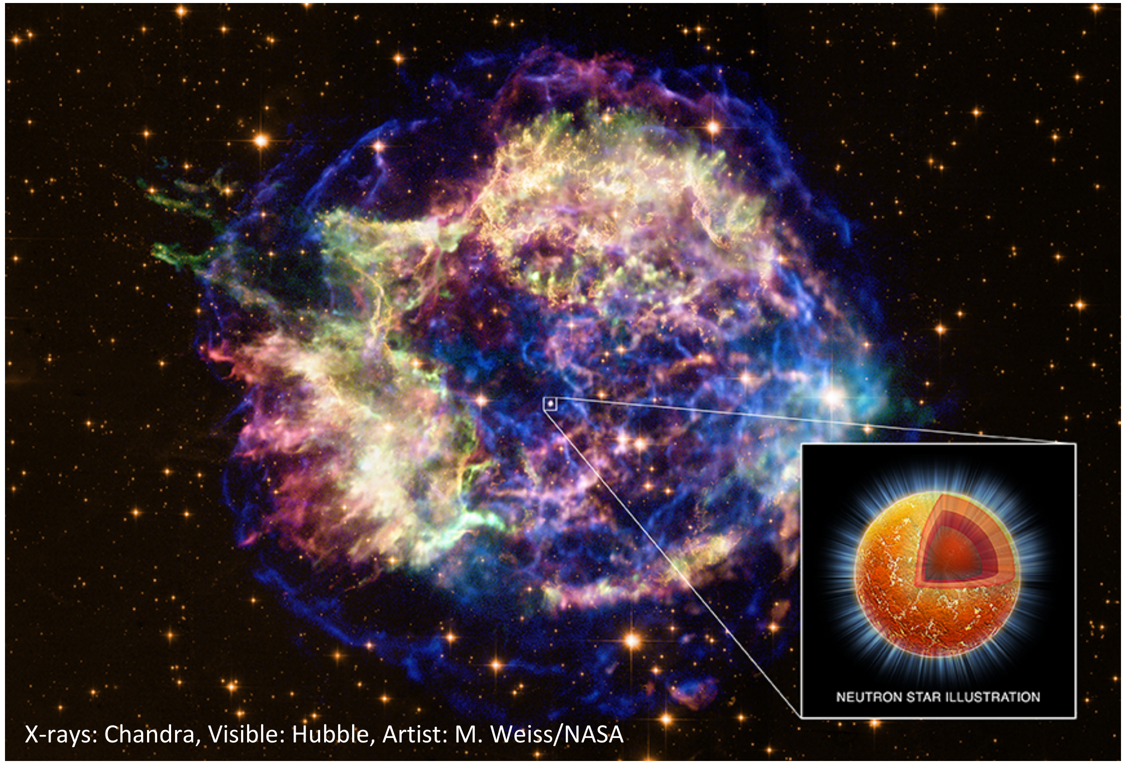
Neutron Stars



X-rays: Chandra, Visible: Hubble, Artist: M. Weiss/NASA

Sharon Morsink, Department of Physics

University of Alberta, Edmonton, Canada

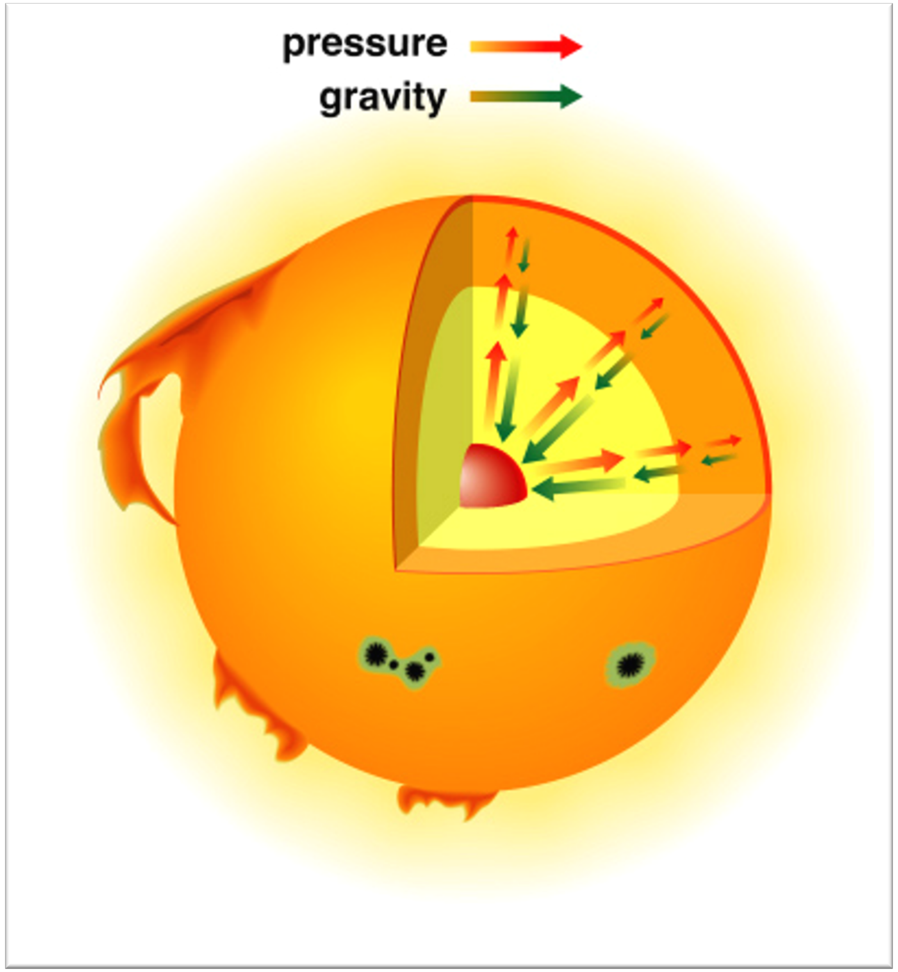
EXPLORE 2023 Summer School, Friday September 1, 2023

Introduction to Neutron Stars

- Lecture 1 – Introduction to neutron stars
  - Endpoints of stellar evolution: white dwarf stars, neutron stars, and black holes; hydrostatic equilibrium
  - Degenerate matter; applications to evolved stars and white dwarf stars; Chandrasekhar Limit
  - Concept of a neutron star; beta decay; neutrons, neutrinos, and other particles; Equation of state uncertainty; maximum mass
  - Birth of neutron stars in a supernova; proto-neutron stars and black holes
  - Binary neutron star mergers and r-process elements

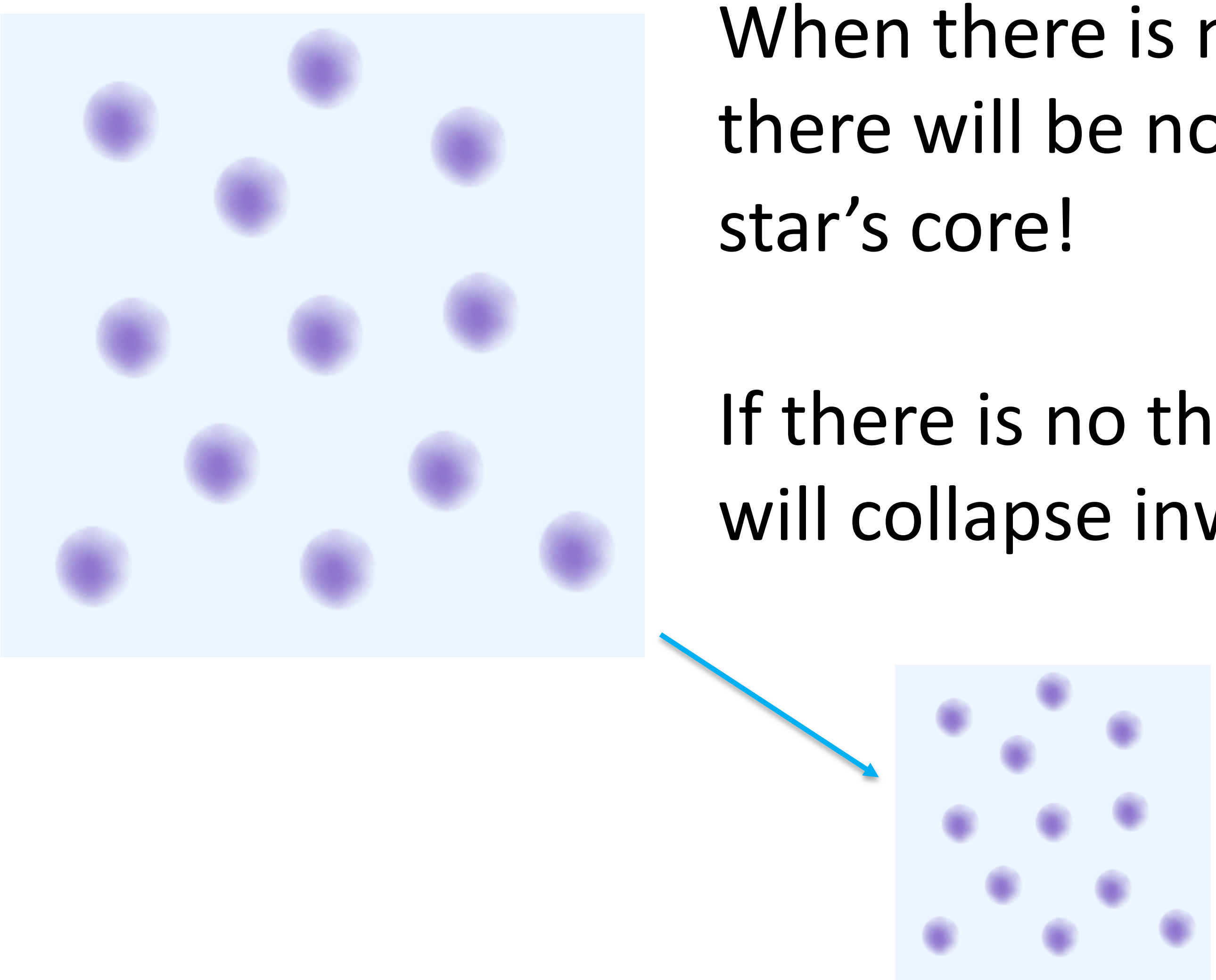
- Lecture 2 – Why neutron stars are ``cool”!
  - Neutron star cooling
  - Superfluidity and superconductivity
  - Spin and magnetic fields; spin-down and spin-up; glitches
  - General relativity and gravitational lensing
  - Neutron star zoo: pulsars, magnetars, central compact objects, etc

Why aren't all stars black holes?



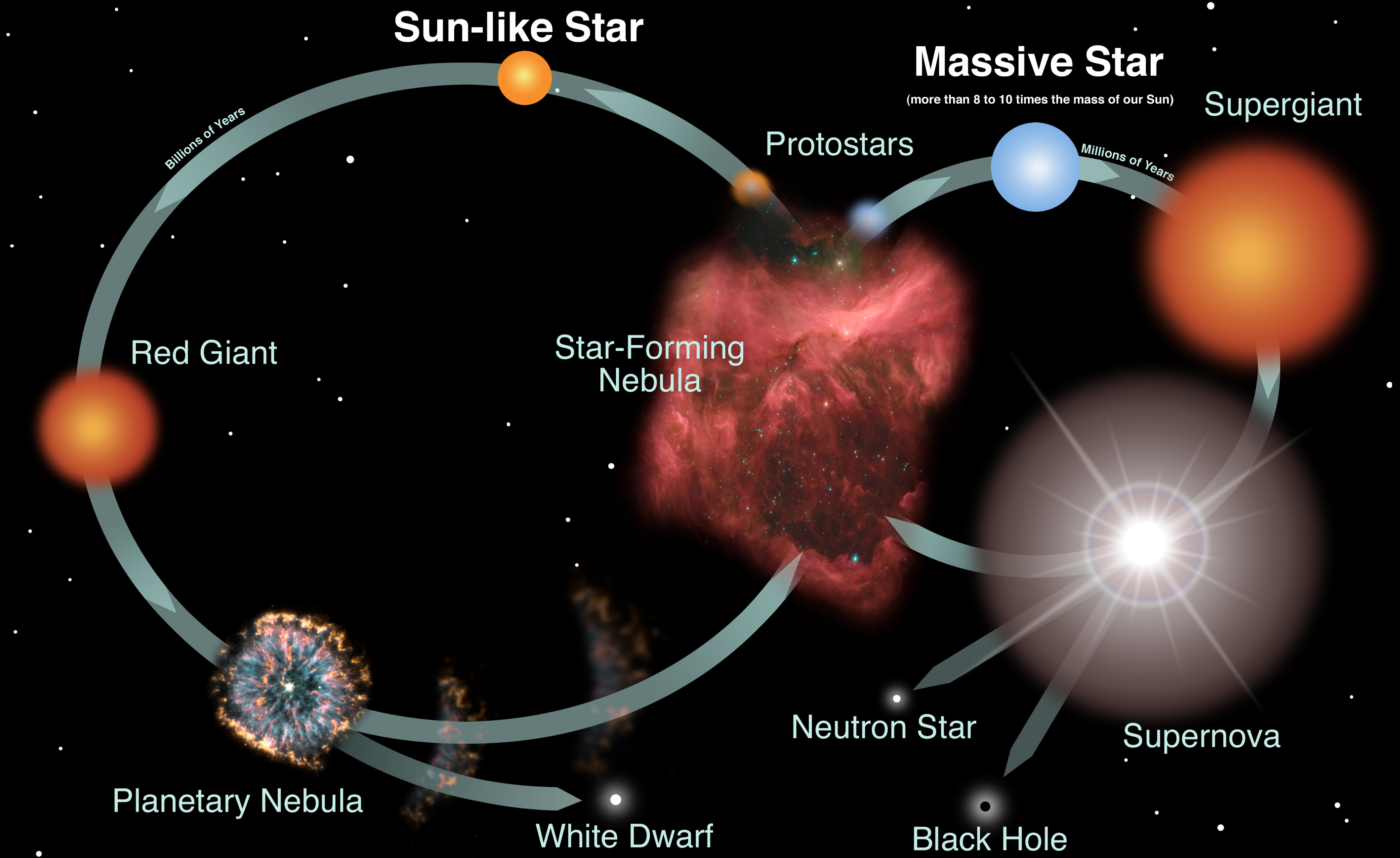
- A normal star is in a balance between gravity and pressure called hydrostatic equilibrium.
- Nuclear fusion reactions in the core provide the heat and outward pressure that balance gravity.

What happens when there is no energy source for a star?



When there is no fuel for nuclear reactions there will be no heat generation in the star’s core!

If there is no thermal pressure, the core will collapse inwards.



Sun-like Star

Massive Star

(more than 8 to 10 times the mass of our Sun)

Supergiant

Protostars

Billions of Years

Millions of Years

Red Giant

Star-Forming Nebula

Neutron Star

Supernova

Planetary Nebula

White Dwarf

Black Hole

Credit: NASA and the Night Sky Network

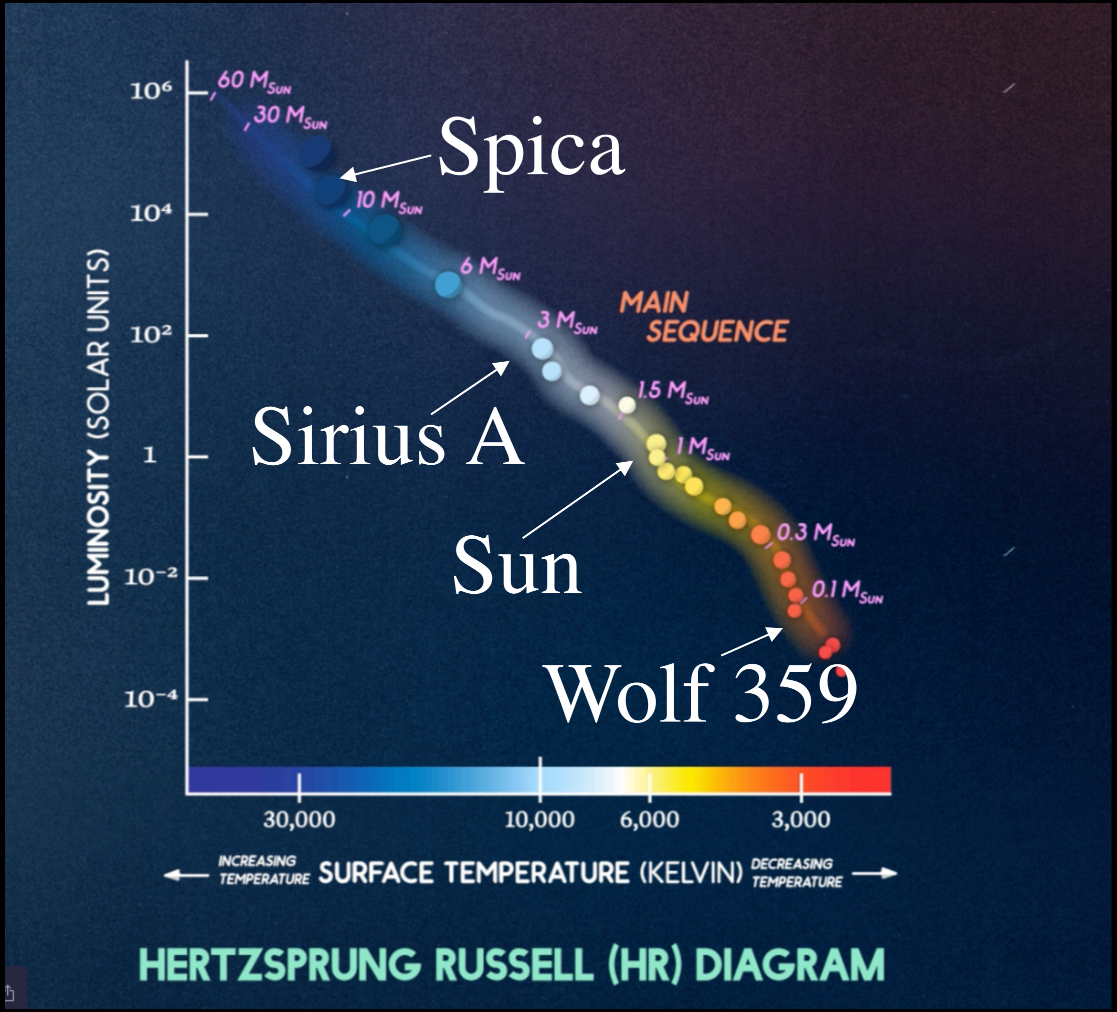
Adult Stars: The Main Sequence

Larger Mass ⇒ Larger Size ⇒ Higher Temperature ⇒ Brighter Light … But Shorter Life

Brighter

↑

Dimmer



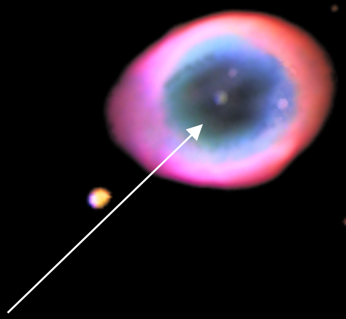
Sirius A

Low Mass Stars: Mass < 8 M_{sun}
At end of life expand into a “Planetary Nebula”

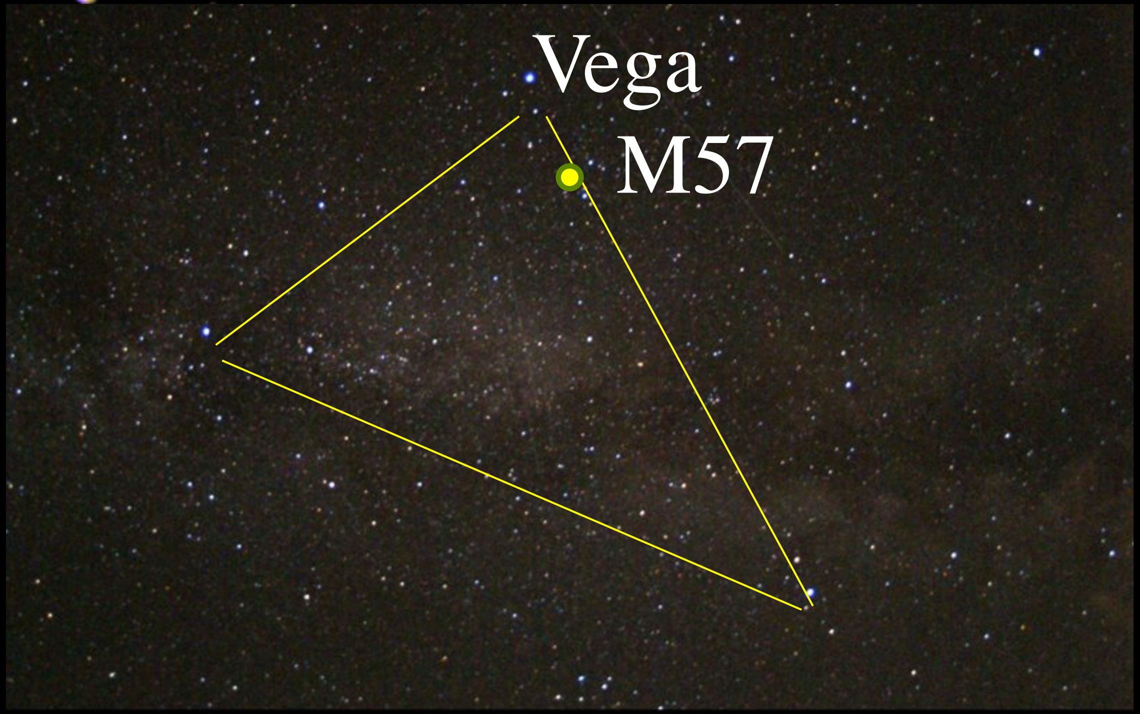
M57 The Ring Nebula
Images by Tom Owen

M27 Dumbell Nebula

The Ring Nebula, M57



White Dwarf Star at centre of nebula
Core of the dead star



Summer Triangle at the 2004 Rascal Star Party

© 2004 David Lee

Nebula = remains of the outer parts of the dead star

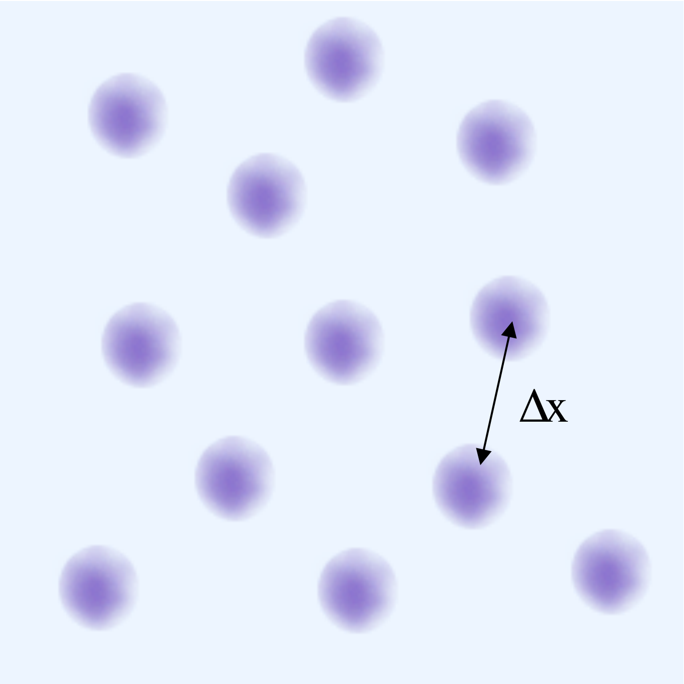
The Sirius Binary System

Sirius A = Bright adult star; Sirius B = faint White Dwarf Star

Visible Light Image: McDonald Observatory.

