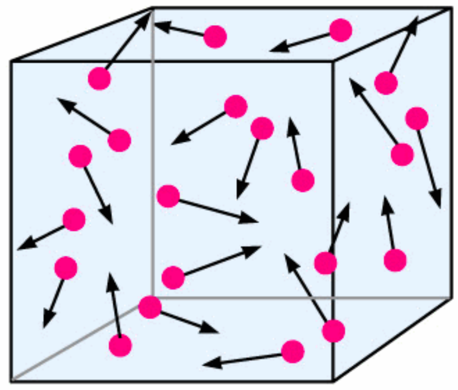
Maximum mass of a white dwarf

1.4 M_{sun}

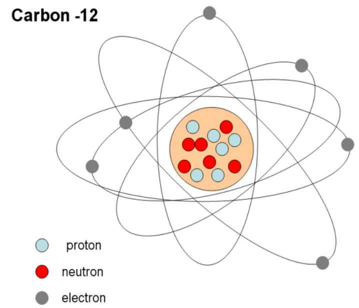
What happens if M higher than 1.4 M_{sun}?

Normal gas

Pressure is the force exerted by atoms in a gas.
Temperature is how fast atoms in a gas move.
Low densities



air:0.001225 g/cm3



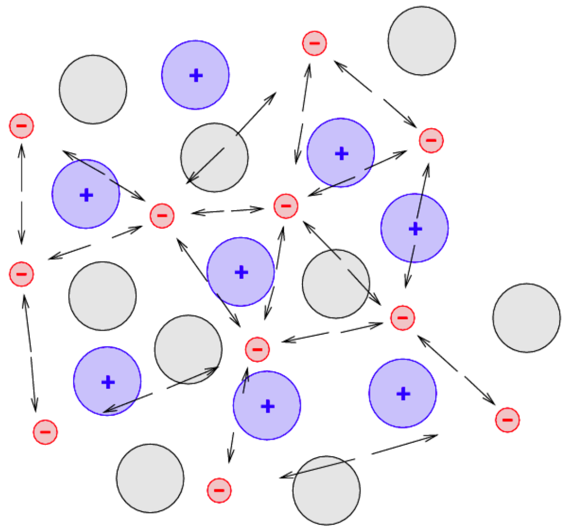
Degenerate gas

Very **high density**.

Motion of atoms is not due to kinetic energy, but instead due to **quantum mechanical motions**.

Pauli's exclusion principle states that in a given system, no two electrons can have the same energy state.

Once all available energy states are filled, the gas cannot be compressed further – this creates a **degeneracy pressure, a consequence of quantum Mechanics!**



How to model highly magnetized stars

Einstein Equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Geometry

1. Spherical: TOV
2. Perturbation
3. Fully-GR

Energy Content

1. Matter: particles
2. Fields: magnetic field