X-ray Image: Chandra X-ray Observatory

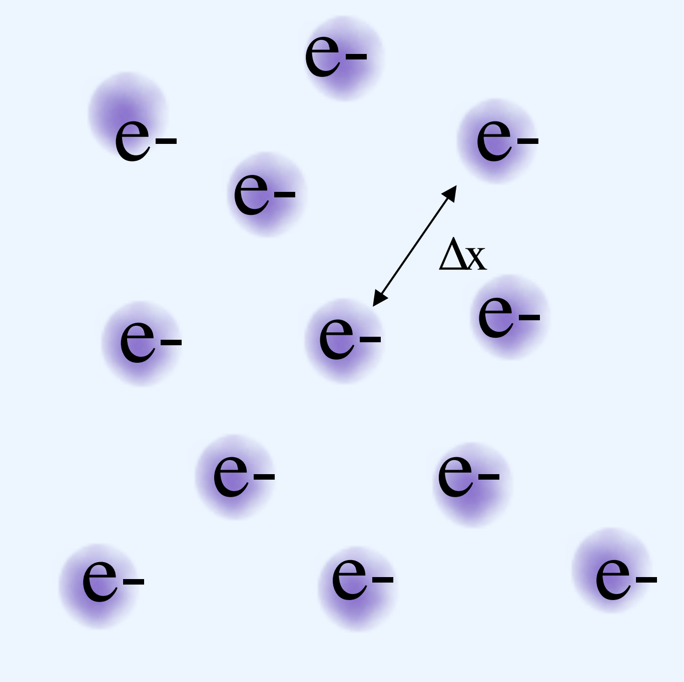
What happens when a gas of fermions is compressed at low temperature?



- From Pauli exclusion principle no two fermions are in the same state.
- For typical inter-particle distance Δx Heisenberg uncertainty gives Fermi momentum to the particle of order
$$p \approx h/\Delta x$$
- Fermi energy $E_F \approx p^2/m$
- The resulting pressure is known as Degeneracy Pressure which is larger than ideal gas pressure if
$$kT < E_F$$

⇒At high density degeneracy pressure can dominate even at high temperatures!

White Dwarf Star



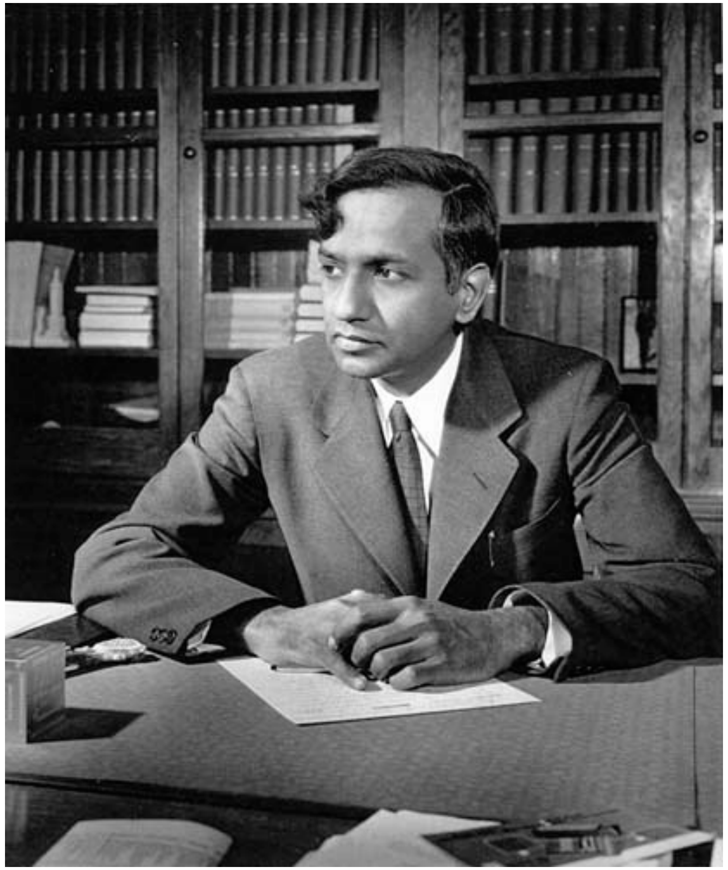
- Gas of ionized Carbon (and some O, Ne) and electrons

- Electrons have momentum from Heisenberg uncertainty and provide degeneracy pressure

- C ions move more slowly, and only provide a very small thermal pressure

- Electron degeneracy pressure can support a gas of ions and electrons against gravitational collapse “forever”

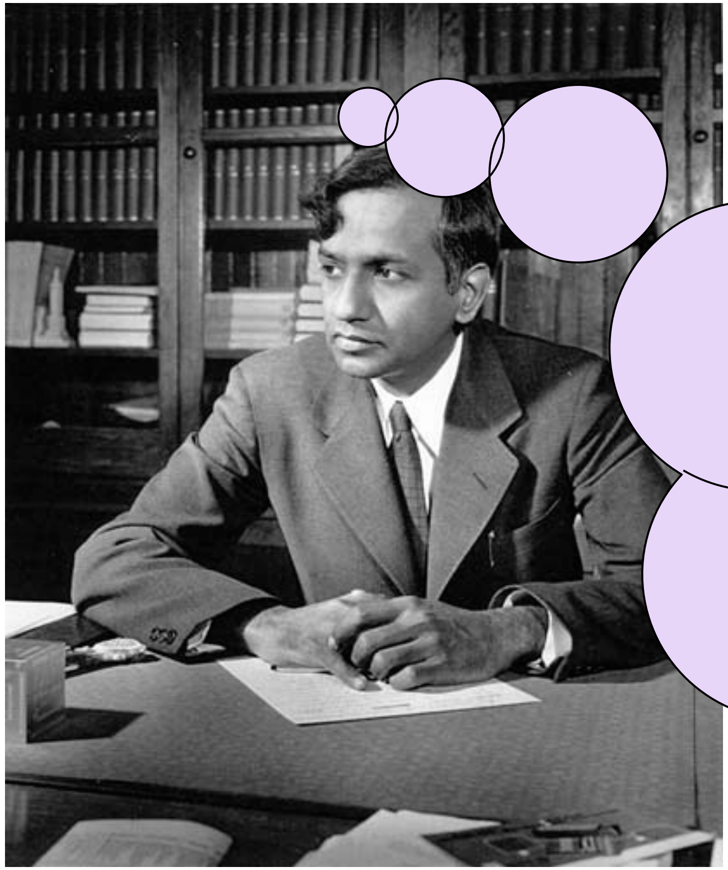
The Chandrasekhar Limit



- In 1930 Chandrasekhar realized that the equation for the electron velocity in a white dwarf star is fatally flawed

$$v = \frac{\hbar}{m\Delta x}$$

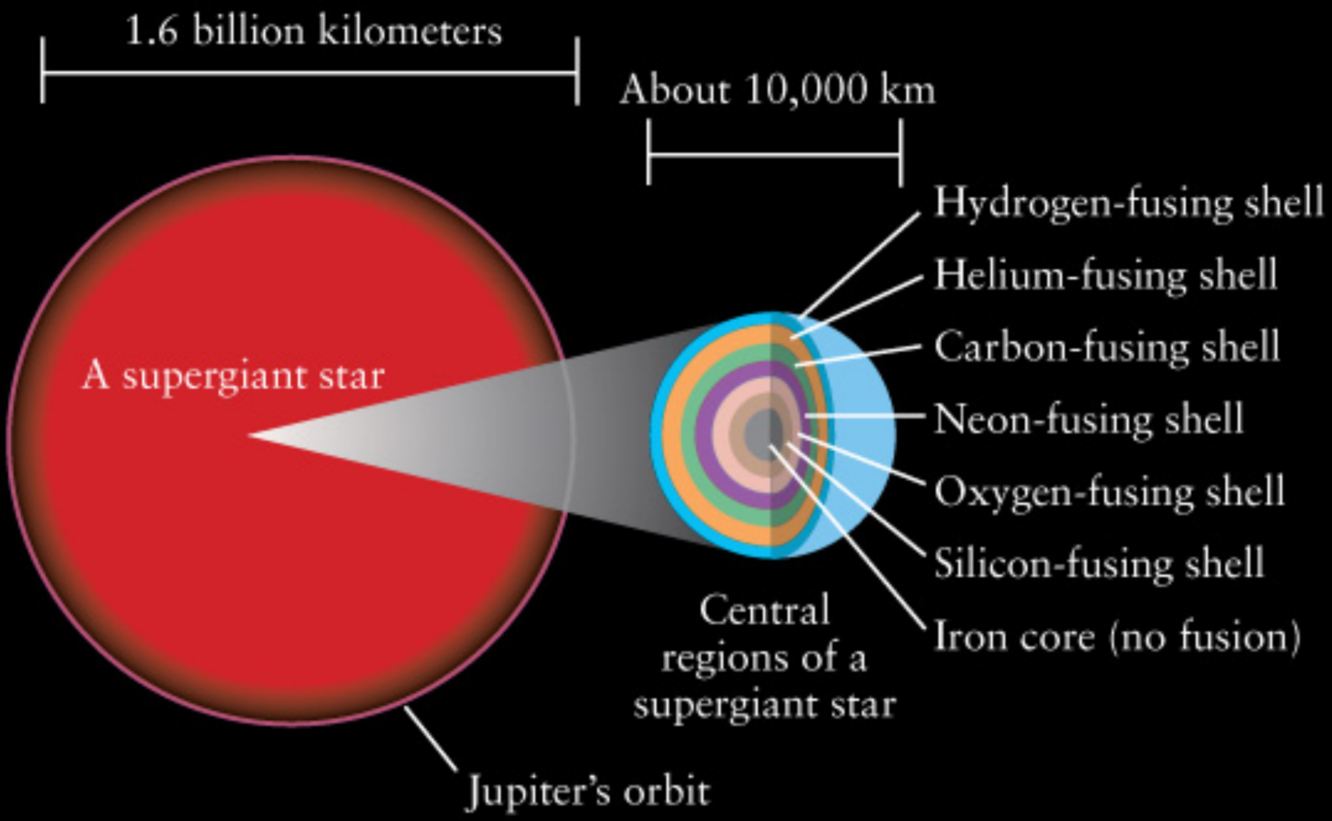
Einstein's Special Relativity limits White Dwarf Stars!



- Einstein's Special Relativity tells us that electrons can't travel faster than light speed.
- But in order for a high mass white dwarf star to exist, ultra-high density and faster than light speeds are required.
- High mass stars can't end their lives as a white dwarf.
- High mass stars must end their life in a complete gravitational collapse!

Chandrasekhar's upper mass limit of 1.4 M_{sun} for White Dwarfs!

Type II Supernova= Core Collapse SN
Collapse of a High Mass Star M > 8 M_{Sun}



The neutron

- A neutron has a mass that is slightly larger than the mass of a proton

- Isolated neutrons are unstable and decay with a half-life ~ 10 minutes through the beta decay reaction

$$n \rightarrow p + e^- + \bar{\nu}$$

- The inverse beta reaction is called “electron capture”

$$p + e^- \rightarrow n + \nu$$

- Electron capture can only take place if we can supply extra energy to the electrons larger than the mass difference:

$$\Delta E = (m_n - m_p - m_e)c^2 = 1.3\mathrm{MeV}$$

Critical Densities for a Star

- 10^3 kg/m^3 < ρ < 10^6 kg/m^3 : electron degeneracy pressure can support a gas of ions and electrons against gravitational collapse (I.e. white dwarf stars, cores of some giants)

- $\rho > 10^6$ kg/m^3 : degenerate electrons have enough energy that electron capture

$$p + e^- \rightarrow n + \nu$$

is favoured over beta decay. $\Rightarrow$ Neutron-rich gas results

This sometimes called “Beta Blocking” and/or neutronization

Neutron Degenerate Pressure

- Neutrons have a mass close to 2000 times larger than an electron
- For non-relativistic degenerate matter: $v = \dfrac{\hbar}{m\Delta x}$
- A neutrons need to be closer together than electrons in order to achieve the same average speed!
- Neutron degeneracy requires MUCH higher densities!
- $\rho \approx 2 \times 10^{11}$ kg/m^3 = nuclear density at which the Fermi energy of a neutron is $E_F \approx 1$ MeV

$\Rightarrow$ Neutron degeneracy can support a star if $T < 10^{10}$ K

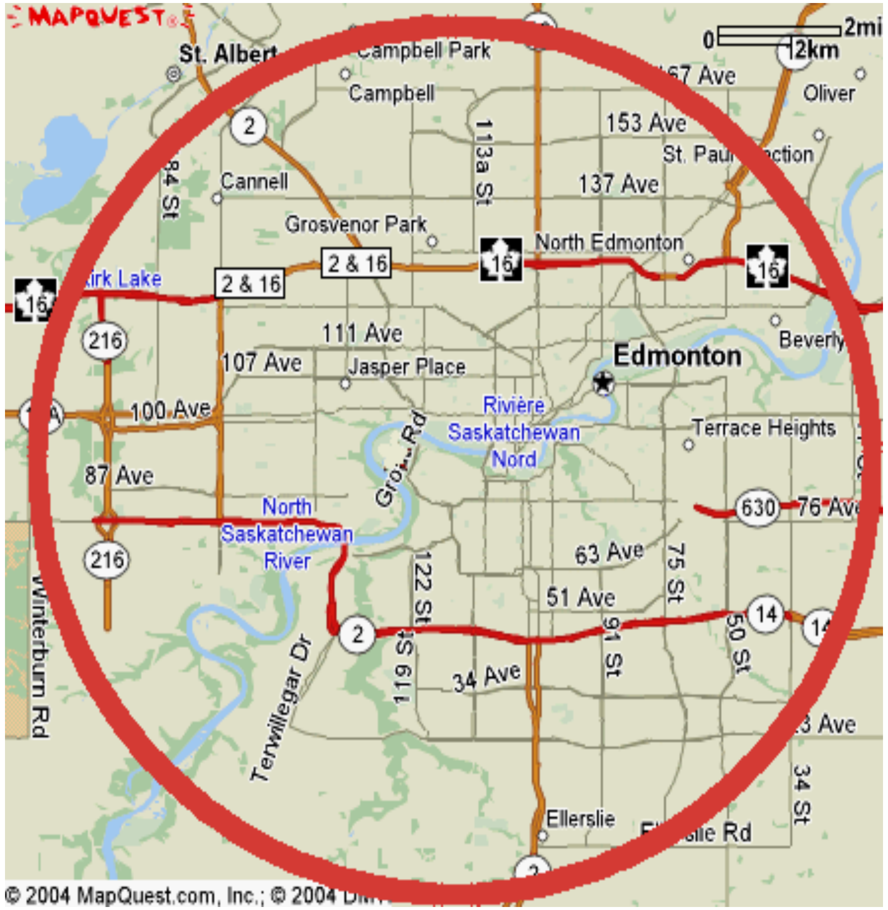
Typical Neutron Star Parameters

- Mass $\approx 1.5\ M_\odot$
- Radius ≈ 10 km $\approx 10^{-5}\ R_\odot$
- Surface Gravity:

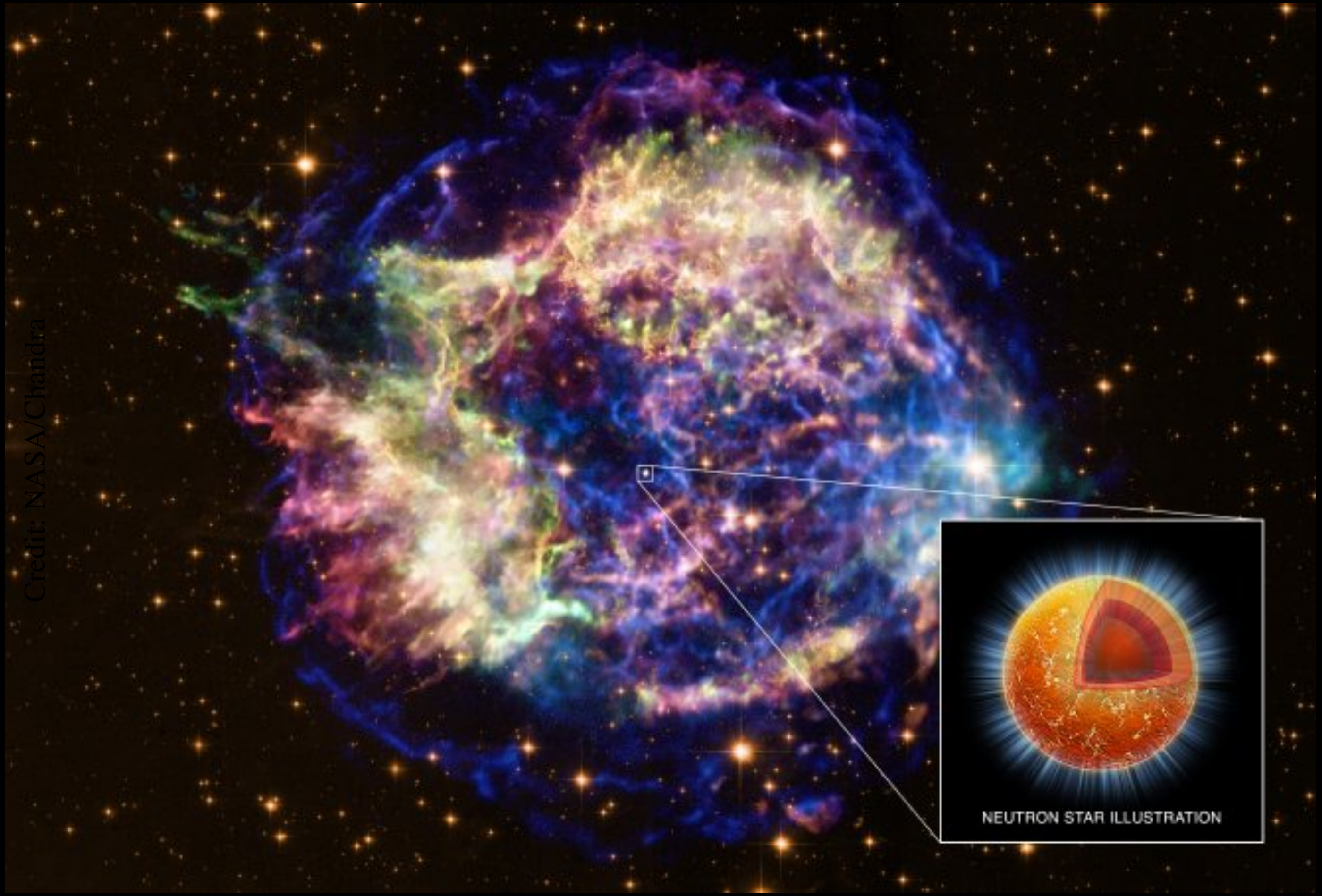
  $GM/Rc^2 \approx 0.1$ - $4/9$
- Escape Velocity:

  $v_{esc}^2 = 2GM/R$
- Maximum rotation rate ≈ 1000 Hz

  (after setting $v_{rot} = v_{esc}$)
- Escape velocity & rotational velocity can be a significant fraction c!



Type II Supernova



Credit: NASA/Chandra

- Core shrinks
- Neutron star forms
- Explosion triggered when infalling gas smashes into the neutron star

Formation of a neutron star triggers a supernova explosion!

The Discovery of Neutron Stars

- November 28, 1967 - Jocelyn Bell discovered radio pulses that repeated every second.
- Best explanation: the "pulsars" are rotating neutron stars
- The discovery of neutron stars made it seem more likely that black holes could exist.

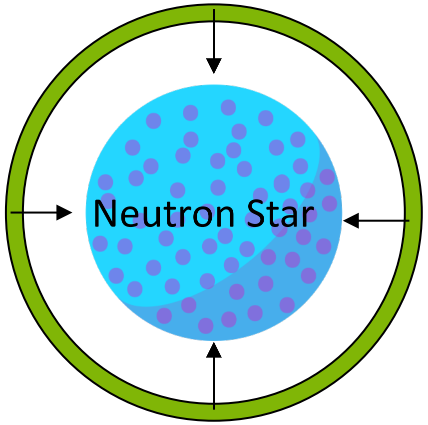
Dame Jocelyn Bell Burnell receiving Honorary PhD, 2016, U Alberta
Photo: Richard Siemens

How do Black Holes Form?

- Black holes are the result of total gravitational collapse
- Neutron stars have a maximum mass, similar to the Chandrasekhar mass limit for white dwarf stars.
- Upper mass limit is not known exactly.
- Maximum mass for a neutron star is somewhere between

  2.2 M_{sun} – 3.0 M_{sun}
- The existence of a maximum neutron star mass suggests that black holes might be formed when extremely high mass stars die

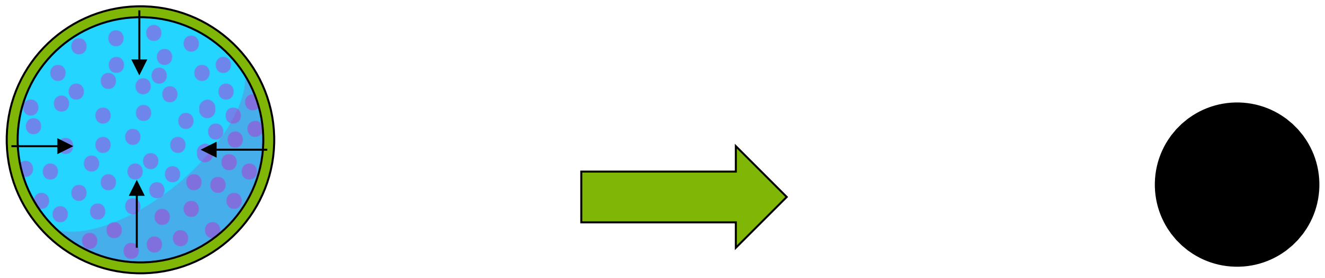
Core Collapse Supernovae with Higher Mass Main Sequence Stars: M > 25 M_{sun}



- In some "weak" explosions, outer layers of gas can fall back onto the neutron star
- Neutron stars have a maximum mass near 3 M_{sun}
- The extra gas can destabilize the Neutron Star making it collapse inwards!

$M > 25\ M_{sun}$ (mass limit is uncertain)

- The collapsing Neutron Star forms a Black Hole!
- This process is called a “Fallback Supernova”

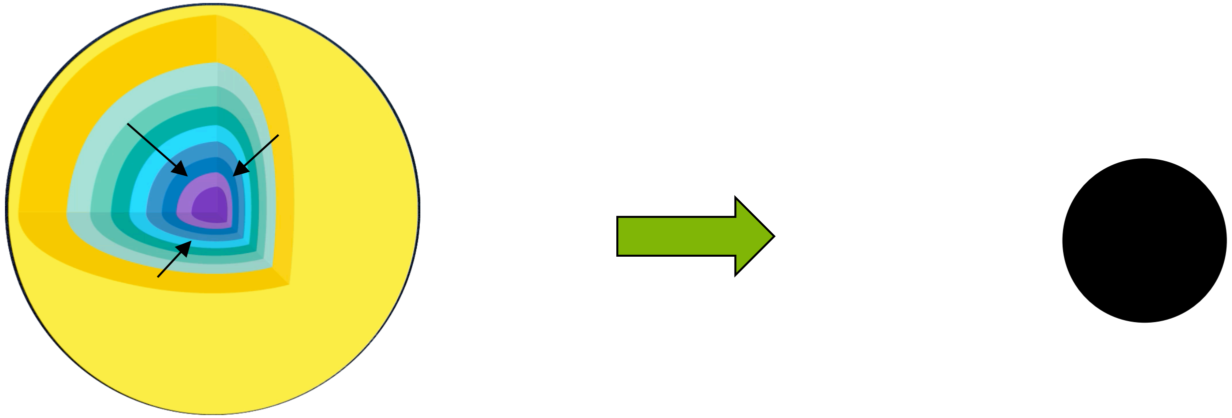


Neutron Star

Black Hole

Higher Mass Main Sequence Stars:
$M > 40\ M_{sun}$ (mass limit is uncertain)

- The collapsing giant fails to start an explosion, and directly forms a black hole
- We call this a “failed supernova”



Collapsing Giant Star

Black Hole

A Failed Supernova forming a Black Hole?

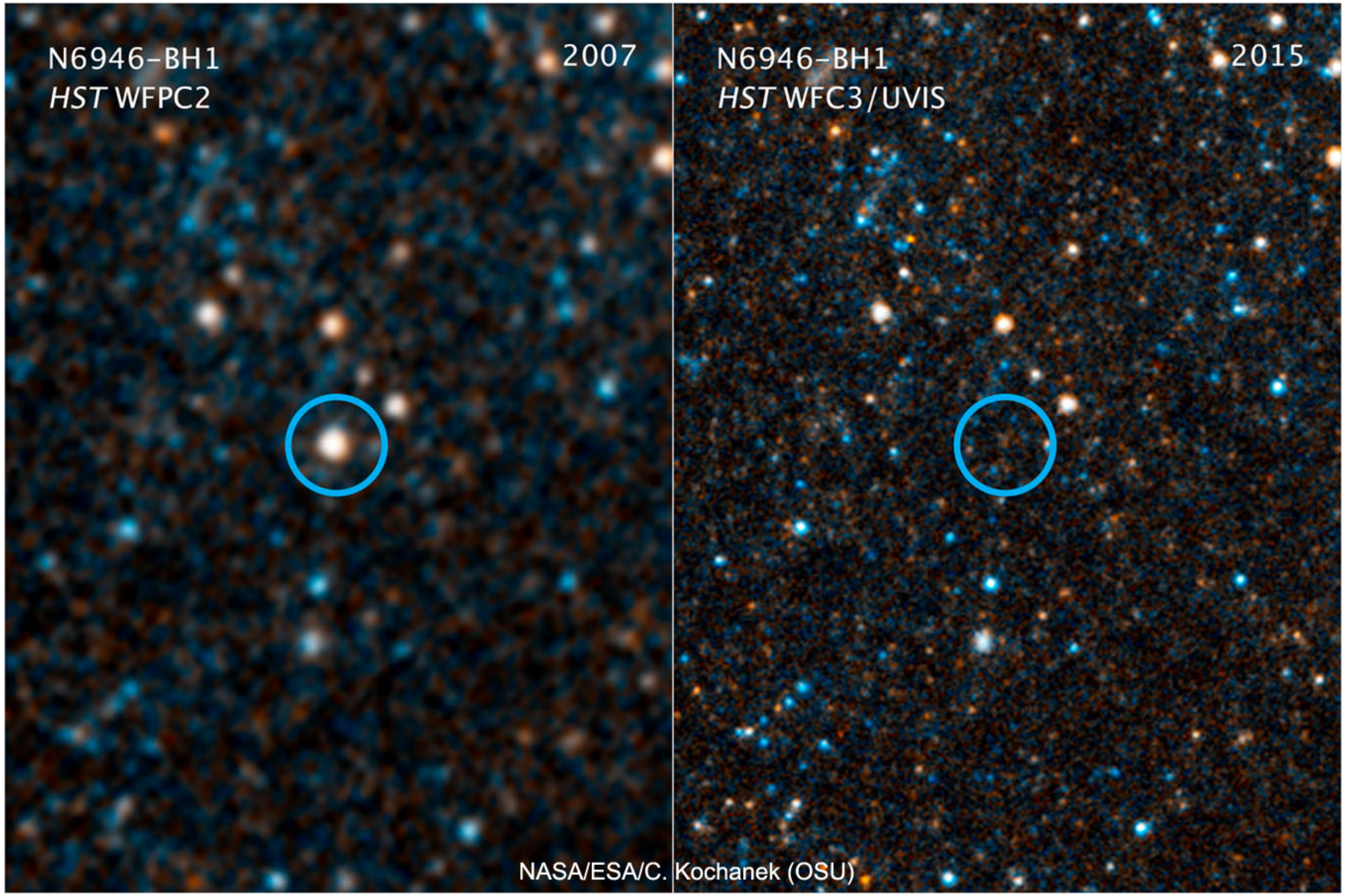
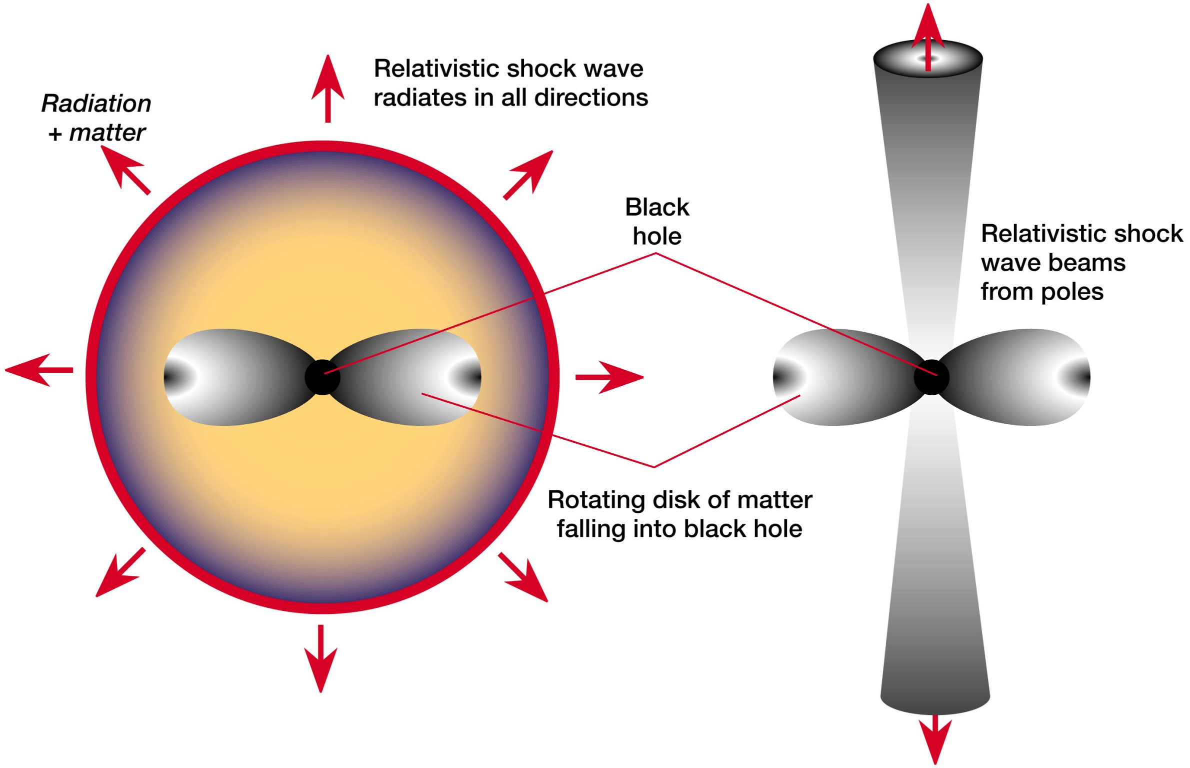


Image Credits: NASA

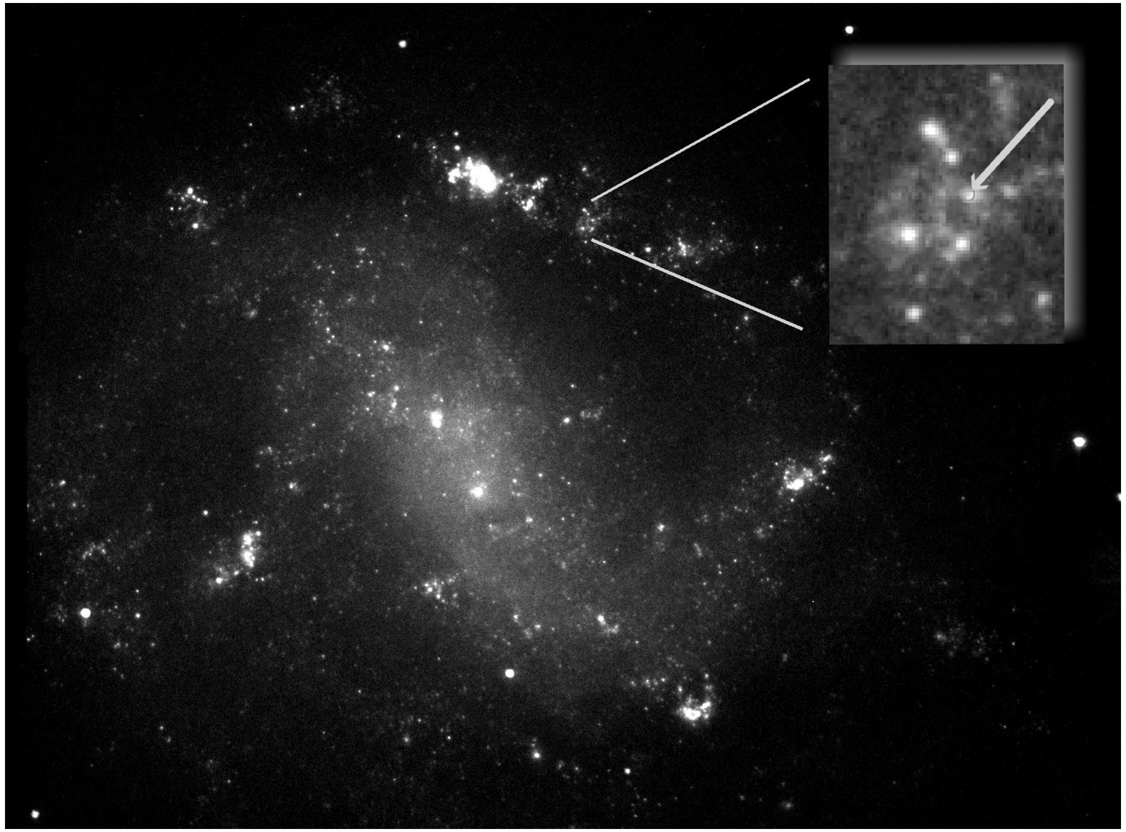
Collapse of a Rapidly Rotating Massive Star



- If the collapsing star is rapidly rotating, a disk of gas can form around the black hole
- This could produce a HYPER bright supernova called a Hypernova or a Collapsar!

Drawing Credit: NASA/Marshall Space Flight Center,
after Baron (*Nature*, 395: 635, 1998).

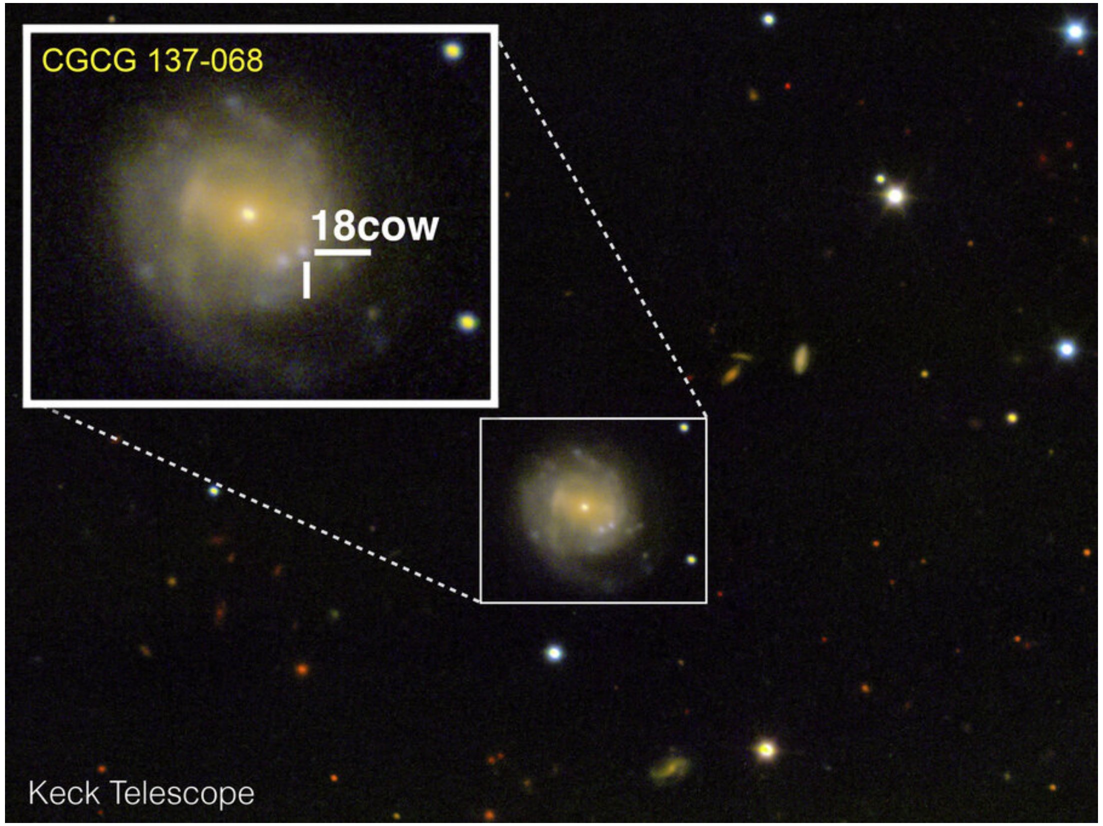
Black Hole formed in a Gamma-Ray Burst?



- Maybe some black holes are born with a burst of gamma-rays?
- We often see bright bursts of gamma-rays.
- “Long Gamma-ray Bursts” may be the birth of black holes

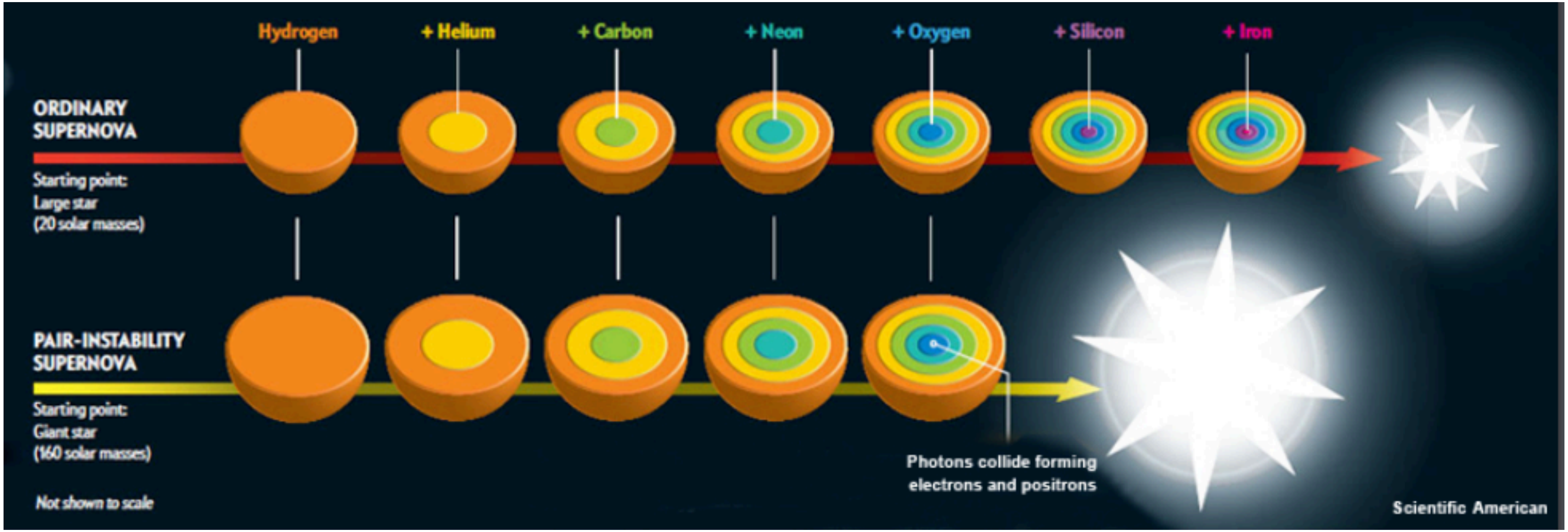
Gamma-ray burst in galaxy **ESO 184-G82**
Credit: S. Holland, J. Hjorth, J. Fynbo (Survey of Host Galaxies of GRBs Team), ESA, NASA

Holy Cow?!?



- 18cow is an unusual supernova explosion seen in another galaxy in 2018
- The dying star had a mass around 80 M_{Sun}
- Speculation: this explosion might have produced a black hole!
- At the moment this is an unproved hypothesis

Pair Instability Supernova:
Nothing left behind!



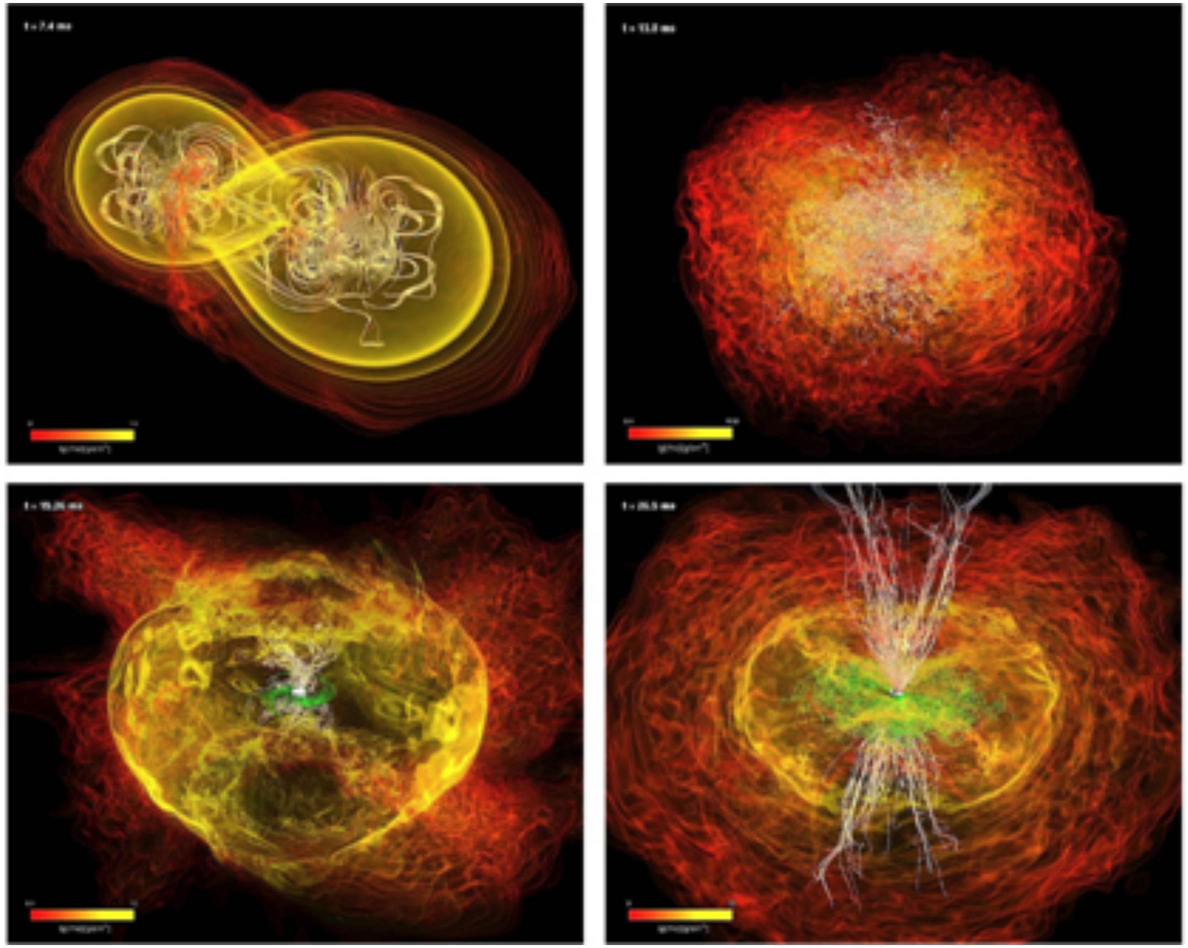
Scientific American

What about gold?

- Gold’s most common isotope has 79 protons and 88 neutrons
- This is an example of an r-process element = “rapid neutron capture process”
- Supply lots of fast-moving neutrons to a nucleus with lots of protons
- Neutrons can be captured by the nucleus to make heavier isotopes
- If neutrons arrive more rapidly than they decay, then elements like gold can form

Binary NS-NS Mergers:

Production of gravitational waves, gold, short gamma-ray bursts, black holes!



Computer simulations by L. Rezzolla and M. Koppitz

Summary of Part 1

- When main sequence stars die, they can produce one of the following remnants: a white dwarf, a neutron star, a black hole, or nothing at all!
- White dwarf stars are supported by electron degeneracy pressure
- Neutron stars are (at first approximation) supported by neutron degeneracy pressure
- Explosions are fun!

Neutron Stars: Part 2

- Neutron stars are more than just neutrons!
- A ball of pure neutrons would be unstable, since neutrons will seek the lower energy state and transform into protons, electrons, and anti-neutrinos (beta decay)
- The beta decay reaction releases energy, so this would be a neutron bomb!

Beta Equilibrium

- A neutron star is in beta equilibrium with beta decay and inverse beta decay occurring at the same rate

$$n \leftrightarrow p + e^{-} + \bar{\nu}$$

- In equilibrium there will always be some protons and electrons
- When these two reactions take place, neutrinos and anti-neutrinos are emitted, carrying away thermal energy
- Neutrinos cool down a neutron star after a supernova!

Supernova 1987a:
Core Collapse SN in LMC

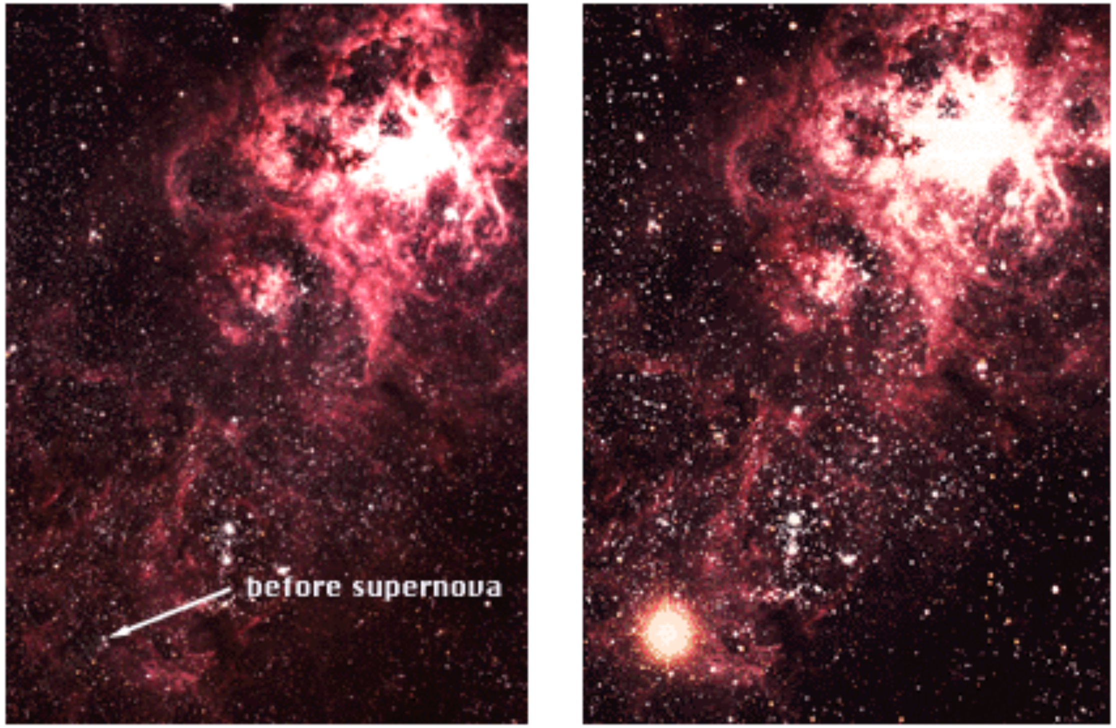


Image by David Malin, AAO

- 12 neutrinos were detected from this supernova by Kamiokande detector in Japan!
- This SN most likely formed a neutron star (no direct detection yet)
- 2002 Nobel prize to Masatoshi Koshiba (leader of Kamiokande detector)

Other Particles: example the muon

- Muon = “heavy electron” = μ^-
- Muon mass ~ 200 electron mass
- Normally muons decay into electrons:

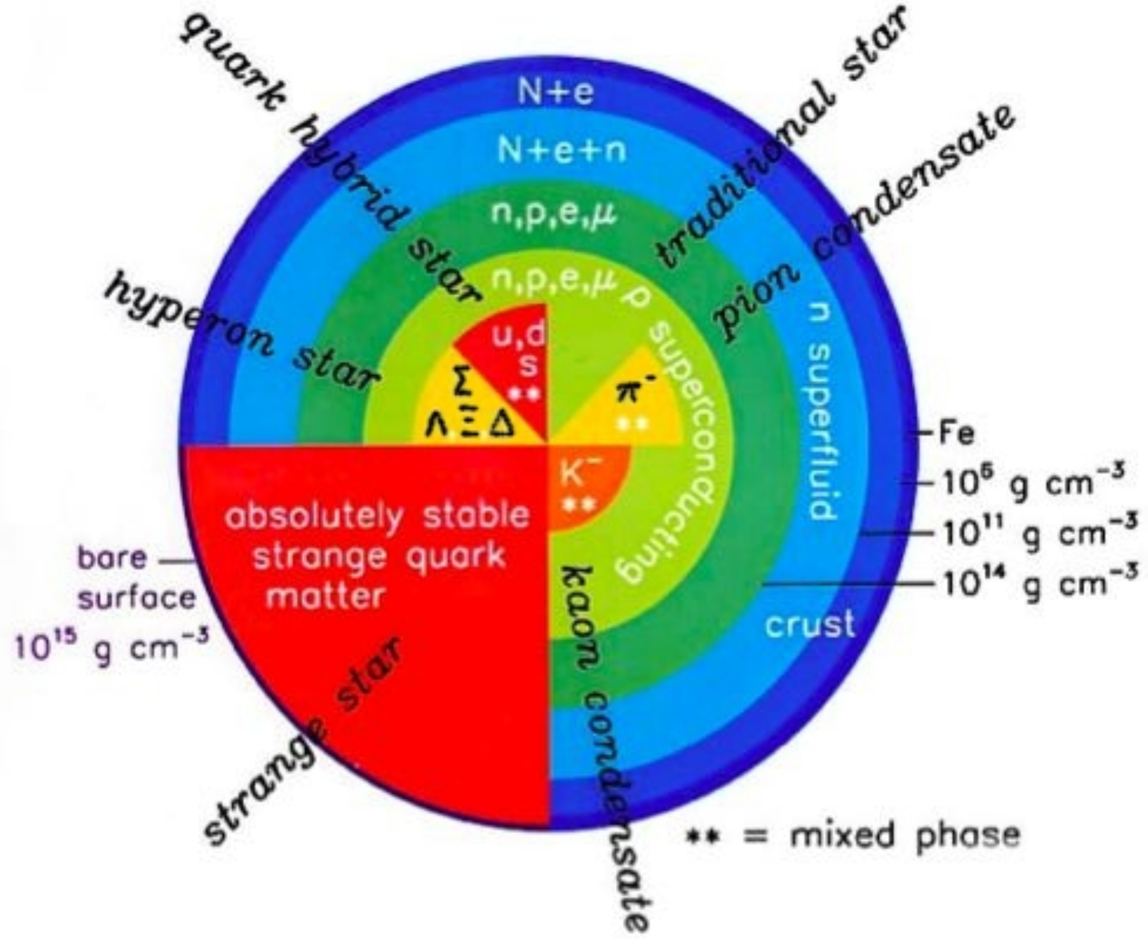
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- Inverse reaction producing muons can occur if degenerate electrons have enough energy!
- Normally we also have muons in a neutron star!

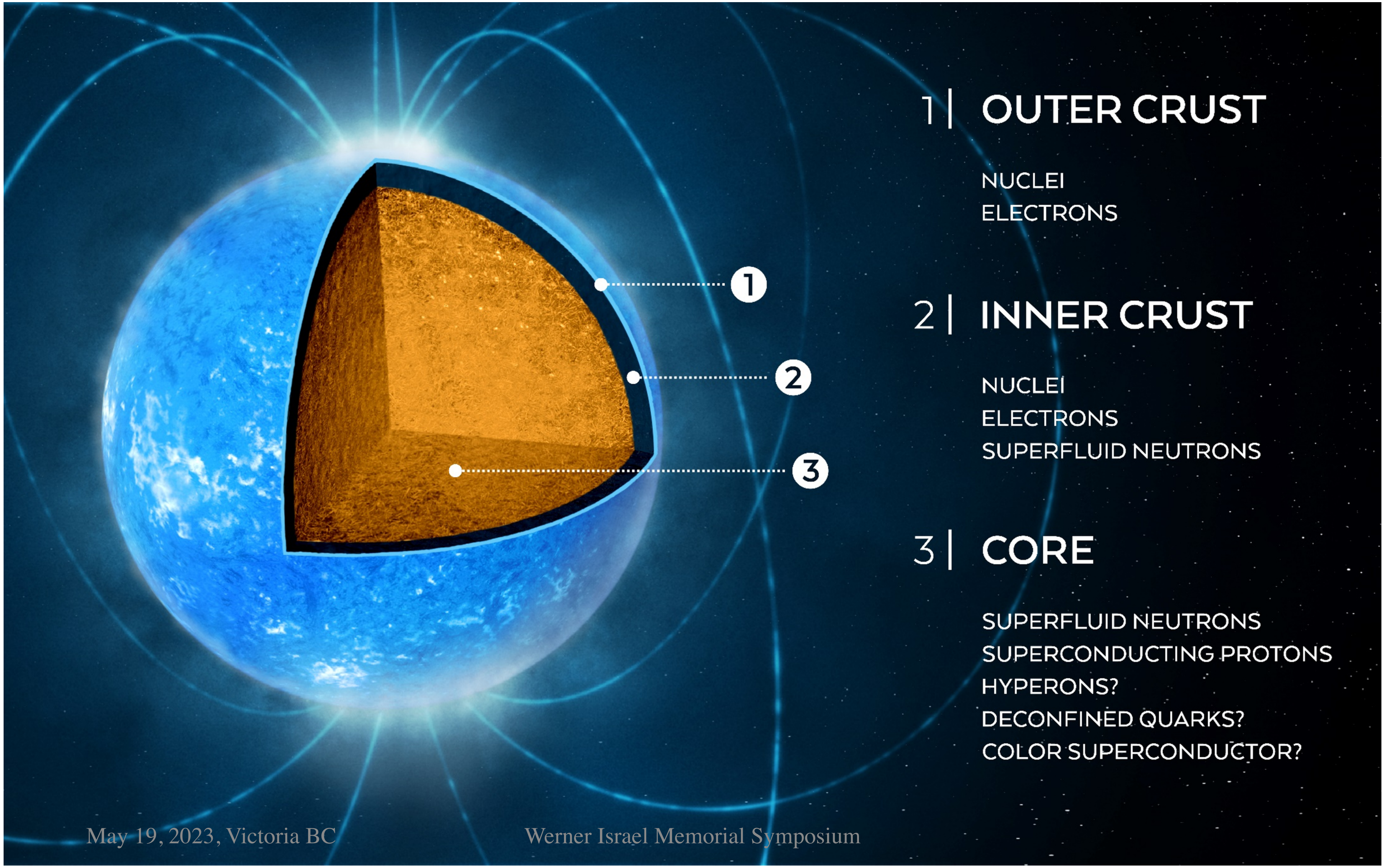
Flavour-Changing Reactions

- Quarks come in different “flavours”
- Regular matter is made up of up and down quarks
- Proton = up + up + down; Neutron = up + down + down
- Other flavours called ”strange”, “charm”, “top”, ”bottom”
- The strange quark is like a heavy down quark
- At high densities some of the down quarks in a neutron can transform into a strange quark creating a heavy baryon called a Hyperon

Many possible compositions for a "neutron star"!



The neutron star interior



1 | **OUTER CRUST**

NUCLEI
ELECTRONS

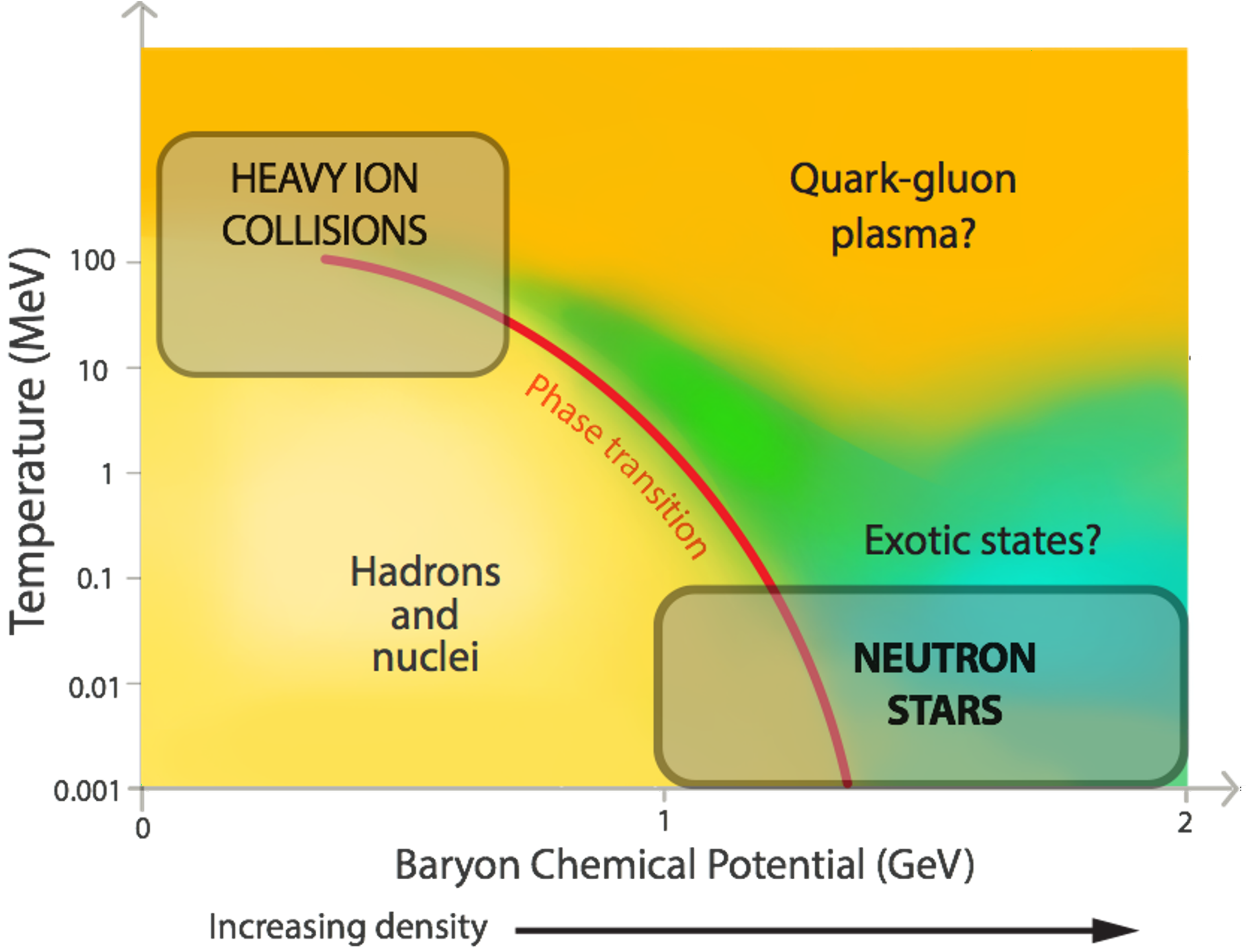
2 | **INNER CRUST**

NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS

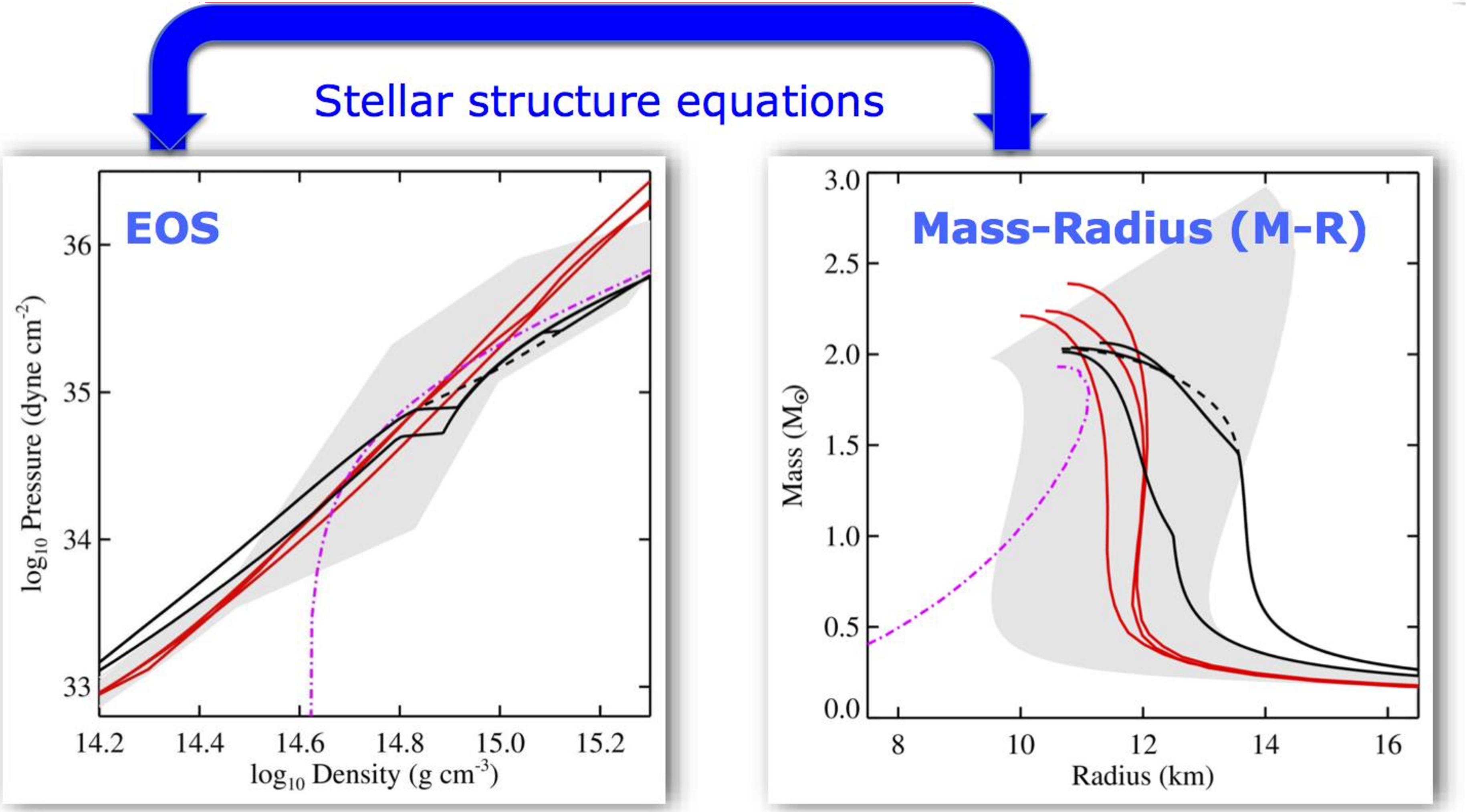
3 | **CORE**

SUPERFLUID NEUTRONS
SUPERCONDUCTING PROTONS
HYPERONS?
DECONFINED QUARKS?
COLOR SUPERCONDUCTOR?

Possible Phase Diagram for Dense Matter

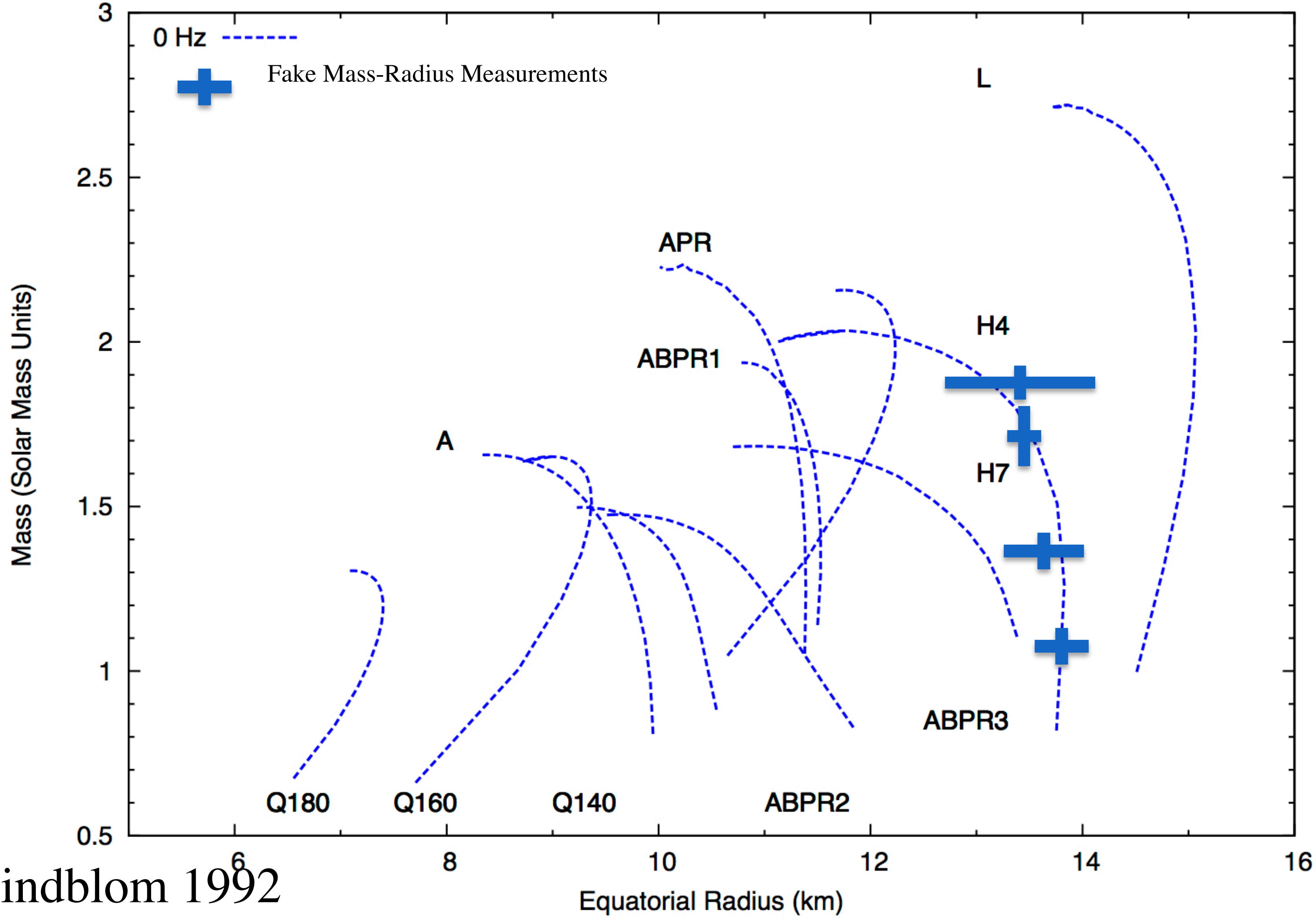


Equations of State vs Mass-Radius Curves



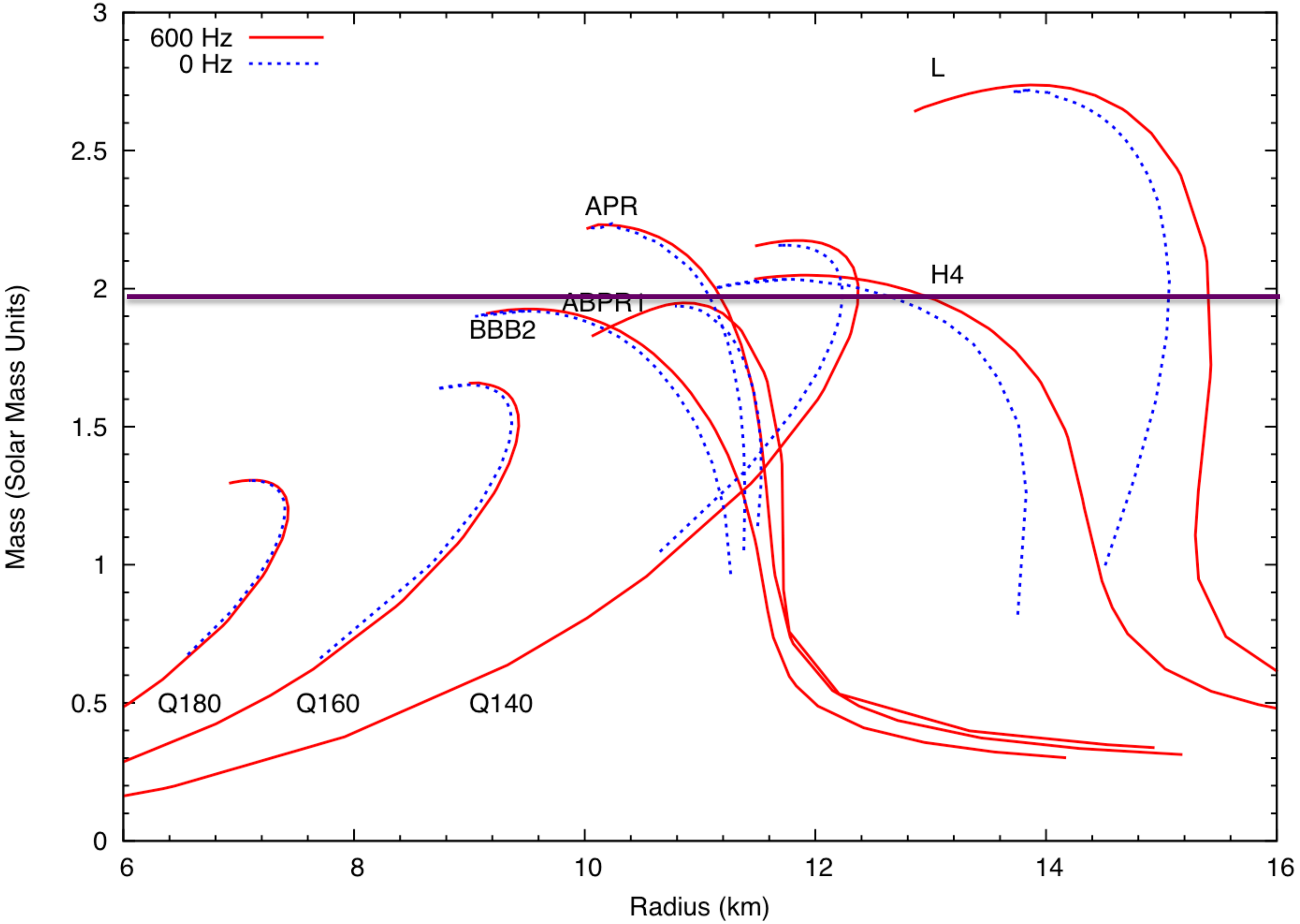
Stellar structure equations

Measurements of M and R as probes of nuclear physics???



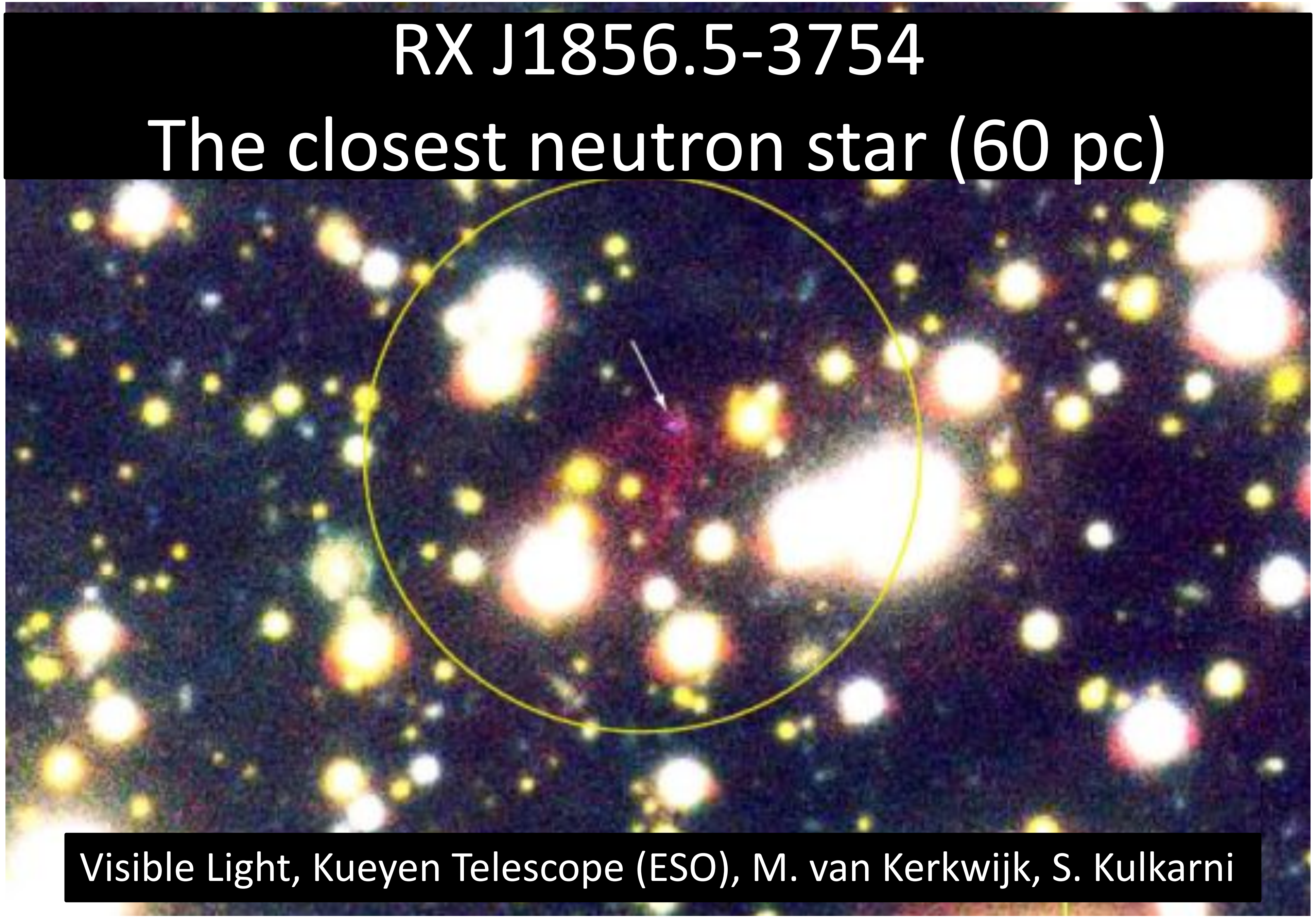
Lindblom 1992

Mass Measurements:
High mass can rule out an EOS!



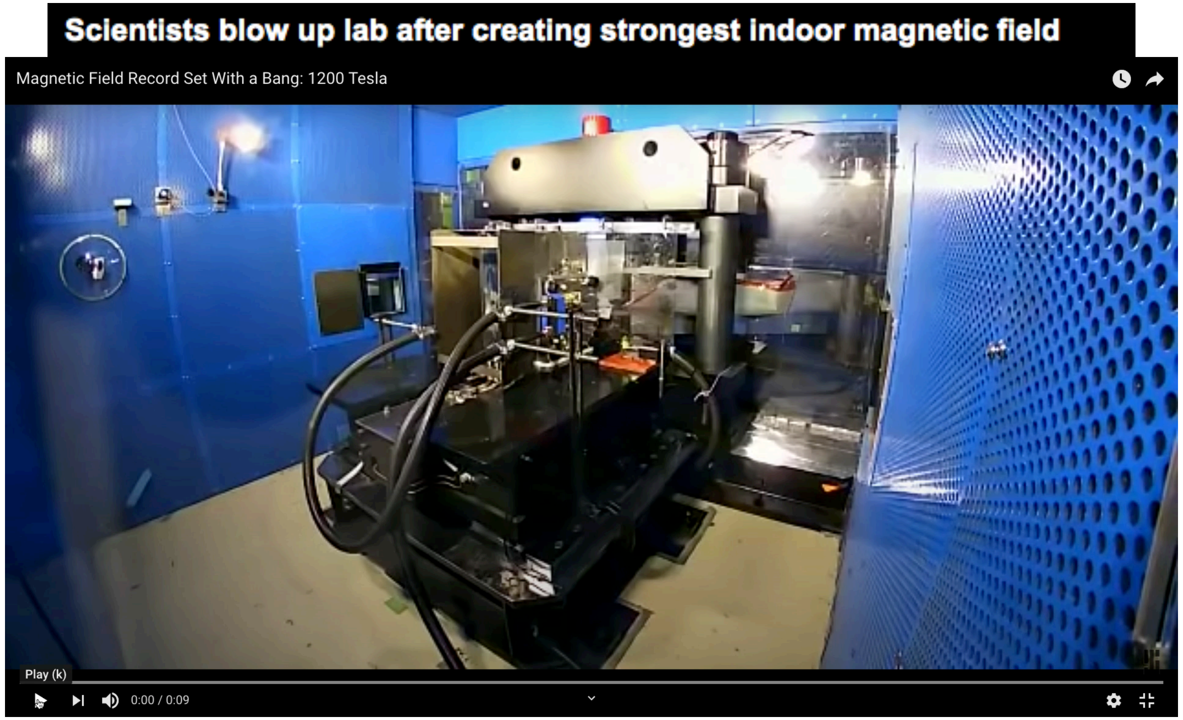
Measurement of Shapiro Delay gives M=2.0 $M_\odot$ (Antoniadis+ Science 2013)

RX J1856.5-3754
The closest neutron star (60 pc)



Visible Light, Kueyen Telescope (ESO), M. van Kerkwijk, S. Kulkarni

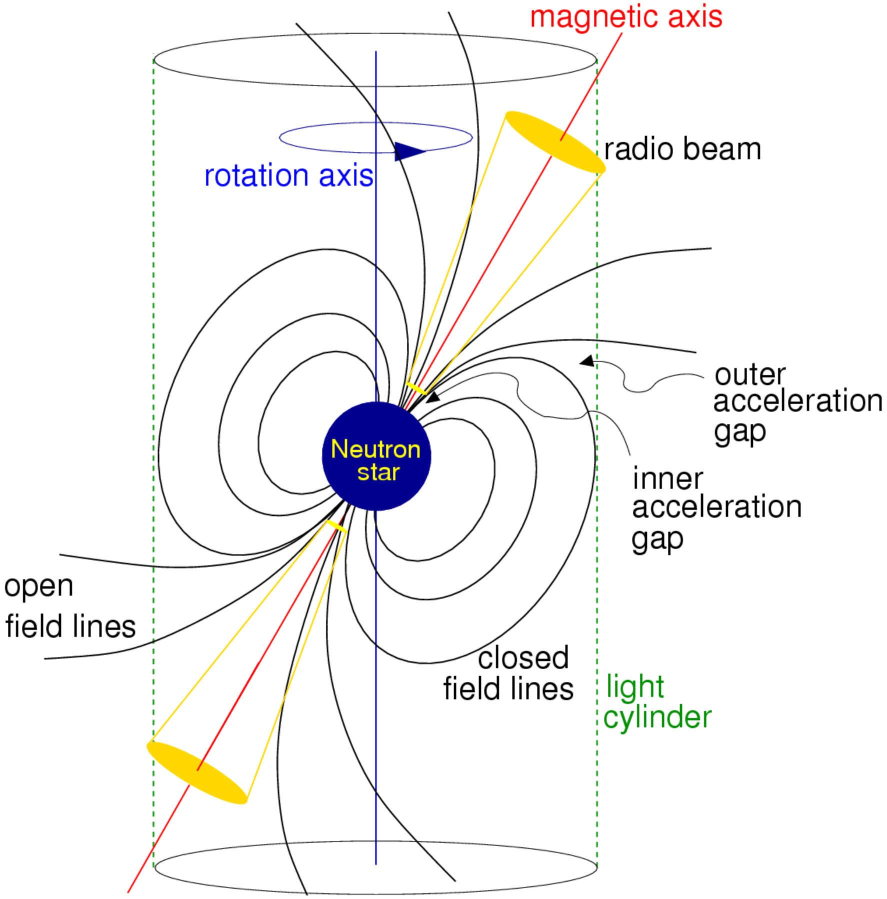
The strongest magnetic fields: Pulsars



Scientists blow up lab after creating strongest indoor magnetic field

Magnetic Field Record Set With a Bang: 1200 Tesla

1200 Teslas, University of Tokyo



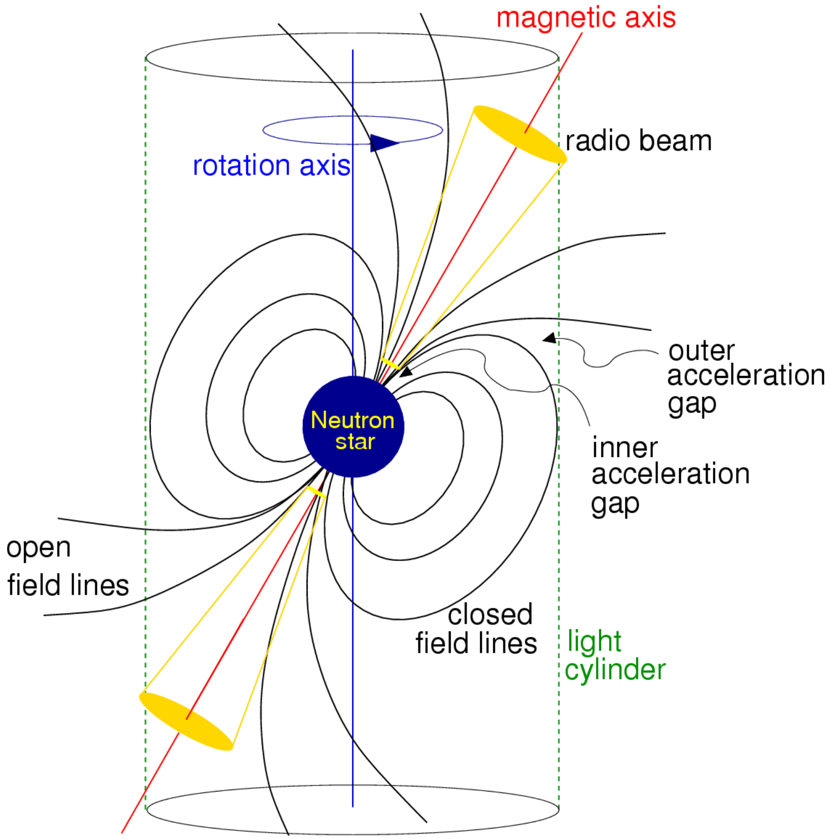
10,000 – 10,000,000,000 Teslas

Neutron Star Zoo

- Pulsars – pulsed radio emission from electrons magnetic funnels; pulsations from spin of neutron star
- ms pulsars – pulsars with spin periods near 1 ms
- X-ray and/or gamma pulsars = pulsed x-ray or gamma ray emission along with radio
- Magnetars = highest magnetic field neutron stars
- Central Compact Object = neutron star found in a supernova remnant
- Many others if found in a binary system

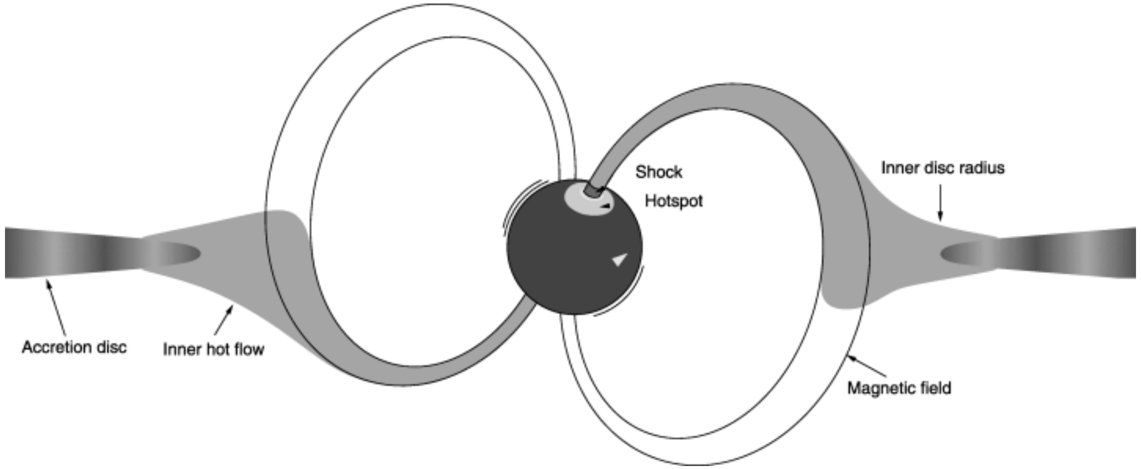
Neutron Star Spin Down

- A non-axisymmetric spinning magnet emits magnetic dipole radiation
- All EM radiation carries away energy and angular momentum
- The radiation causes the neutron star's spin to slow down
- ``Magnetic Braking"



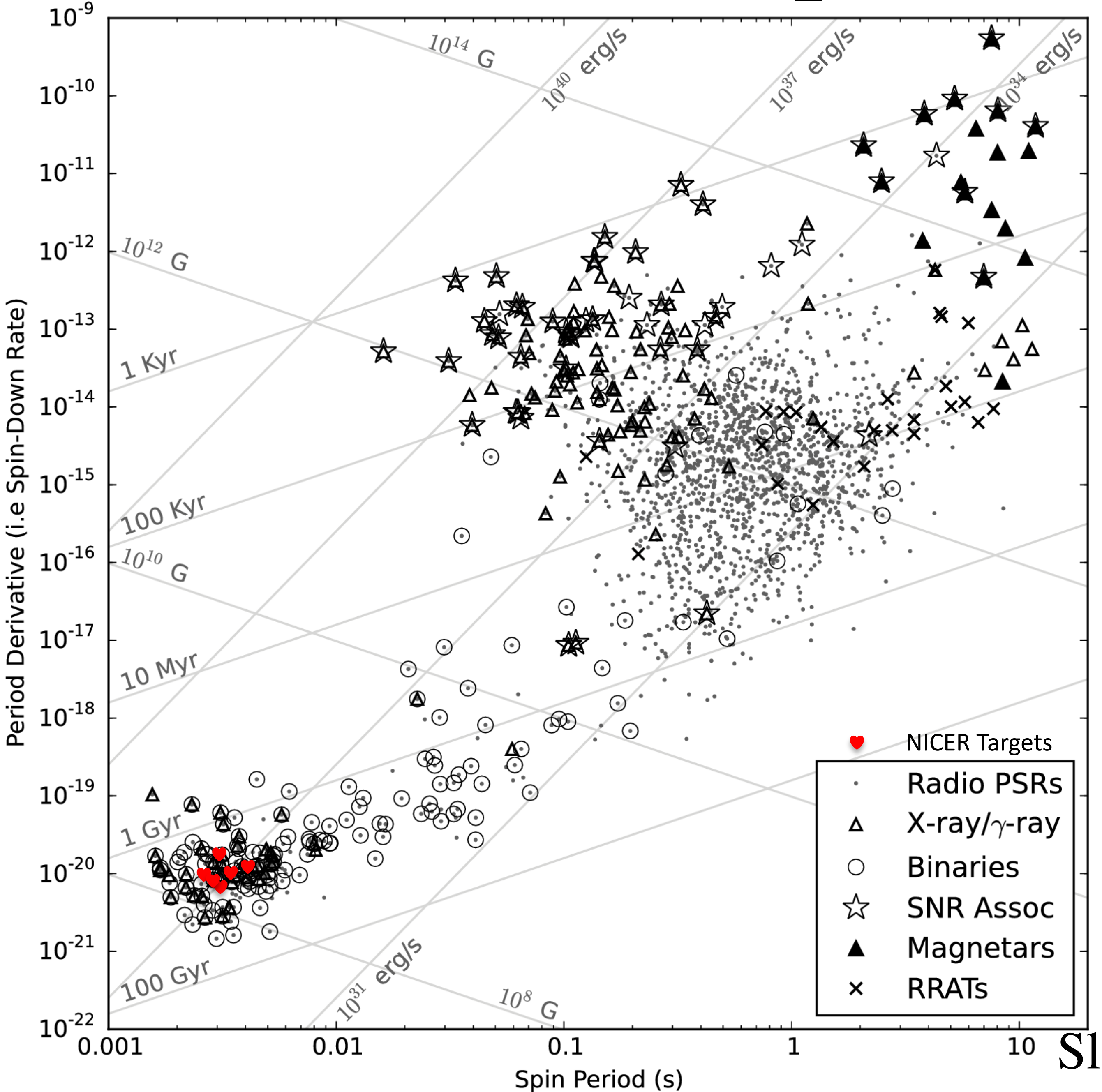
Neutron Star Spin Up

- When a neutron star is close to another star in a binary, gas can flow to the NS in an accretion disk.
- This gas will land on the NS adding mass and angular momentum!
- This causes the NS to spin faster!
- After accretion stops, the NS slowly loses angular momentum again.



Pulsar P-Pdot Diagram

Rapid Change in Spin



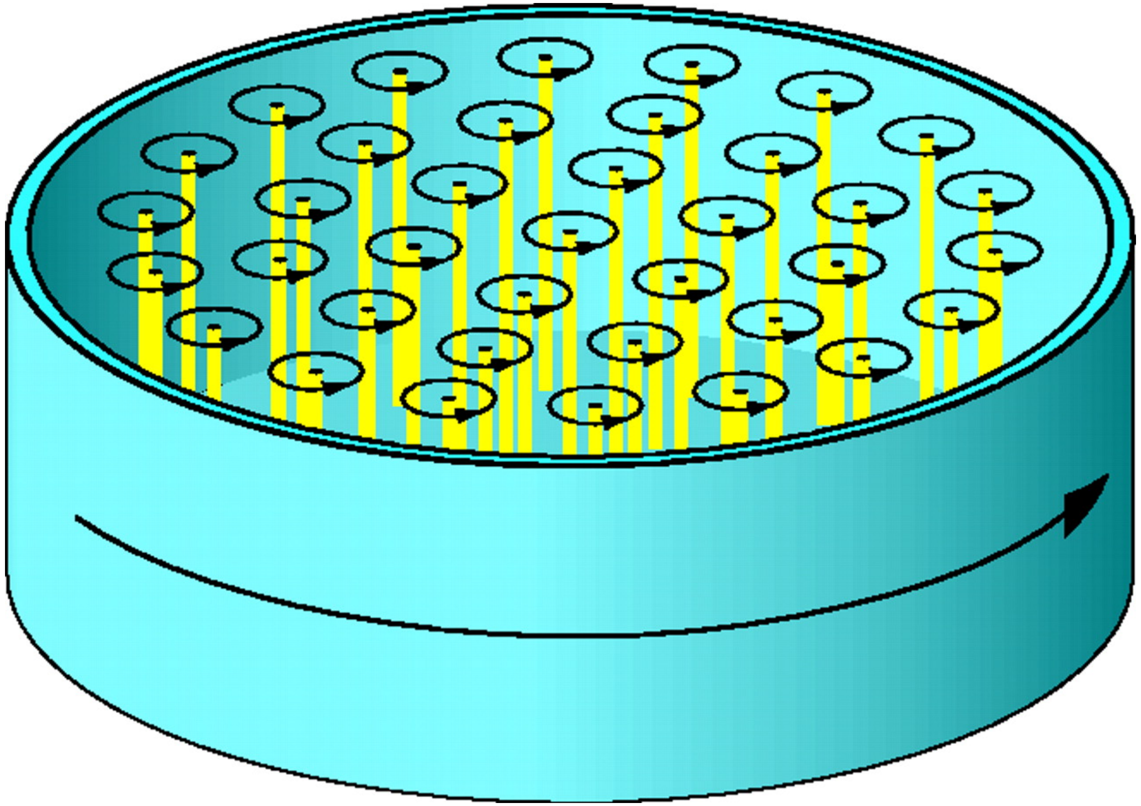
Stable spin

Fast spin

Slow spin

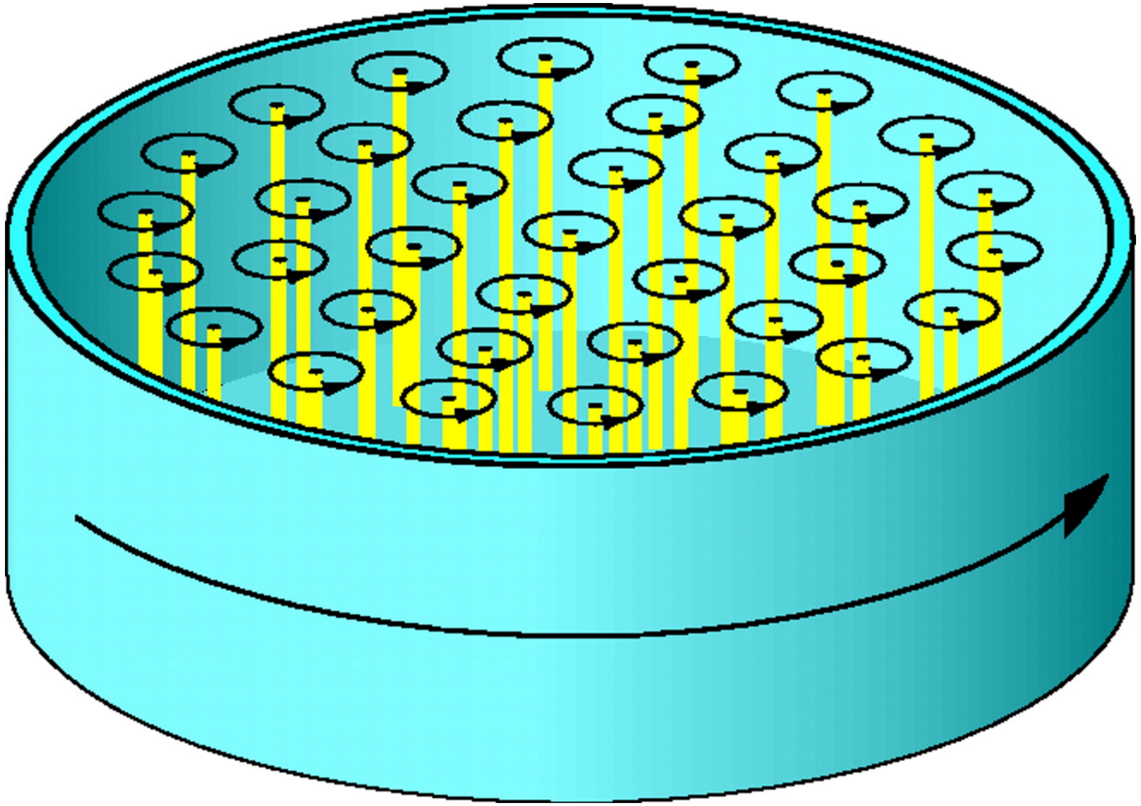
From Essential Pulsar Astronomy by Scott Ransom

Rotation in a Superfluid



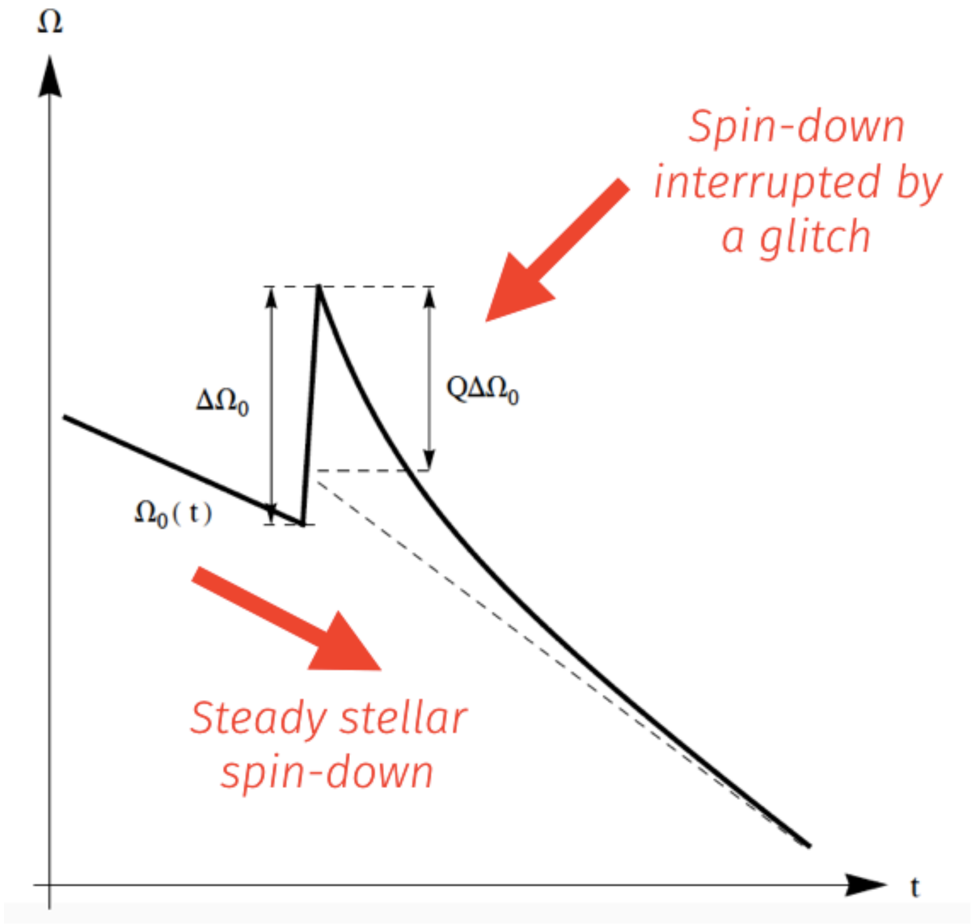
- When a superfluid rotates, the rotation is confined to quantized flux tubes
- Changes in rotation rate require destroying or creating new vortices
- Difficult to change the spin rate of a rotating superfluid!

Superfluid Neutrons?



- In a neutron star, it is possible for neutrons to pair up, creating effective bosons
- These effective bosons could behave like a superfluid
- Similarly, protons can pair up, possibly creating a superconductor
- The superfluidity ``resists” the magnetic braking effect

Spin Glitches

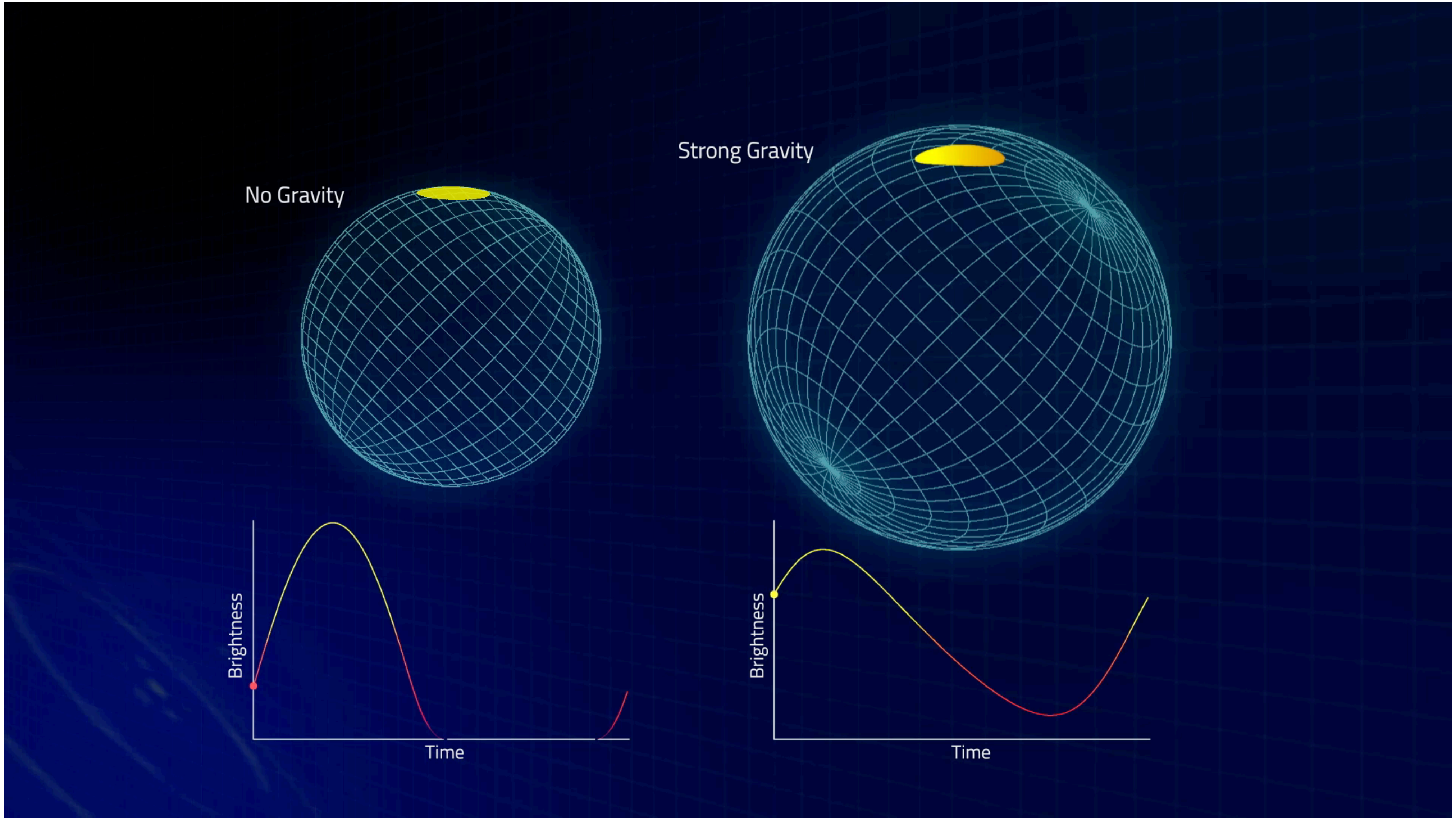


Spin-down interrupted by a glitch

Steady stellar spin-down

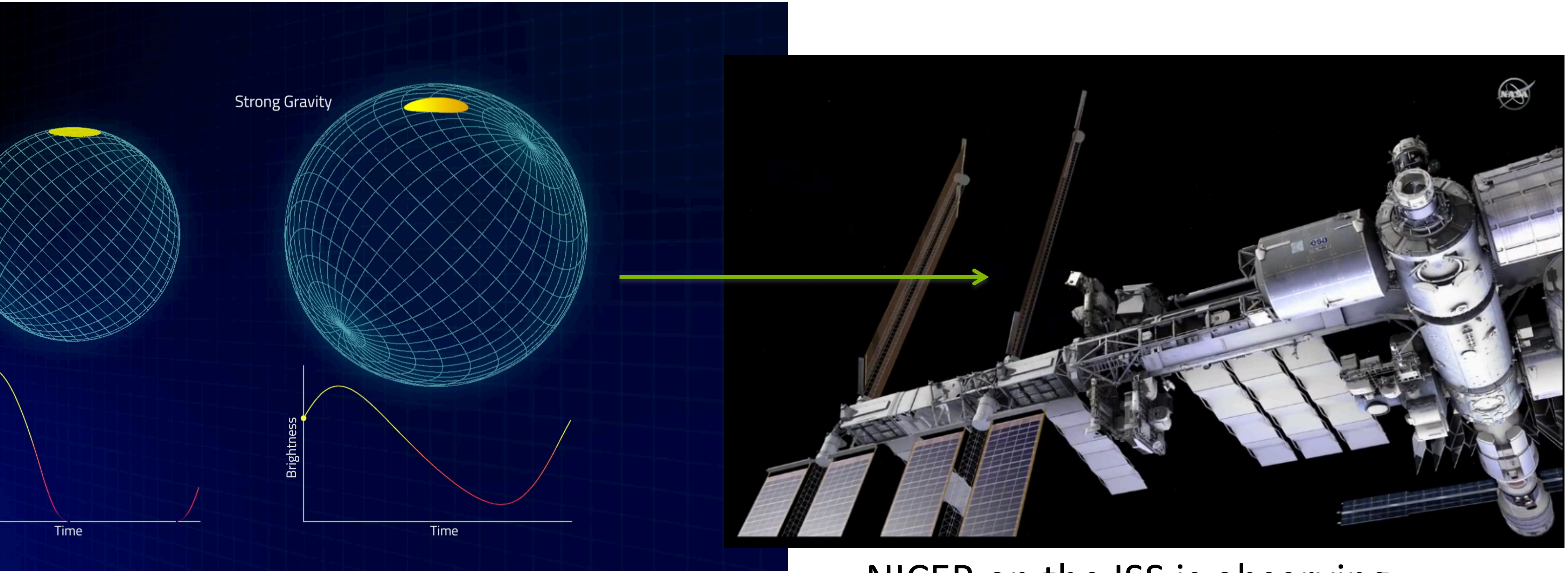
- Magnetic braking slows down the NS crust
- The superfluid interior tends to keep its spin constant
- During a glitch, some of the superfluid's angular momentum is transferred to the crust, spinning up the crust briefly

Neutron Stars' gravity bends light!



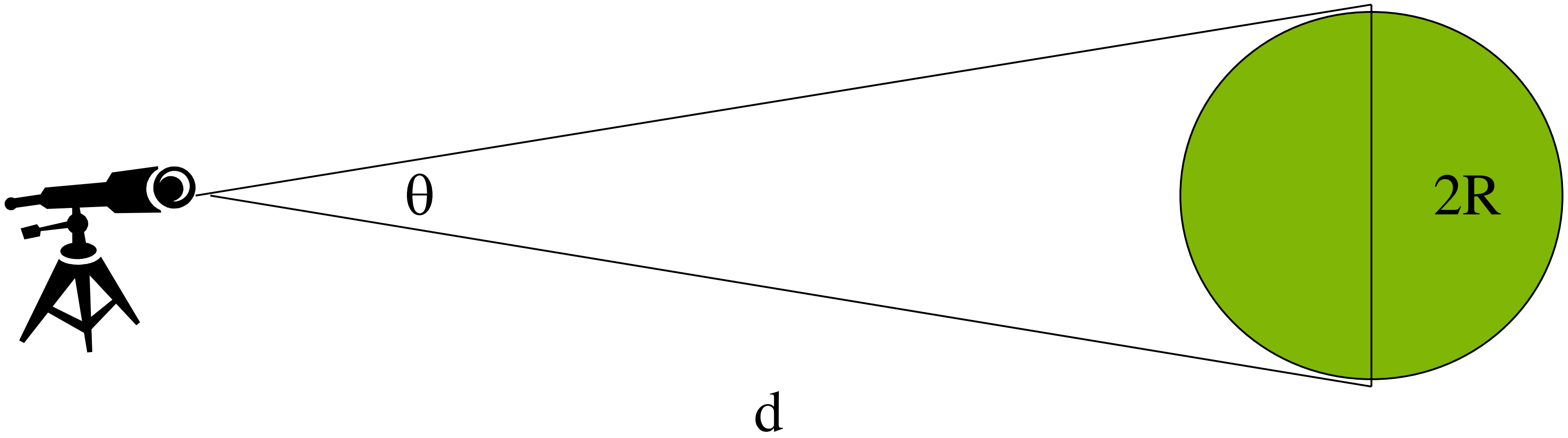
Animation by Brock Moir (U of A undergrad), Sharon Morsink, Zaven Arzoumanian, NASA

NASA’s NICER X-ray Telescope



NICER on the ISS is observing neutron stars and black holes!

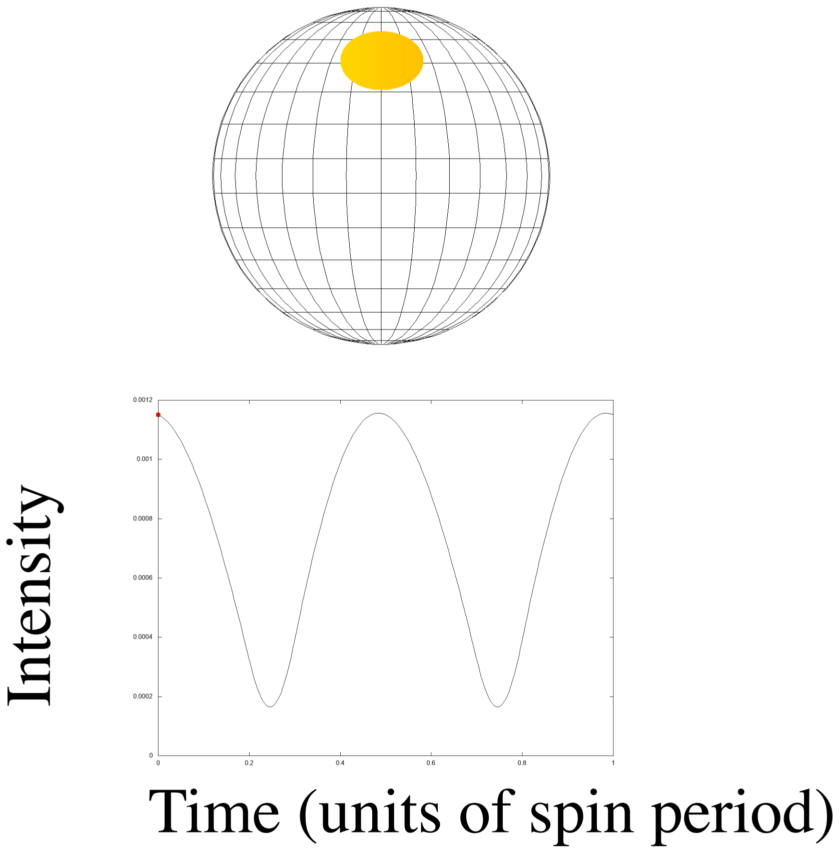
How do you measure a star’s radius?



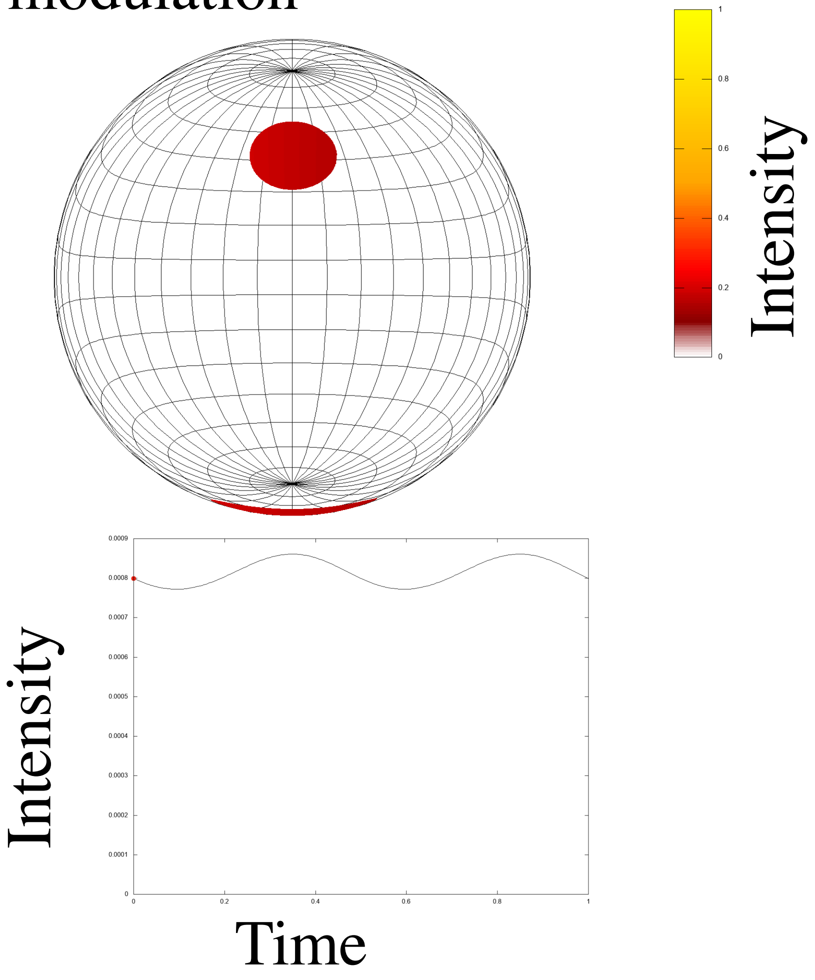
$\theta = 2R/d$

Dependence of Pulse Profiles on M/R

M/R = “compactness” affects how much of the star is visible due to light-bending; larger M/R → less modulation

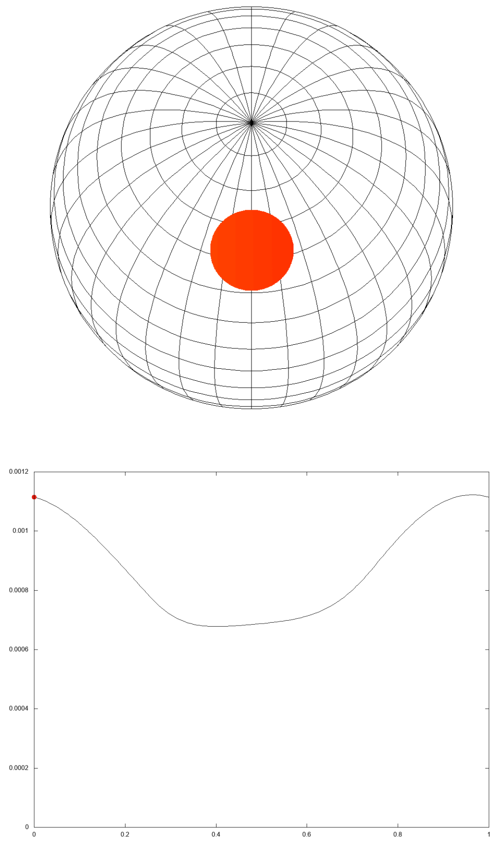


Newtonian Gravity

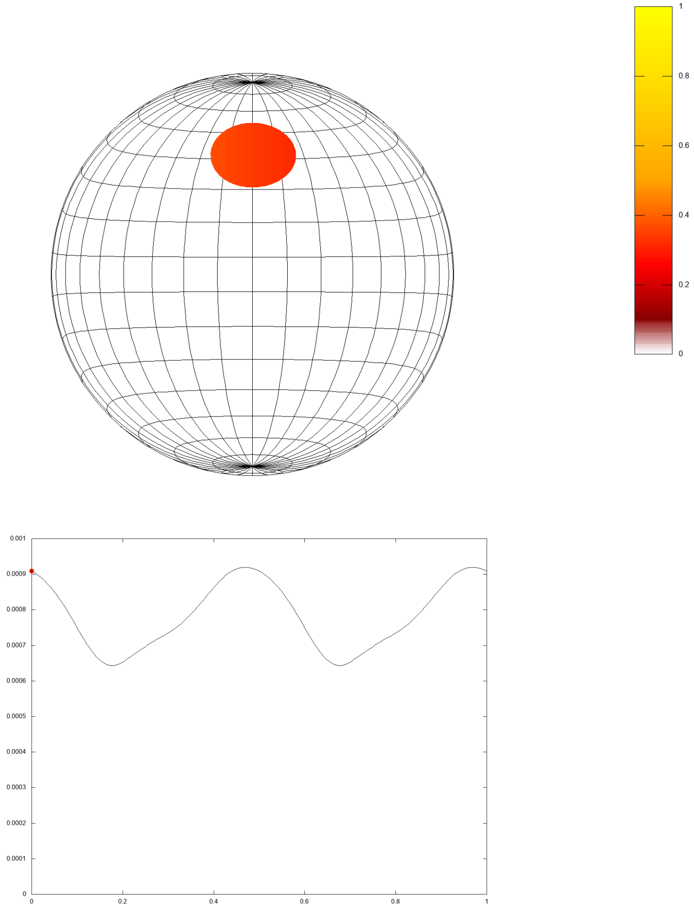


General Relativity M/R = 0.25

Effect of Observer’s Viewing Angle

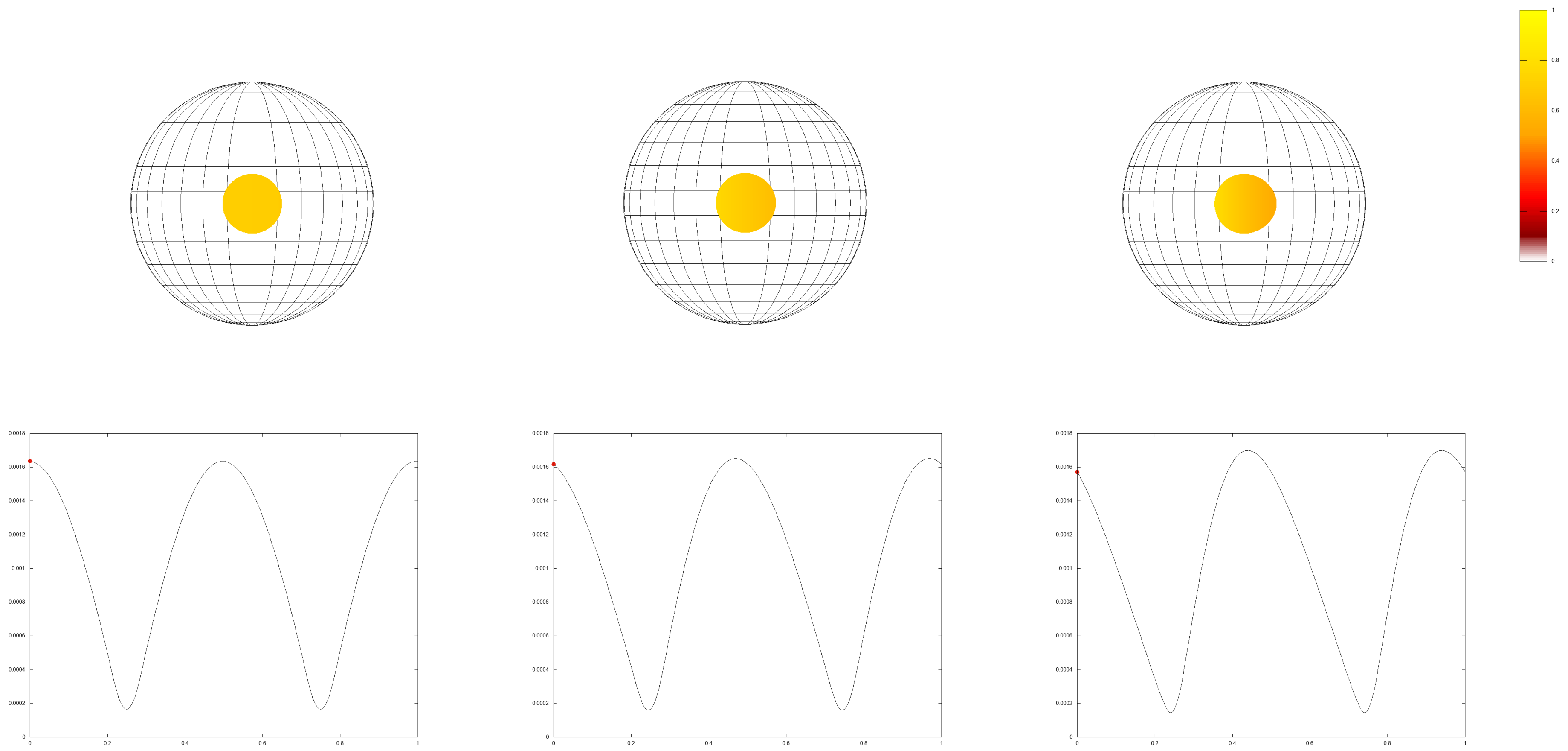


30 deg from Spin Axis



90 deg from Spin Axis

Effect of Rotational Speed $\propto R \sin i \sin\theta$



$v/c = 0.01$ $v/c = 0.1$ $v/c = 0.2$

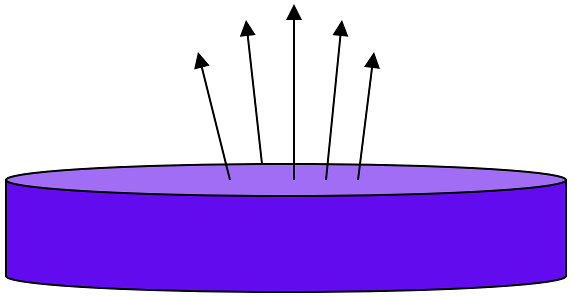
Anisotropic Emission

Beaming affects:

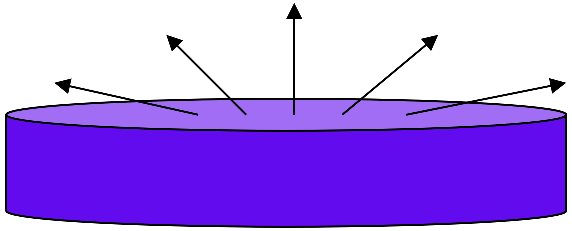
- Modulation: Normal beaming (A) gives higher pulsed fraction than anti-beaming (C)
- timing asymmetries: peak emission occurs earlier for C than for A
- Pulse shape: double-peaks or flattened peaks possible with C

Anisotropy depends on the photon wavelength.

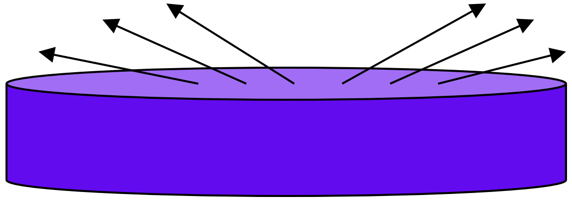
We require phase resolved spectroscopy!



A = Beamed towards the normal



B = Isotropic emission

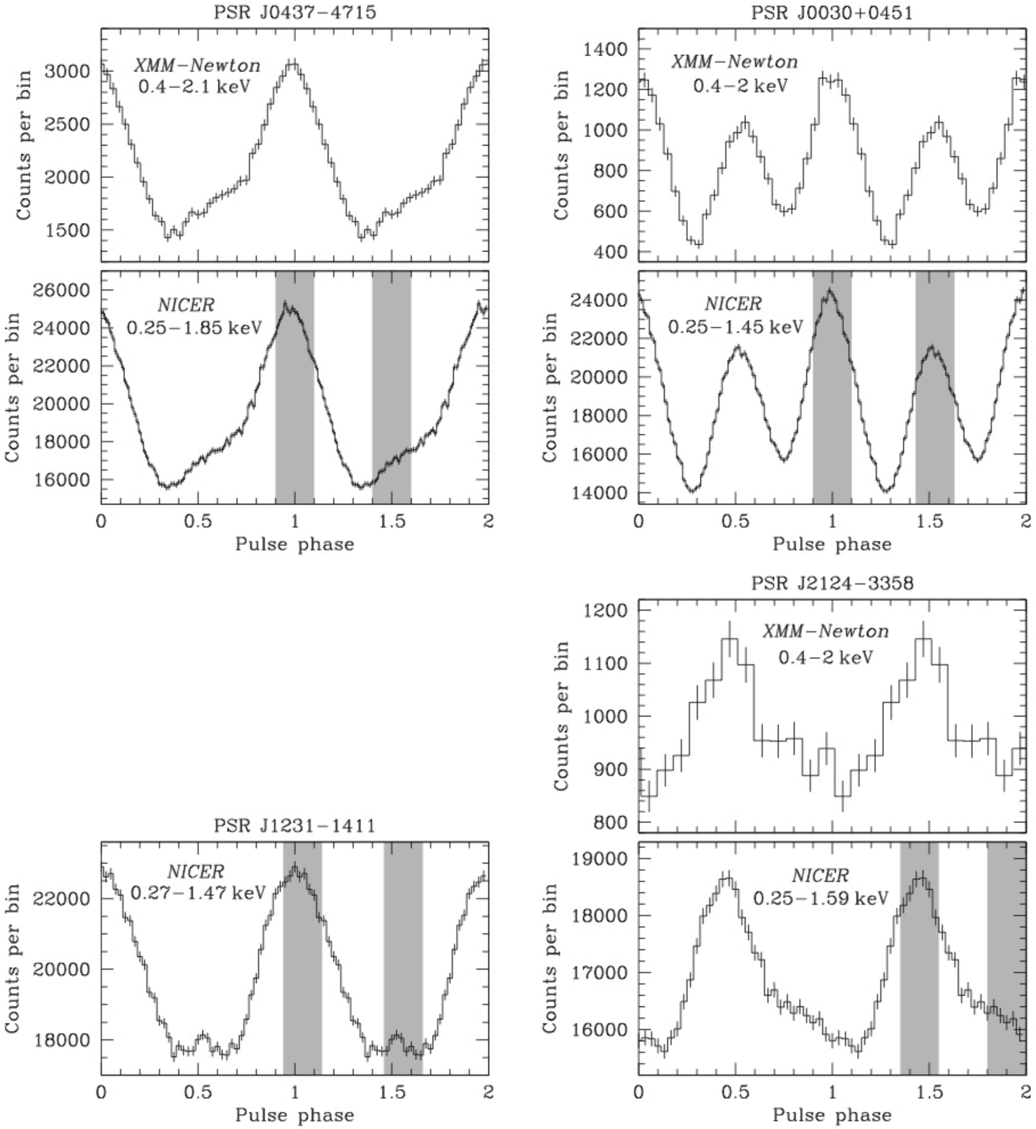


C = Beamed towards the surface

Pulse Profile Modelling

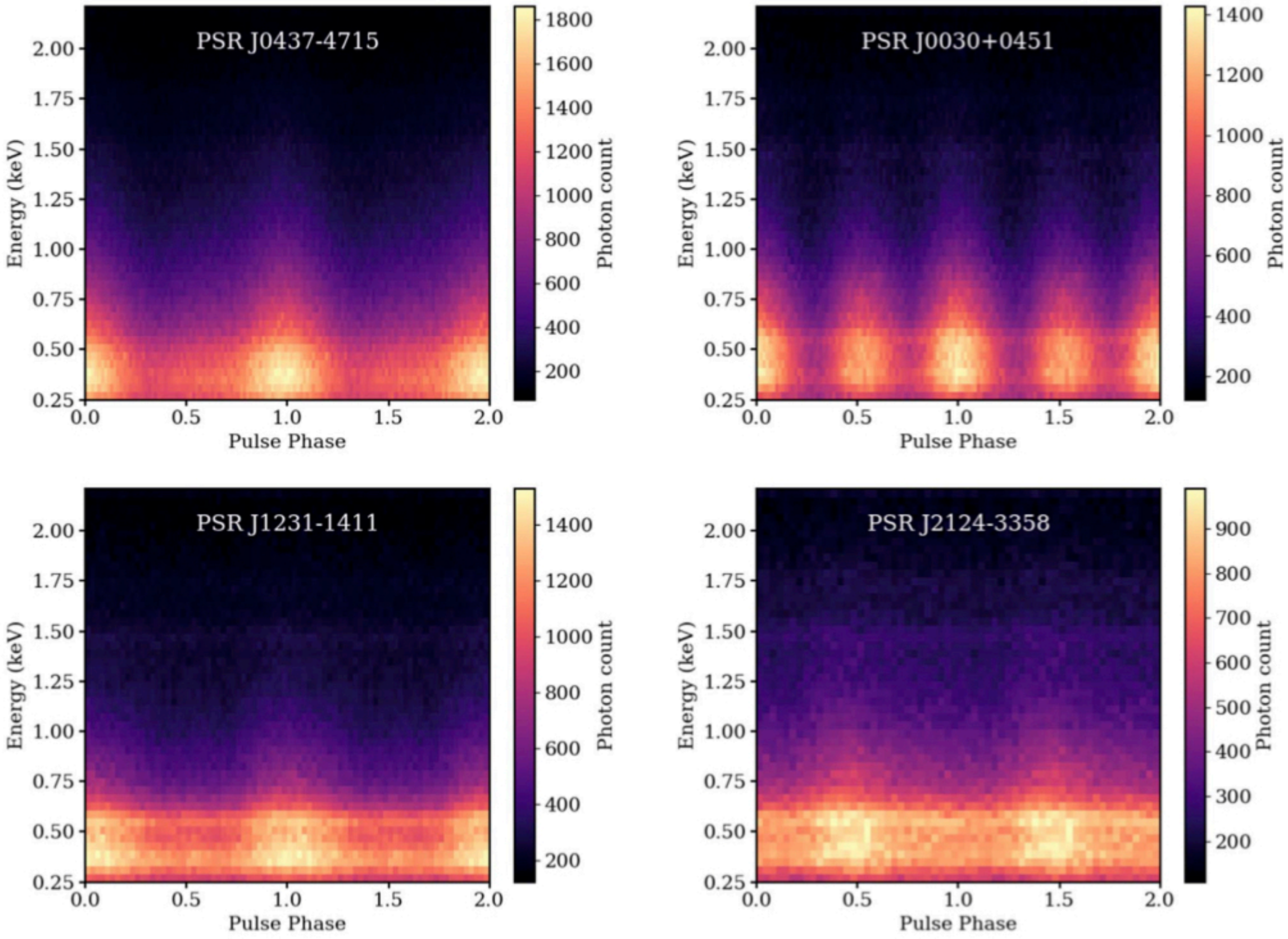
- Forward problem: (Easy!)
  - Make assumptions about NS properties, spot geometry, emission spectrum & beaming
  - Relativistic raytracing (using Schwarzschild metric) to predict flux versus time in telescope
- Inverse problem: (Difficult!)
  - Observe pulse profile and infer the NS properties
  - NICER X-ray telescope

NICER Pulse profile data



Bogdanov et al, ApJL 2019

NICER Pulse profile data



Bogdanov et al, ApJL 2019

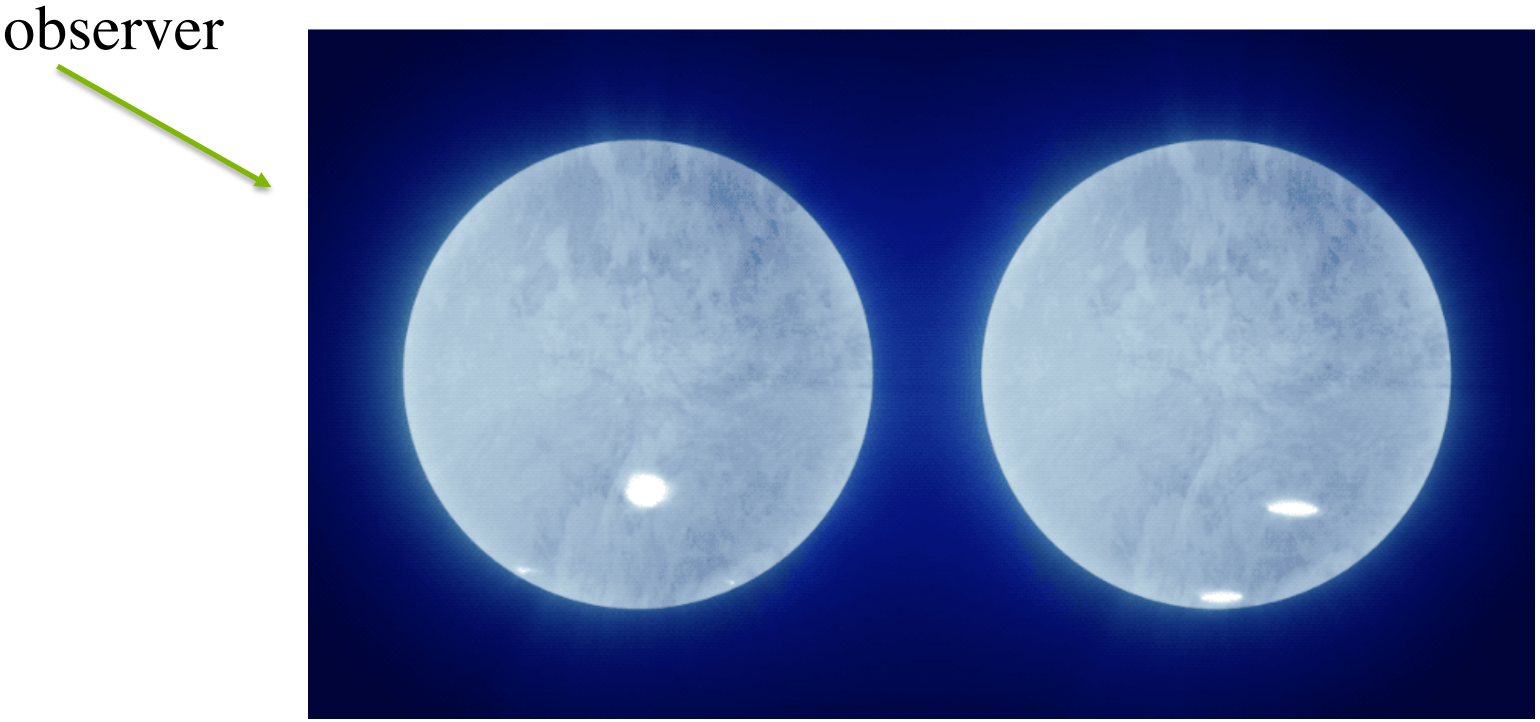
First Results on J0030

- No independent radio mass measurement
- Two independent analyses (crescents or ovals) led by Amsterdam (Riley+) and Maryland (Miller+)
- M = $1.34^{+0.15}_{-0.16}$ M_{sun} R = $12.71^{+1.14}_{-1.19}$ km (Riley+)
- M = $1.44^{+0.15}_{-0.14}$ M_{sun} R = $13.02^{+1.24}_{-1.06}$ km (Miller+)

- Similar observer inclinations, and spot locations

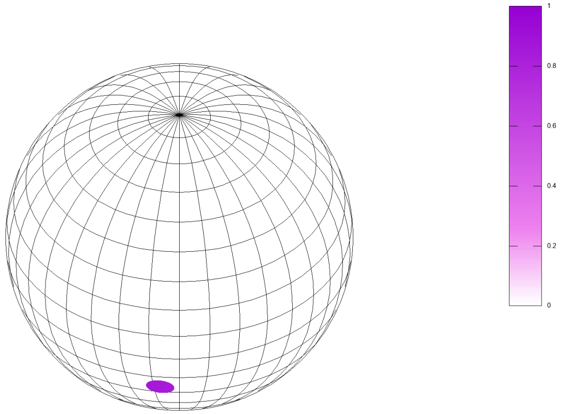
- Differences in M, R values show systematic errors coming from models

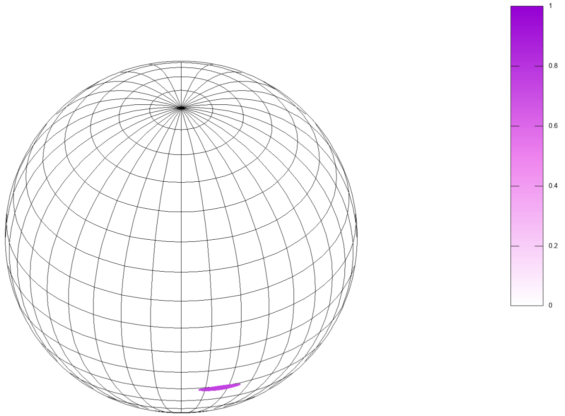
Inferred Spot Geometries



In both cases the hot spots are in the opposite hemisphere than the observer!!!! Not dipole-like!

Inferred Spot Geometries





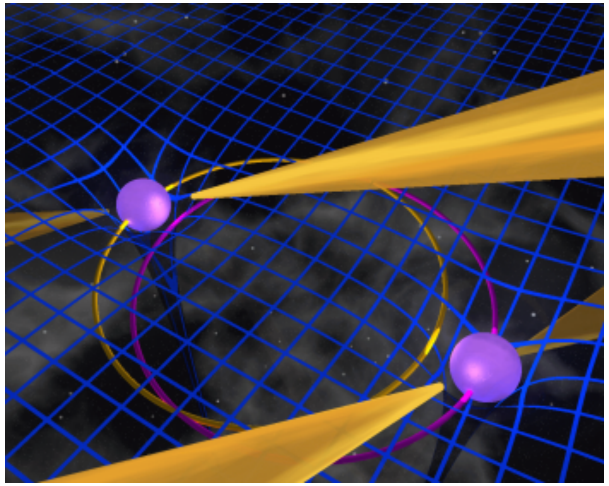
From the observer's point of view the third Antarctic spot is barely seen, while the "horns" of the crescent aren't seen.

SUMMARY

- Neutron stars have extremely high densities at their cores
- They can exhibit many types of extreme physics:
    - Strange particles!
    - Ultra-strong magnetic fields!
    - Strong gravitational light-bending!
    - Superfluidity and superconductivity!
    - Maybe a place for dark matter to accumulate?
    - Almost any type of physics can be applied here!

Extra slides

Binary NS-NS Mergers

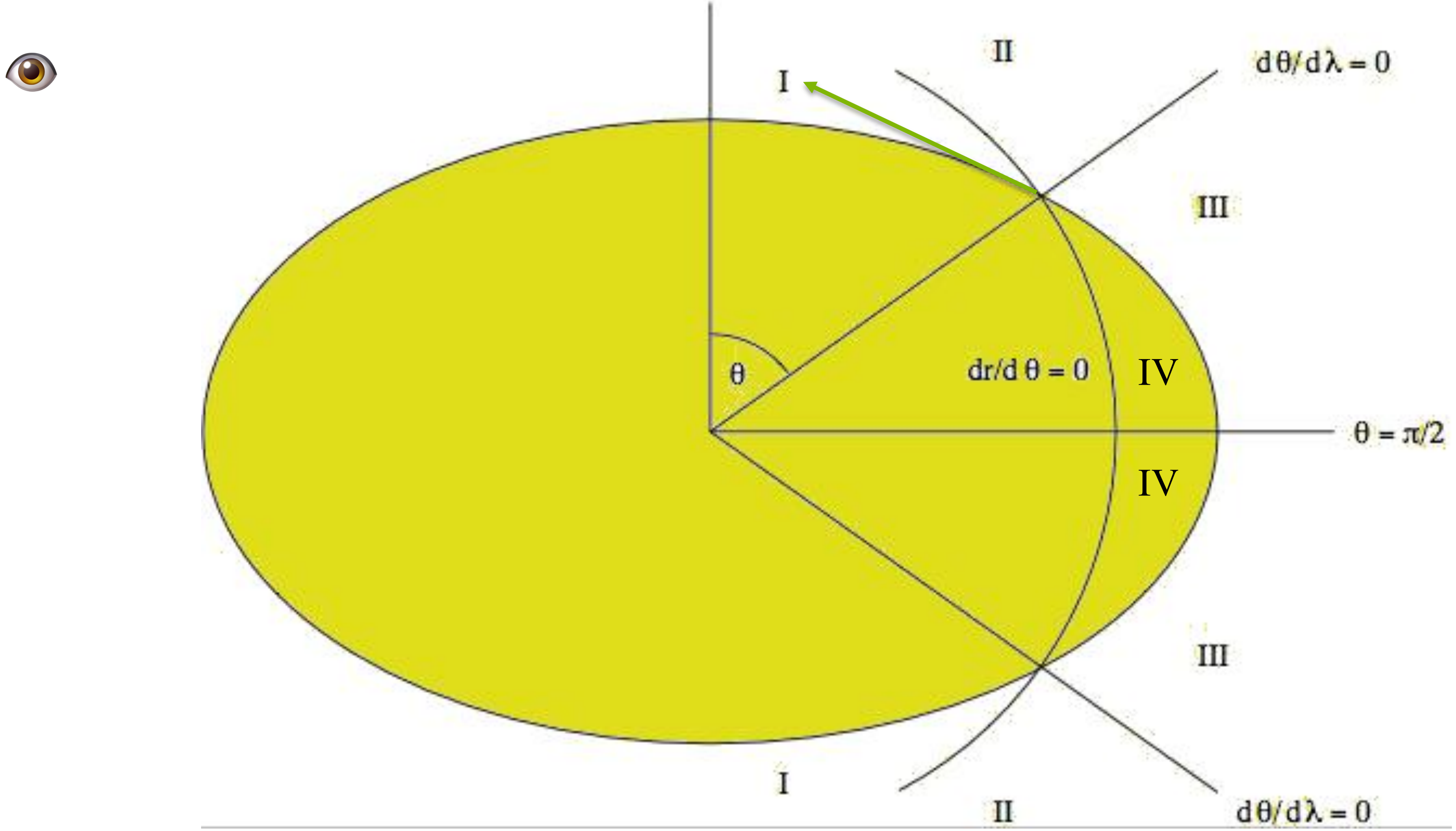


LIGO – The Laser Interferometric Gravitational Wave Observatory

GW170817 – LIGO’s first observation of NS-NS merger
Did merger produce NS or BH????

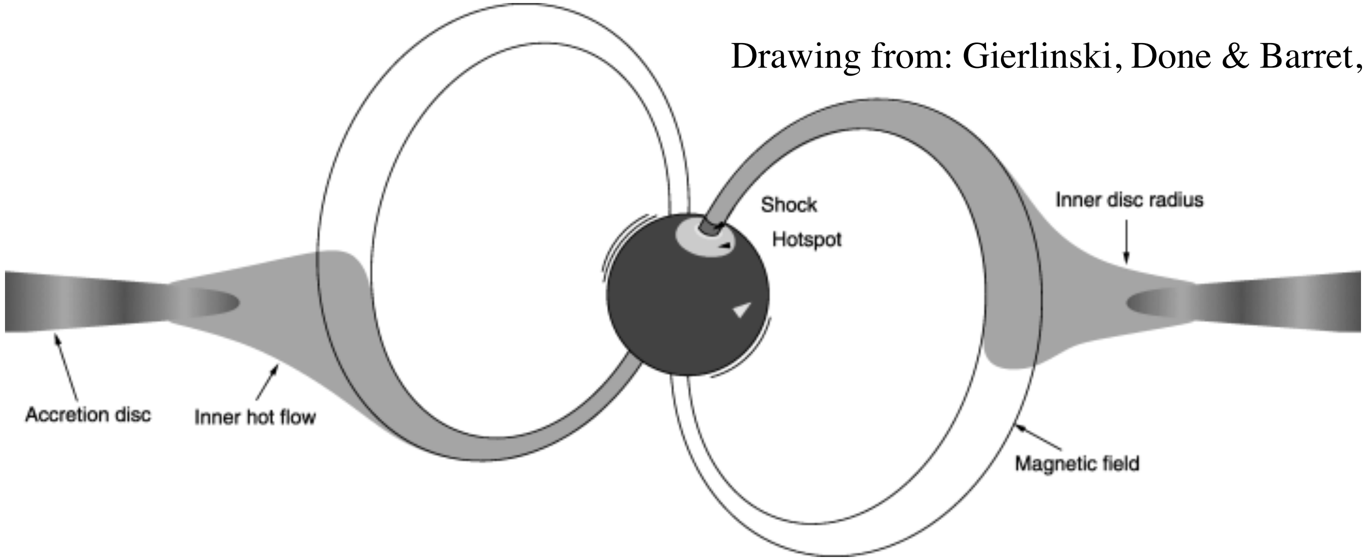
Neutron Star Radius’ Role: Tidal deformation can “waste” orbital energy making inspiral evolve faster than for point particles
Rough limits R < 14 (ish) km

Effect of Stellar Oblateness



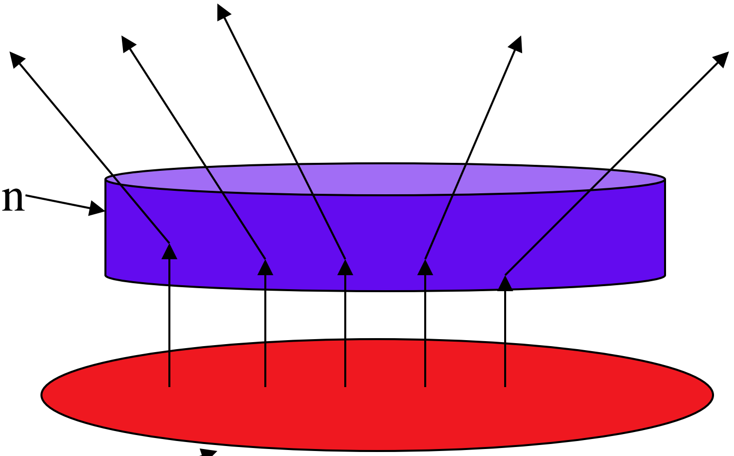
Morsink, Leahy, Cadeau & Braga 2007 ApJ

Hot Spot Model for Accreting X-ray Pulsars



Drawing from: Gierlinski, Done & Barret, 2002, MNRAS

Side View of Hot Spot:



Electron plasma above spot Compton scatters “seed” blackbody photons

Anisotropic emission (anti-beaming)
Sunyaev & Titarchuk

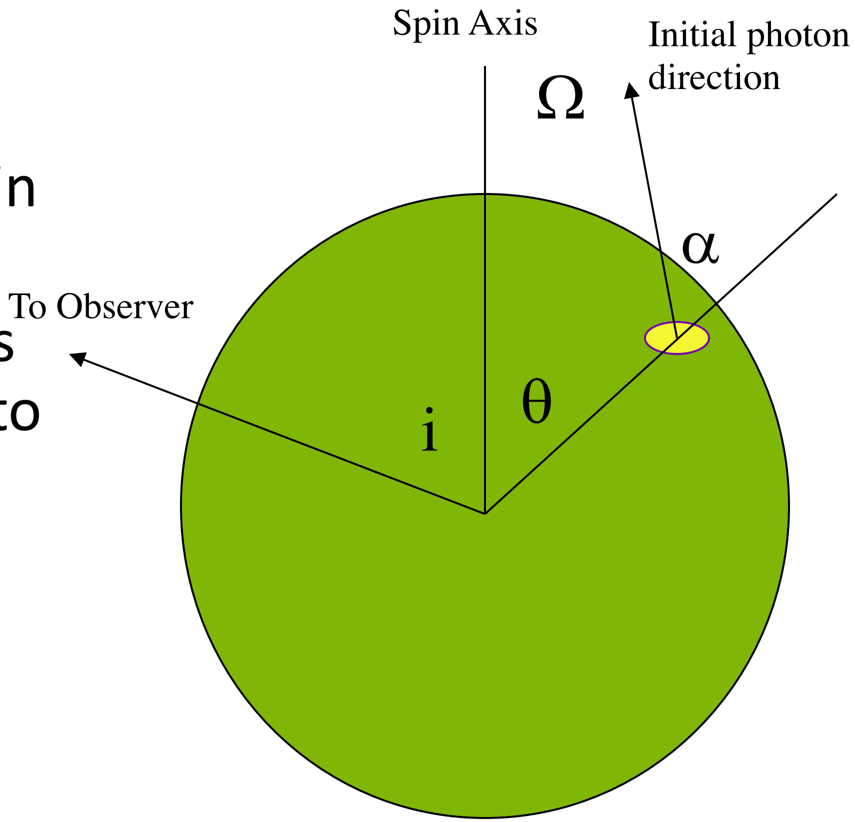
Isotropic emission

Blackbody emission from surface of star

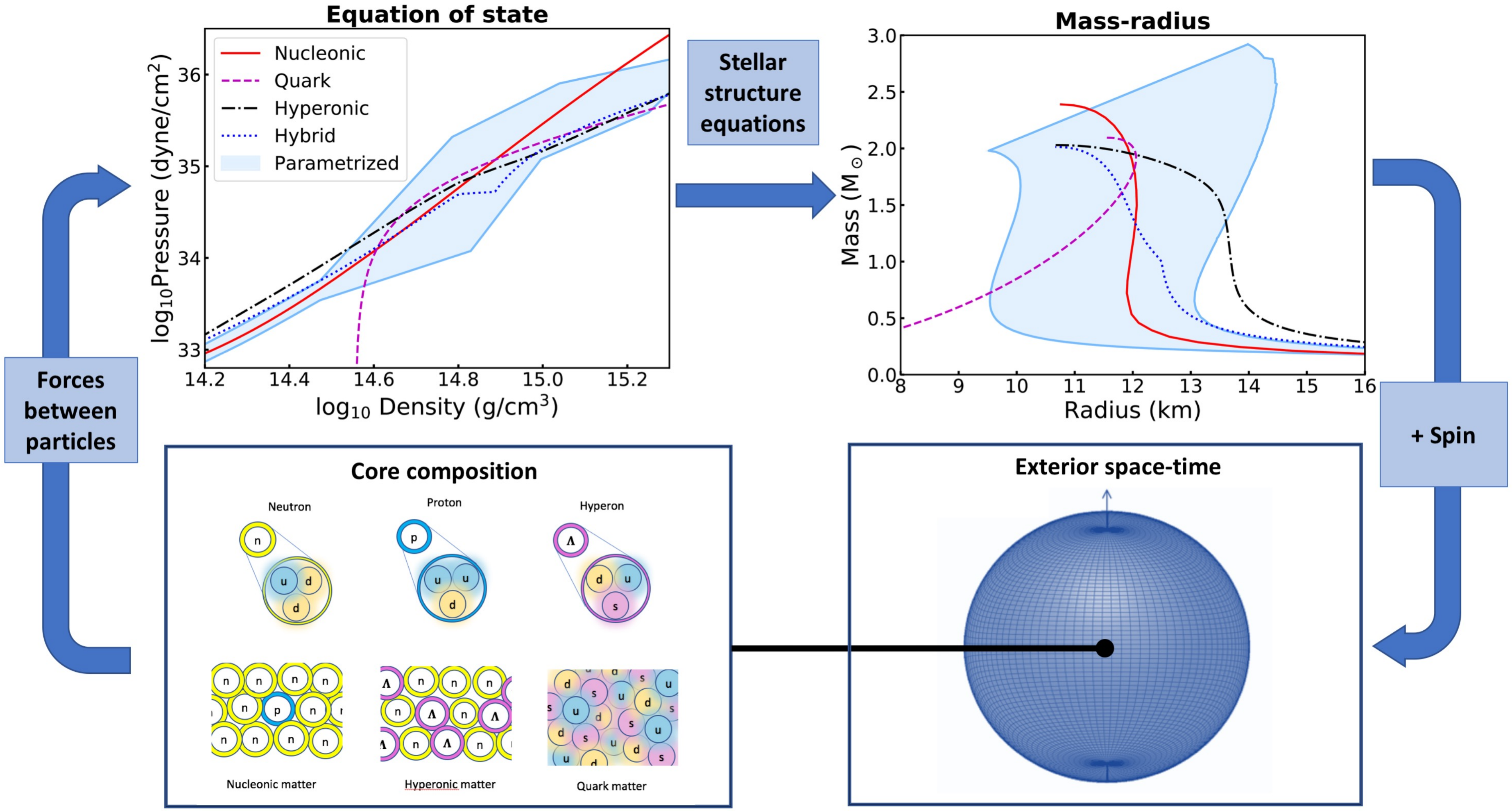
Inclination and emission angle

- θ = angle between the hotspot's centre and the spin axis
- i = angle between the observer and the spin axis (orbital and spin angular momenta aligned)
- α = angle between the photon's initial direction and the normal to the surface.

- Relative values of I and θ affect visibility, modulation and timing asymmetries.
- Independent of photon energy



Relating nuclear physics to space-time



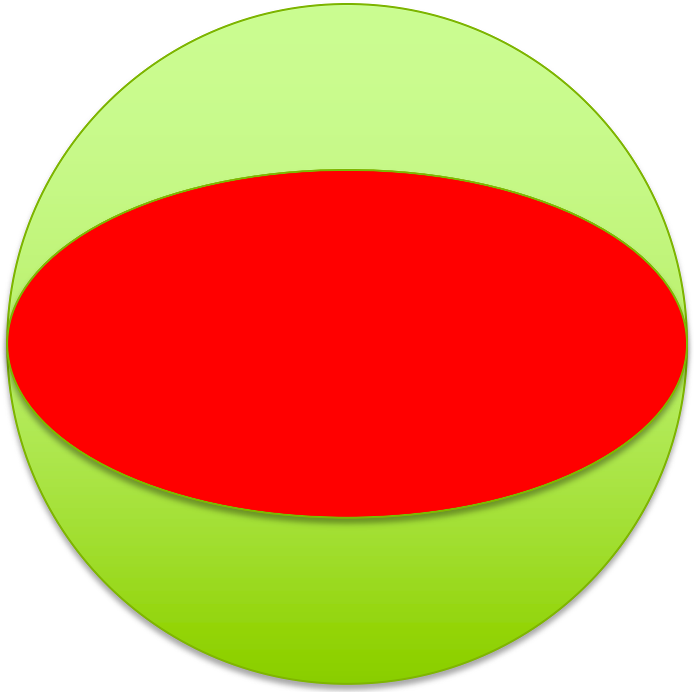
Stellar structure equations

Forces between particles

+ Spin

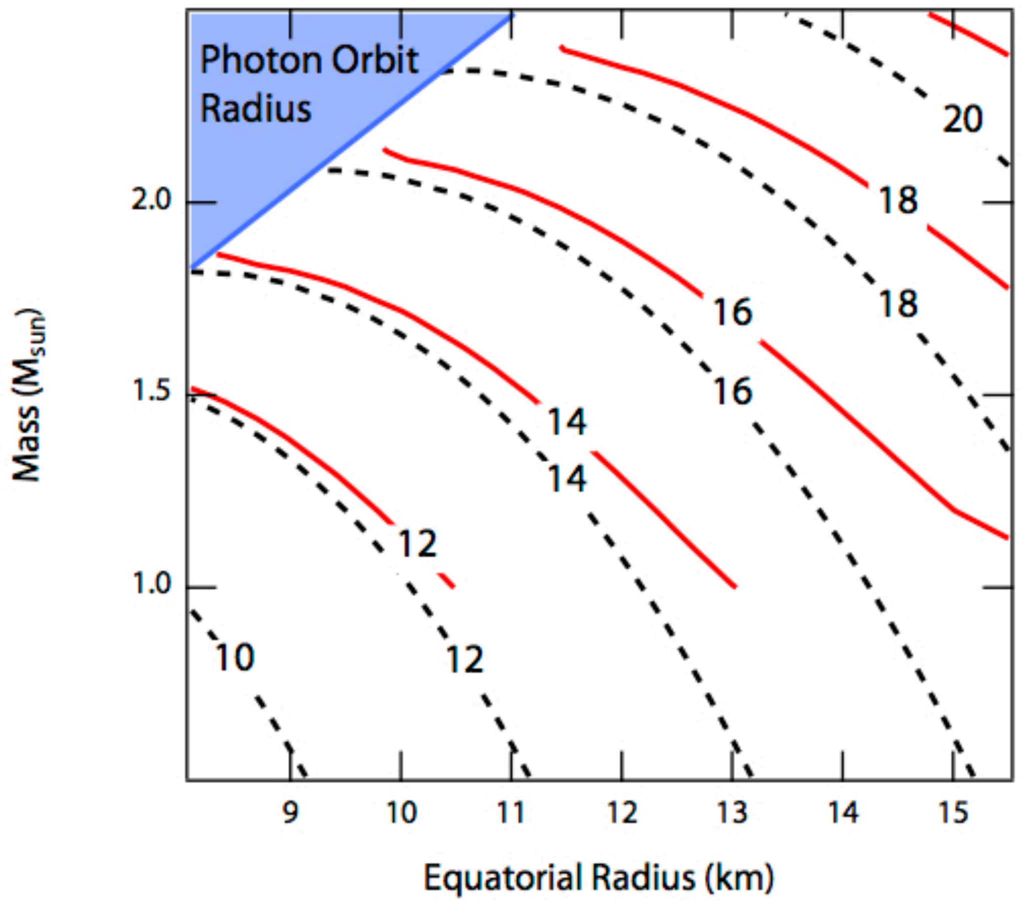
Figure: Adapted from Ray et al. 2019

Rotational Effect on Luminosity Radius



- An oblate star with the same equatorial radius as a spherical star has a smaller cross-sectional area A
- Flux ∝ A so assuming a sphere underestimates the equatorial radius of the star

Luminosity Radius vs “Real” Radius



Pure Blackbody: Baubock, Ozel, Psaltis, Morsink, ApJ 2015

Assuming a spherical star could lead to underestimating the radius by 3-5%

Generalization to more realistic Atmosphere by UofA MSc Student Charlee Amason

----------- Luminosity Radius for zero spin $R_L = R(1-2M/R)^{-1/2}$

—— Luminosity Radius for spinning star (600 Hz)